Hybrid Integrated Components for Optical Display Systems -- Electroactive Polymer Based Micro-Opto-Electro-Mechanical Actuators

by
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Abstract

The current worldwide market for TV and projectors is a multi-billion dollar business. It is expected that laser based displays will gradually replace standard lamp projection systems, attributed to their outstanding performance in: large colour gamut, high contrast and long lifetime. One of the technical obstacles to overcome for wide acceptance of lasers displays is the speckle noise, which is an image degrading phenomenon inherent in the coherent laser light.

The demand of the market gives the motivation of the project BIA-286 (founded by Research Council of Norway, Project number 182667): hybrid integrated components in laser display systems for speckle reduction. As part of the project, the thesis focus on de-speckle solutions based on electroactive polymer (EAP) technology and micro-electro-mechanical systems (MEMS) technology. To be more specific, in the present work we are looking for modulators, with working mechanism of polymer electro-mechanical actuation, to apply in laser display systems for speckle reduction. The modulators are expected to possess the merits such as compact, efficient, easy implantation and low cost.

Two working packages are included in the thesis: material investigation/optimization and modulator design/fabrication. As one of most widely used EAPs, dielectric elastomers (DEs) are investigated, since their physical properties can be tuned by modification of their chemical structures. The target of DE material investigation/optimization is obtaining a polydimethylsiloxane (PDMS) with fast response time and requiring low driving voltage. In-depth understanding of PDMS, i.e. the polymer micro-structure dependent electro-mechanical properties, is established (Reported in Article I). The PDMS network structures are modified to achieve the desired physical properties. PDMS with highly cross-linked network and minimum residual groups show fast response time, but require high driving voltage.

We proceed to optimize PDMS electro-mechanical performance via network swelling, as reported in Article II. Cross-linked PDMS is swollen by silicone oil. By introducing short chain miscible solvent, polymer chains are surrounded by highly mobile solvents. The ease of chain movement results in lower driving voltage requirement. Meanwhile, the response time of PDMS increased, but the increase is rather moderate comparing with the increase in Article I.
Next, PDMS material optimization is carried out by filling PDMS with TiO$_2$ nanoparticles (reported in Article III). The PDMS-TiO$_2$ nanocomposite is prepared by in-situ polymerization. The dielectric constant of PDMS-TiO$_2$ composite increases with the filler concentration. An optimization point is found at 5 wt% TiO$_2$ particles. Comparing with neat PDMS, the driving voltage is reduced (due to the increased dielectric constant), and the response time is improved (due to the decreased chain mobility).

The second working package focuses on designing and fabricating of DE based modulators, either as spatial light modulators (SLM) or de-speckle modulators. A SLM with PDMS film sandwiched between two metal electrodes is reported in Article I. An air gap structure is proposed and demonstrated in Article II. The reliability of the SLM is improved by avoiding direct contact between the deformable PDMS surface and the rigid electrodes. An alternate strategy for improving the modulator reliability is replacing the top metal electrodes with transparent conductive polymer (PEDOT: PSS), as reported in Article IV. This SLM has a sandwich structure PEDOT: PSS/PDMS/Gold electrode. Reliability of the device is improved since PDMS is more compatible with PEDOT: PSS than metals.

The DE material is applied in de-speckle modulators. A modulator by using dynamic gratings for speckle reduction is proposed in Article V. To achieve a high de-speckle efficiency, the DE material with response speed of 10 µs is employed. By dynamically splitting the laser beam into different high orders and then passing through a diffuser, varied speckle patterns are generated on the screen. The speckle noise is smoothed out by adding these speckle patterns together in the integration time of human eye. A de-speckle modulator with DE material as dynamic gratings is fabricated and demonstrated for 50 % speckle reduction.

Besides the DE based modulator, we also look for other speckle reduction techniques. Two piezoelectric benders have been employed for speckle reduction, as reported in Article VI. Speckle noise is suppressed to 6 % and 9 % in free space geometry and imaging geometry respectively, by dynamically changing the illumination angle of the laser beam on a random phase diffuser.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>CP</td>
<td>Conductive Polymer</td>
</tr>
<tr>
<td>CPO</td>
<td>Copper-Phthalocyanine Oligomer</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>DE</td>
<td>Dielectric Elastomer</td>
</tr>
<tr>
<td>DMD</td>
<td>Digital Micromirror Device</td>
</tr>
<tr>
<td>DOE</td>
<td>Diffractive Optical Element</td>
</tr>
<tr>
<td>EAP</td>
<td>Electroactive Polymer</td>
</tr>
<tr>
<td>ERFP</td>
<td>Electrostrictive Relaxor Ferroelectric Polymers</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>GLV</td>
<td>Grating Light Valve</td>
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<tr>
<td>IG</td>
<td>Ionic Gel</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium Tin Oxide</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-Electrical-Mechanical Systems</td>
</tr>
<tr>
<td>MOEMS</td>
<td>Micro-Opto-Electro-Mechanical Systems</td>
</tr>
<tr>
<td>MW</td>
<td>Molecular Weight</td>
</tr>
<tr>
<td>OLED</td>
<td>Organic Light Emitting Diode</td>
</tr>
<tr>
<td>PANI</td>
<td>Polyaniline</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>PEDOT</td>
<td>Poly(3,4-ethylenedioxythiophene)</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate</td>
</tr>
<tr>
<td>PMN-PT</td>
<td>Lead Magnesium Niobate-Lead Titanate</td>
</tr>
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</table>
Preface

This thesis is submitted in fulfilment of the requirements for the degree of Philosophiae Doctor at the University of Oslo, Norway.

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1 Introduction

1.1 Overview of the electroactive polymer technology

Electroactive polymers (EAPs) have attracted considerable interests in applications of electro-mechanical actuators. Traditional actuators include electro-magnetic actuators, motors, hydraulic cylinders and pneumatic actuators. The relatively big size, heavy weight, complex transmission and high cost of production limit their application area and motivate the research on alternative technologies [1]. EAPs are polymers that exhibit a change in size or shape when stimulated by an electric field and are emerging as a new class of actuation material. The advantage of the EAP based modulators involve lightweight, low cost, durability, easy fabrication, simple actuation configuration, etc [2].

EAPs can be broadly categorized into two major classes: electronic EAPs and ionic EAPs. Further subdivision based on their actuation mechanism and type of material involved is also possible. Dielectric elastomers (such as silicones [3-6], polyurethanes [3, 7], acrylcs [4, 8, 9]), electrostrictive relaxor ferroelectric polymers (such as polyvinylidene fluoride [3] and poly(vinylidenefluoride-co-trifluoroethylene)) [10-12] and liquid crystal elastomers [13-15] can be put under electronic classification. The actuation of electronic EAPs is generally from Maxwell stress or electrostriction. Ionic gels (such as polyacrylic acid gels [16, 17]), ionic polymer-metal composites [18-20] and conductive polymers (such as polypyrroles [21, 22] and polyanilines [23, 24]) fall under the ionic classification. The actuation mechanism for ionic EAPs involves the diffusion or mobility of ions. A comparison of EAP material properties is given in Table. 1.

The actuation mechanisms and configurations vary with the type of EAPs. Taking electrostrictive relaxor ferroelectric polymers as an example, when the voltage is applied, the polar groups start to align with regard to the electric field and result in crystal elongation. This deformation is reversible when electric field in opposite direction is applied. Poly(vinylidenefluoride-co-trifluoroethylene) has been investigated by Zhang’s group [25]. A microfluidic pump is realized using this material, as shown in Figure 1. In this microfluidic pump, the polymer diaphragm bends up and down under with applied electric field, pumping the fluid through the channel along the preferred flow direction.
### Table 1. Classification of EAP materials and their physical properties comparison.

<table>
<thead>
<tr>
<th>EAP materials</th>
<th>Electronic</th>
<th>EAPS</th>
<th>Ionic</th>
<th>EAPS</th>
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<td>3.2</td>
<td>0.1</td>
<td>0.1</td>
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<td>38</td>
<td>4.8</td>
<td>43</td>
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<td>22</td>
<td>1.8</td>
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<td>IG--Polyelectrolyte</td>
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<td>CP--PANI</td>
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<th>DE--Polyurethane</th>
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<th>IG--Polyelectrolyte</th>
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<td>Fast</td>
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<td>Fast</td>
<td>Slow</td>
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<td>Specific density (g/cm³)</td>
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<td>0.39</td>
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<td>43</td>
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<td>Maximum strain (%)</td>
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<td>38</td>
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<td>0.1</td>
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Hybrid Integrated Components for Optical Display Systems -- Electroactive Polymer Based Micro-Opto-Electro-Mechanical Actuators

1.2 Dielectric elastomer: actuation mechanism and configurations

Dielectric elastomers have been reported to have large achievable strain/stress, fast response speed, long life time, high reliability and durability [27]. Some types of DE, such as polydimethylsiloxane (PDMS), is chemical and environmental inert. It has resistance to high temperature, UV radiation and chemical attack. Moreover, the physical properties of DEs can be tuned based on application requirements, by modifying its micro-structure. Attributing to these merits, DE materials are are progressively emerging as one of the best-performing materials and they are investigated in these work.

The actuation mechanism of DE is electro-mechanical, that a mechanical movement of DE is achieved by applying electrical energy. Under electric field, DE deforms either by Maxwell stress or electrostriction, or both. The Maxwell stress effect arises from Coulomb electrostatic interactions among free charges between two electrodes. The change of electric field distribution inside the DE is manifested as strain [28]. For DE with elastic modulus $Y$ and relative dielectric constant $\varepsilon_r$, subjected to an electric field $E$, the Maxwell stress induced strain $S_{\text{Maxwell}}$, which is in the direction perpendicular to the electrodes, is calculated by:

$$S_{\text{Maxwell}} = -\varepsilon_0\varepsilon_r E^2 / Y$$

Figure 1. Schematic drawing of the microfluidic pump using P(VDF-TrFE) as the active polymer material (see Ref. [25]).

Detailed explanation of the actuation mechanisms and configurations for other EAPs refers to [1, 3, 26]. The present research focuses on dielectric elastomer (DE), which is going to be introduced in the following section.
where \( \varepsilon_0 = 8.85 \text{ pF/m} \) is the dielectric constant of vacuum, the minus sign indicates that it is always a compressive strain. The field induced deformation in silicones and acrylics elastomers is primarily due to the Maxwell stress effects [9, 27].

Electrostriction arises due to the change of material dielectric properties under electric field. The electrostriction induced strain \( S_{\text{electrostriction}} \) is calculated by:

\[
S_{\text{electrostriction}} = -Q \varepsilon_0^2 (\varepsilon_r - 1)^2 E^2
\]

where \( Q \) is the electrostrictive coefficient. From the equation, there is a direct coupling between electric polarization and mechanical strain response. Electrostriction contributes largely to the electromechanical response of polyurethanes.

In this work, one of the silicones, PDMS, are focused. Therefore it is the Maxwell stress induced strain which is mostly concerned.

The basic element of DE based actuator is shown in Figure 2, where a DE layer is sandwiched between two electrodes. At least one of the electrodes is compliant to couple to the DE deformation. For Maxwell stress induced strain, when the electric field is applied via electrodes, the electrostatic attraction between opposite charges and the repulsion of like charges on the electrodes generate stresses on DE. The DE contract in thickness and expand in area [26].

![Figure 2. Typical configuration of DE based actuators. The DE actuated by means of electrostatic forces applied via electrodes on the sides of DE material.](image)

The basic element as shown in Figure 2 can be incorporated into a wide variety of configurations. Several representative dielectric elastomer actuator configurations are given in Figure 3. The DE films can be stretched over a frame, rolled into a scroll, formed into a tubular shape, or laminated on a flexible substrate to form unimorphs and bimorphs. The most suitable configuration depends on the application requirements and the properties of DE films.
Unimorph and bimorph actuators are benders. In unimorph benders, the DE films are sandwiched between two electrodes. As one end of the DE film is fixed, when voltage is applied, the free end of the DE film bends according to the polarity of the applied field. A bimorph is stacking of two unimorph benders. Unimorph and bimorph benders have application potential in low force robotic grippers. Diaphragm actuators can exploit both directions of planar expansion of the DE films. This kind of actuators is promising in applications such as pumps and loudspeakers. Spider and bowtie actuators are designed to couple both planar directions into a single linear direction. They have been used in robotic leg applications such as the self-contained hexapod robot [29]. Spring rolls are interesting from the perspective that they are capable of providing a combination of large linear strains with relatively large output forces [30, 31]. It capable of both bending and elongation [32].

1.3 Applications of dielectric elastomers

Many applications have involved the DE actuation technology. The best example is given by Swiss Federal Laboratories in 2005 EAP arm wrestling competition [33]. The present robot, as shown in Figure 4, is driven by an array of rolled DE actuators. 250
rolled DE actuators with small diameters are arranged in two groups according to the human muscle configuration in order to achieve an arm-like bidirectional rotation movement. The robot is weight 15-20 kg and powered by a computer-controlled high voltage amplifier. Though the robot lost the arm wrestling competition against human component, it demonstrated the very bright feature for DE as artificial muscles.

Figure 4. (a) The spring roll DE actuator in robot. (b) Demonstration of arm wrestling robot. (see Ref. [33]).

Attributing to its light weight, simple actuation mechanism, easy processing, reliable and bio-compatible, DE material is an excellent candidate in compact MEMS devices. In the present work, the DE technology has been employed in MEMS modulator for optics applications, i.e. for light modulation and speckle reduction. Details of these two applications are introduced in this section.

1.3.1 Dielectric elastomer for MEMS spatial light modulator

Traditional SLMs are primarily based on silicon technology. Grating light valve (GLV) [34], which is originally developed at Stanford University, is made by an 1D array of tiny movable silicon nitride ribbons mounted on a silicon base. Digital micromirror device (DMD) [35], which is invented by Texas Instruments, uses a 2D array of tilting silicon micromirrors. Spatial optical modulator (SOM) [36], invented by Samsung, uses an array of movable ribbons made of polarized lead zirconate titanate (PLZT). Commercialized products based on these technologies are existing in the market, but the complex processing steps result in high cost of the device.

DE materials have been considered as promising candidates in MEMS spatial light modulators. The configuration and operation principle of a typical DE based SLM is illustrated in Figure 5. A thin DE film is sandwiched between top reflective electrode and rigid substrate with bottom electrodes. If no voltage is applied, the polymer has a plane
surface. The top electrode works as a flat mirror, reflecting the incoming light. If voltage is applied through the top and bottom electrodes, the polymer surface deforms into a sinusoidal shape according to the electric field distribution. From the reflective top electrodes, higher diffraction orders of the light are propagated with different angles. By selecting/blocking different diffraction orders, the light intensity of the incoming lights can be modified.

Figure 5. Operation principle of the EAP based spatial light modulator. (a) no voltage is applied; (b) voltage is applied.

DE based SLMs have many advantages comparing with traditional silicon based SLMs. Firstly, the fabrication process is simple, therefore the yield is increased and the cost is reduced. Secondly, a continuously reflective membrane is used on the top of DE, giving 100% optical fill factor. Thirdly, since the number of pixels is determined by the bottom electrodes, the resolution of the SLM is improved by enlarging the number of the bottom electrodes.

Many DE based SLMs have been investigated [37-44]. One technical obstacle in fabrication is the surface quality of metal films on DE. Buckles in metal film was reported in [44], as shown in Figure 6. The cause is explained as the big thermal expansion coefficient (CTE) difference between metal films and PDMS. During metal evaporation, the metal has a high temperature and causes the heating of PDMS. After cooling to room temperature, PDMS shrinks, resulting in the formation of buckles. An optimized fabrication procedure is proposed by Sakarya’s group in [37, 38]. Two silicon chips are bonded together with an intermediate 5 µm DE layer in between. The top silicon is deposited with 50 nm silicon nitride layer as etch stop and 80 nm aluminium layer for reflectivity and conductivity. A reflective surface with high optical quality is obtained.
when the bulk silicon of the top chip is etched away. A fabricated SLM chip together with the far-field diffraction patterns are shown in Figure 7. The SLM works at 10 Hz. A 2D deformable micromirror device are reported by Kuck’s group [45]. Their technology is compatible with CMOS technology for bottom electrodes matrix addressing. A 512 x 464 pixel SLM has been successfully fabricated. Silicones are applied as the electroactive polymers to form gratings. The driving voltage is 250 V DC for bias voltages and 15 V AC for signal voltage. Working frequency at 1 kHz is reported for this device.

![Figure 6. Buckles in thin metal film on PDMS (See Ref. [44] ).](image)

![Figure 7. (a) Photography of a packaged SLM. (b) Far-field diffraction pattern of a semi-actuated (up) and a full-actuated SLM (down).](image)

### 1.3.2 Dielectric elastomer for MEMS de-speckle modulator

DE based modulator is suitable for optical modifications, such as speckle reduction. A short introduction about speckle phenomenon and state of the art de-speckle technologies are given in this section. Advantages of DE based de-speckle modulator are discussed.

In comparison of conventional lamps, the use of lasers in projection display provide many advantages such as wide colour gamut, long life time, highly directional light, high light intensity, etc. The imaging quality produced by laser projector is unbeatable even by
the latest LED, OLED technology. It has been considered as the light source for next generation. However, one major technique obstacle, which prevents applications of laser displays, is the speckle phenomenon. Speckle is induced by the light scattering and interference of coherent radiation from a screen with roughness in the scale of optical wavelength. A typical speckle pattern produced by green laser is illustrated in Figure 8. The constructive and destructive interference pattern observed on the screen masks the image information and therefore its reduction is highly desirable in projection displays. The fundamental theory of speckle formation, its statistical properties and de-speckle methods are described thoroughly by Goodman in [46]. Speckle phenomenon is evaluated by the speckle contrast $SC$. The definition, given by Goodman, is:

\[ SC = \frac{\sigma}{\bar{I}} \]  

(3)

where $\sigma$ is the standard deviation and $\bar{I}$ is the mean value of light intensity in the speckle pattern. A speckle contrast lower than 4% is desired to avoid disturbance a human observer [47]. This is challenging since a fully coherent and polarized laser produces speckle contrast of $SC=1$.

![Figure 8. A typical speckle pattern generated by green laser on a de-polarized screen.](image)

Considerable efforts have been made to minimize the speckle noise [47-61]. An efficient strategy is creating a number of speckle patterns in a short time. The averaging function of human eye can smooth the speckle noise by adding all these speckle patterns together in the integration time of human eye. Theoretically if $N$ number of independent speckle patterns are generated within 30 ms, a typical value of human eye integration time, the speckle contrast is suppressed to $SC=\bar{I} / N^{0.5}$ [46]. Dynamic speckle patterns can be generated by inserting moving or rotating diffusers into the beam or by moving the projection screen itself. Several configurations based on the moving diffusers and screens
method have been reported, including moving/rotating random phase diffusers [47, 54], moving screen and rotating diffuser [55], two spatially separated screens that are in relative motion to each other [56]. Alternative strategy for speckle reduction includes: using a static phase plate based on binary phase code [57] or on Barker code [58, 59], using ultrasonic wave induced diffraction grating [60] and using several partially coherent laser beams [61], etc.

Trisnadi [53] has reported a method to reduce speckle using moving diffusers with optimized binary phase patterns. The predetermined phase patterns are obtained by mapping the rows or columns of a Hadamard matrix [62] to the diffuser, as shown in Figure 9. In this example, 16 phase patterns are produced based on 16×16 Hadamard matrix.

In order to apply this technology into laser projection display with GLV as display chip, a 64×64 Hadamard matrix is applied for producing diffuser with 64 phase patterns. The diffuser is made by etching of the phase patterns in a fused-silica wafer. It is placed at a plane conjugate to the GLV and is set in transverse oscillatory motion by a voice coil. Within the integration time of the detector, laser beam goes through 64 phase patterns. The measured speckle image, as shown in Figure 10(b), is an average of 64 images. By using the diffuser, the speckle contrast reduced from 0.70 to 0.09, which is close to the theoretical value $0.07/64^{0.5}$.

Figure 9. Mapping from the 16×16 Hadamard matrix to sixteen phase patterns. (see Ref. [62])
Figure 10. Images and sampling of intensity fluctuation of (a) the original speckle and (b) the reduced speckle. (see Ref. [62])

Speckle reduction is achieved by applying the listed de-speckle techniques. However for those methods which need mechanical vibration or rotation of the diffuser or screen, a motor should be involved in the system. This increases the noise level and decrease the system reliability. It is also difficult for practical implementation. The methods based on binary phase code or Barker code are only applicable in line-scan projectors. Trisnadi’s method requires a huge diffuser with pre-determined phase patterns, since each pixel in the screen should be corresponded to a diffuser. When a laser array is used, the illumination optics is complicated and the cost increases.

In this work, DE based MEMS modulators are employed for speckle reduction. The modulator has similar structure as spatial light modulators. It utilizes polymer dynamic gratings for speckle reduction. When light illuminated at the polymer grating, a diffraction pattern is generated. The diffraction patterns passes through a random phase plate, projects to the screen and creates a speckle pattern. The speckle pattern is determined by the shape of the grating. By dynamically change the shape of the grating (i.e. changing the spatial frequency, the orientation), the speckle pattern is changing with time, accordingly. Adding these dynamic speckle patterns together in the integrating time of human eye, the speckle noise is reduced.

Attributing to the merits of DE material, the DE based de-speckle modulator have several advantages. Firstly, the DE is electro-active and no motor or mechanical vibration/rotation is needed. Therefore, the reliability is improved and the noise is minimized. Secondly, the de-speckle modulator is compact and lightweight because it is fabricated by MEMS micro-machining technologies. The system implantation is more
flexible. Thirdly, the fabrication process is simple and straightforward. The production cost is reduced. Last but not least, the modulators are made of chemical and environmental inert material. According to experiments in [63], it can stand 80 °C, 80% humidity, and long-time laser exposure without any degradation, providing the capability to work in harsh environments.

1.4 Challenges of DE and DE based modulators

Though promising, there are still several technical obstacles for DEs and DE based modulators to overcome for their wide application. The first challenge is the high electric field requirement. Typical operating voltages for DE films (10-100 µm in thickness) range from 500 V to 10 kV [26]. Pelrine’s group [5] suggested that compact voltage amplifiers could be designed to solve this problem. However, the high driving voltages inevitably brings safety issues, especially in biomedical applications. Many efforts have been asserted aiming at low driving voltage of DEs. A comprehensive study was carried by Zhang’s group [64]. Different hardeners were added into silicone to form DE with varied physical properties. The study concluded that the silicone which has the lowest elastic modulus and highest dielectric constant exhibits the highest strain response. In order to reduce the driving voltage while maintaining the same strain, the elastic modulus of DE should be decreased and the dielectric constant should be enhanced. Fillers with high dielectric constant are widely used to mix with DE materials to enhance the dielectric constant. Zhang’s group reported in [64] that silicone with 20 wt% copper-phthalocyanine oligomer (CPO) fillers shows almost 80% increase in dielectric constant (from 3.27 to 5.85). The reduction of driving voltage is 28%. Szabo’s group increased the dielectric constant of silicone from 3 to 8 by mixing 70 wt% PMN-PT particles inside silicone matrix [65]. Enhancement of silicone dielectric constant from 6 to 8 was obtained by Carpi’s group, by mixing 30 wt% of TiO₂ particles into silicone [2].

The slow response speed of DEs is another challenge in developing DE actuators. Though DEs have been considered having the fastest response speed among EAP materials, the response speed is still relatively slow comparing with silicon based modulators and actuators. The response speed of DEs, which is typically in the range of milliseconds to seconds [37, 64], is originated from its intrinsic viscoelastic properties. The response speed in this range maybe good enough for some DE applications such as in energy harvesters, robots, pumps, and loudspeakers. However, a faster response speed is necessary for applications like spatial light modulators (SLM), tuneable gratings, optical
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switches and variable optical attenuator [66]. For example, in DE based spatial light modulators, a response speed in microsecond is necessary to eliminate the motion-blur in HD line-scan display systems. Techniques for improving the response speed involve reducing the viscosity of DEs. For cross-linked polymers, this is achieved by increasing the cross-linking density. Higher cross-linked elastomer exhibits less viscosity and reacts faster to the stimulation. However, the elastic modulus increases with the cross-linking density, meaning a higher driving voltage is needed to activate the DEs. This is a trade-off situation between response speed and driving voltage. Optimisation of the polymer network structure is desired to achieve both the response speed and low driving voltage.

Other challenges in developing DE actuators include selecting of suitable compliant electrodes. In DE actuator configurations, the electrodes contact with DE and couple to the deformation. It is important to find compliant thin electrodes to deform with the DE and without generating an opposing stress or losing conductivity during DE actuation. In early stage of DE actuator development, thin metal films were deposited on the surface of DE material as electrodes. This has been approved impractical. Cracking on metal films during DE deformation was observed because of the stiff metal films and the big CTE difference between metal and polymer. Kofod’s group investigated a number of compliant electrodes for DE actuators, including carbon black, rubber electrodes, glue electrodes, grease electrodes and dust electrodes [67]. It turns out that grease electrodes shows best performance in DE actuators. Nevertheless the messy nature of grease electrodes and their uniformity problems have driven researchers to investigate more sophisticated alternatives. The most recent development of compliant electrodes is single wall carbon nanotubes, which has been presented by Yuan’s group in [68].

The choice of DEs in different applications is also important. To date, the development of DEs focuses on two types: acrylics and silicones. These two types of DEs show great electro-mechanical performance under applied electric field. Generally speaking, actuator designed using acrylic elastomer is impractical since its property is largely dependent on temperature. Silicone, on the other hand, shows resistance to temperature variation and environmental degradation. Its physical properties remain constant over a wide temperature range. High actuation efficiency is a further advantage of silicone over acrylic attributed to its lower viscosity. At last, silicones are more biocompatible than most carbon-based polymers [69], and therefore are more suitable for biomedical applications.
1.5 Aims and tasks of the study

The main objective of the project is to design and fabricate optical components for display systems. Specifically, we are looking for modulators, which are compact, efficient and low cost, to apply in laser display systems for speckle reduction. The solution is a micro-opto-electro-mechanical systems (MOEMS) modulator based on micromachining and dielectric elastomer technology. As part of the project, the present research focuses on two fields: DE material investigation and modulator design/fabrication.

The aim of the material investigation, is finding a DE material, which exhibits high electro-mechanical performance and suitable as actuation material for MEMS modulators. The tasks include:

- Literature survey and theoretical analyse of DE material properties, actuation mechanisms, configurations, challenges and solutions.
- DE electro-mechanical properties characterization: Measurement system design, construction and calibration; material properties testing.
- DE electro-mechanical properties optimization: PDMS micro-structure tuning via cross-linking density controlling, swelling, and dielectric nanoparticles mixing.

The DE materials with optimized properties are applied in MEMS modulators. The target is to design and fabricate a DE based MEMS modulator, which can be implemented into laser display systems for speckle reduction. The MEMS spatial light modulators based on DE technology is another outcome. The tasks in this part include:

- Study and literature survey of the speckle fundamentals, lasers, state of the art of de-speckle methods.
- Finite element method (FEM) simulations of modulators performance: structure dependence, material properties dependence, driving condition dependence, etc.
- Component design and fabrication: designing of the modulator structure based on FEM simulations; planning the fabrication process and performing the device fabrication in clean-room using micromachining technology.
- Speckle reduction characterization: using the fabricated de-speckle modulator in constructed optical systems for speckle reduction; comparing the experiments with the theoretic value; optimization in system level.
- Spatial light modulator characterization.
1.6 Outline of the thesis

The thesis is organized based on the published and submitted journal articles. The first chapter “Introduction” gives an overview about state of the art technologies, the motivation and the scope of the research. In Chapter 2 “Summary of the articles”, the published and submitted journal articles are collected. All articles are briefly described and discussed. Each article represents a stage of the work. These articles are organized in a symmetrical way to show the progress of the research step by step. The full-length articles are enclosed in the end of the thesis. In Chapter 3 “Conclusions”, the investigations are summarized and the contribution of this work to science is concluded.
2 Summary of the articles

In this section, four published and two submitted journal articles are collected and summarized to present the research content during Ph.D studies. The research consists of two packages: the investigation of DE material is focused in Article I, Article II and Article III; the DE applications in SLM and in de-speckle modulator are described in Article IV and Article V. Another technique to reduce speckle noise by using piezoelectric material is reported in Article VI. Collected articles are briefly described based on the research motivation, experiments, results and discussion. The collected articles are organized in terms of the research stage, rather than the publication date. The full-length articles are enclosed in the end of the thesis.

2.1 Article I


Motivation:

The motivation of this work is study of DE materials and improves their electromechanical actuation performance. Because the DE is going to be applied in MEMS modulators for light modulation, a fast response time of DE is required to ensure the modulation efficiency. Moreover, a low driving voltage is always desired from the safety and system simplicity points of view. These two challenges, which are not just to DEs but to all the EAPs, are the primary motivations in this work.

Another motivation is establishing the material characterization systems. In order to perform materials characterization, reliable and precise measurement systems is necessary. Elastic modulus and response time are the most interested properties in this work and corresponding measurements system is important.
**Experiments:**

Among all DEs, PDMS is chosen as the actuation material, attributed to its fast response, softness, and chemical/environmental resistance. Most importantly, its physical properties can be tuned by modifying its network structure. The target is obtaining a PDMS with fast response time and low elastic modulus (therefore, need low voltage to achieve the same strain, as indicated by Equation.1). The solution is PDMS microstructure modification. PDMS elastomers have three-dimensional networks, which are formed by hydrosilylation process [70]. In this work, the 3D network of PDMS is formed by vinyl-terminated linear PDMS cross-linked with trimethylsiloxy-terminated methyhydrosiloxane-dimethylsiloxane copolymer in the presence of platinum complex catalyst. The electro-mechanical properties of PDMS depend on both the cross-linked network and the residual chemical groups. The PDMS cross-link density and the amount of chain entanglements in PDMS network is modified by changing the cross-linker concentration, chain length of linear PDMS, functionality of cross-linker.

The measurement systems for response time and elastic modulus characterization are constructed. The response time is measured by an optical-mechanical system, as shown in Figure 11. The testing polymer is deposited on a prism coated with an indium tin oxide (ITO) layer (works as one electrode). A metal needle (works as another electrode) is suspended close to the polymer film. With the voltage applied, a small spot on the polymer (the area under the needle) experience Maxwell stress and deform. The deformation results in light diffraction and scattering, which is detected by the photodetector. The response time is obtained by comparing the detected signal to applied voltage in an oscilloscope.

![Image](image.png)

**Figure 11.** Diagram of the response time measurements. (a) Measurement setup; (b) Applied AC voltage and detected light intensity in oscilloscope.
The elastic modulus of the polymer is obtained by Hertz equation [71] using a mechanical measurement system, as illustrated in Figure 12. A metal probe with sphere indenter is fixed with a load cell. The probe is controlled to move perpendicularly to the polymer surface by a control stage. When the indenter touches the polymer surface, the contacting force is detected by the load cell. According to Hertz equation, there is a linear relationship between indentation depth of power 3/2 and the force on indenter. The elastic modulus is a function of the gradient and it is acquired by fitting indentation depth with regard to detected force.

Results and discussion:

The influence of the cross-linker concentration, linear PDMS chain length and functionality of cross-linkers on response time and elastic modulus are presented in Table 1, Table 2 and Table 3, respectively. From Table 1, a fastest PDMS elastomer (9 μs) is obtained at 10% cross-linker concentration, indicating that an ideal network is formed with minimum residual groups. According to the experiments, this network is not formed when the function groups of cross-linker (Si-H) are equal to that of the linear PDMS (C=C), but is achieved in the presence of extra Si-H groups. This is attributed to oxidation/hydrolysis side reactions of Si-H groups, via reaction with other compounds such as oxygen and moisture in air [72].
Table 1. Dependences of response time and elastic modulus on cross-linker concentration.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Cross-linker Concentration</th>
<th>C=C:Si-H</th>
<th>Response time (μs)</th>
<th>Elastic modulus (kPa)</th>
<th>Curing time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>3%</td>
<td>1:0.4</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>A2</td>
<td>4%</td>
<td>1:0.5</td>
<td>11200</td>
<td>8</td>
<td>84</td>
</tr>
<tr>
<td>A3</td>
<td>5%</td>
<td>1:0.6</td>
<td>980</td>
<td>32</td>
<td>63</td>
</tr>
<tr>
<td>A4</td>
<td>8%</td>
<td>1:1.0</td>
<td>65</td>
<td>278</td>
<td>41</td>
</tr>
<tr>
<td>A5</td>
<td>10%</td>
<td>1:1.2</td>
<td>9</td>
<td>601</td>
<td>22</td>
</tr>
<tr>
<td>A6</td>
<td>20%</td>
<td>1:2.4</td>
<td>100</td>
<td>481</td>
<td>6</td>
</tr>
<tr>
<td>A7</td>
<td>40%</td>
<td>1:4.8</td>
<td>700</td>
<td>122</td>
<td>2</td>
</tr>
<tr>
<td>A8</td>
<td>45%</td>
<td>1:5.3</td>
<td>800</td>
<td>79</td>
<td>2</td>
</tr>
<tr>
<td>A9</td>
<td>60%</td>
<td>1:7.1</td>
<td>x</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>A10</td>
<td>65%</td>
<td>1:7.7</td>
<td>x</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>A11</td>
<td>67%</td>
<td>1:8.0</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* A gel-like elastomer cannot be formed.

x The response time is impossible to measure since the polymer is extremely sticky and soft.

From Table 2, the response time increases with molecular weight of linear PDMS. It is due to the increased chain lengths between the cross-linking sites. In other words, the cross-link density is lower with increased chain length of linear PDMS, and polymer with lower cross-link density is slower. When long chain linear PDMS mix with cross-linker, the long-range chain-chain interactions, called “chain entanglements”, dominated the polymer network. The consequence of the entanglements domination (B4, B5) is the significantly increase response time [73]. Therefore a short linear PDMS is the choice to form a cross-linking dominated PDMS network, if fast response speed is desired.

Table 2. Dependences of response time and elastic modulus on linear PDMS chain length.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Molecular weight of linear PDMS (g/mol)</th>
<th>Response time (μs)</th>
<th>Elastic modulus (kPa)</th>
<th>Curing time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>800</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>B2</td>
<td>6000</td>
<td>5</td>
<td>712</td>
<td>28</td>
</tr>
<tr>
<td>B3(A5)</td>
<td>9400</td>
<td>9</td>
<td>601</td>
<td>22</td>
</tr>
<tr>
<td>B4</td>
<td>28000</td>
<td>190</td>
<td>380</td>
<td>7</td>
</tr>
<tr>
<td>B5</td>
<td>62700</td>
<td>500</td>
<td>175</td>
<td>1</td>
</tr>
</tbody>
</table>
* A gel-like elastomer cannot be formed.

According to Table 3, with the decrease of cross-linker functionality (C1 → C4), the cross-link density is smaller; therefore a slower and softer PDMS is obtained. The relationship between response time and elastic modulus show agreement with the “Voiget-Kelvin model” [74], in which the response time is inversely proportional to the elastic modulus.

Table 3. Dependences of response time and elastic modulus on the functionality of cross-linker.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Molecular weight of cross-linker (g/mol)</th>
<th>Functionality of cross-linker</th>
<th>Response time (μs)</th>
<th>Elastic modulus (kPa)</th>
<th>Curing time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1050</td>
<td>9.2</td>
<td>8</td>
<td>781</td>
<td>2</td>
</tr>
<tr>
<td>C2</td>
<td>1950</td>
<td>8.9</td>
<td>8</td>
<td>697</td>
<td>2</td>
</tr>
<tr>
<td>C3(A5,B3)</td>
<td>1950</td>
<td>4.8</td>
<td>9</td>
<td>601</td>
<td>22</td>
</tr>
<tr>
<td>C4</td>
<td>1950</td>
<td>2.2</td>
<td>200</td>
<td>79</td>
<td>48</td>
</tr>
<tr>
<td>C5</td>
<td>1950</td>
<td>1.1</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

*A gel-like elastomer cannot be formed.*

Based on the experiments, PDMS elastomer formed by short chain vinyl-terminated PDMS cross-linking with high functionality cross-linker has the fastest response speed. Such polymer has densely cross-linked networks with minimum residual groups. They are good candidates for MEMS modulators. The PDMS elastomer, which has response time of 9 μs and elastic modulus of 601 kPa is prepared and applied as the actuation material in a MEMS spatial light modulator.

A SLM, as shown in Figure 13(a), is fabricated using micro-machining technology. In this SLM, the actuation material PDMS is sandwiched between rigid glass substrate and thin gold film. Under the applied voltage (250V DC and 100 V AC), the surface of elastomer deforms, forming a sinusoidal grating. The functionality of this PDMS based SLM is demonstrated by illuminating it with a laser beam. As shown in Figure 13(b), the polymer grating successfully diffracted light into higher orders.
Figure 13. Photographs of (a) Fabricated SLM chips using PDMS as actuation material; (b) Diffraction patterns from the SLM.

2.2 Article II


Motivation:

Based on Article I [75], the response time and elastic modulus of PDMS can be tuned by modifying its network structure. A PDMS with fast response time is achieved, but with the cost of increased elastic modulus. Typically PDMS with fast response speed has highly cross-linked network and maintain high elastic modulus. Another strategy, aiming to obtain both fast response speed and low elastic modulus, or to obtain fast response speed with slightly increased elastic modulus, should be explored for improving the performance of PDMS in MEMS modulator.

The structure of SLM proposed in Article I has a metal film directed deposited on PDMS deformable surface. This is not a good choice since the metal film may bring reliability problems due to fatigue and creep, not to mention that the film itself mechanically constrain the deformation of PDMS. Improvement of the SLM structure is desired in the device reliability point of view.
Experiments:

The solution for material optimization is PDMS micro-structure modification via network swelling. Cross-linked PDMS is swollen by silicone oil with molecular weight around 700. Samples with solvent concentration varied from 0% to 90% are prepared and characterized.

The SLM is designed to avoid the direct contact between PDMS deformable surface and rigid electrodes. An air-gap structure is proposed. The air gap between PDMS and signal electrodes allows free deformation of PDMS and avoids fatigue and creep of the electrodes. The SLM is fabricated using micro-machining technology. The fabrication process is described in Figure 14.

Results and discussion:

The dependence of response time and elastic modulus on solvent concentration is plotted in Figure 15. By introducing short chain miscible solvent into PDMS, the polymer network is swollen. Because the polymer chains are surrounded by highly mobile
solvents, the chain movement is promoted. The ease of chain movement results in the decrease of elastic modulus. Meanwhile, the response time of PDMS increased, but this effect is rather moderate. To show the advantage of this optimization method, the properties of PDMS via network swelling are compared with the results from Article I [75]. As shown in Figure 16, in order to obtain a PDMS with similar response time, the PDMS tuned by network swelling has much lower elastic modulus.

Figure 15. Response time and elastic modulus of swollen PDMS with regard to solvent concentration.

Figure 16. Comparison of response time and elastic modulus of PDMS between this work and Article I.

The PDMS, which has elastic modulus 200 kPa and response speed 34 µs, is applied in a SLM. The schematic of the device is shown in Figure 17. It is driven by 200 V DC voltage and 60 V AC voltages to the ITO and interdigital electrodes, respectively. The response time of the modulator is measured as 35 µs. The SLM shows no degradation or
breakdown after millions of actuation cycles. It functioned well after storage in room temperature for a month, indicating good reliability of the device.

Figure 17. Schematic of the air-gap SLM structure: (a) Top view; (b) Cross-section view.

2.3 Article III


Motivation:

From Article I [75] and Article II [76], we see that the fast response time obtain with the cost of increase of elastic modulus. The aim for DE material properties optimization is to achieve fast response and low driving voltage. From Equation. (1), the low driving voltage is accomplished either by decreasing the elastic modulus, or increasing the dielectric constant of DE actuation material. Mixing of polymers with dielectric or piezoelectric fillers to form polymer composites has been recognized as an efficient way to increase the dielectric constant of polymers. According to [77], when fillers with dielectric constant $\varepsilon_{\text{filler}}$ mixed with polymer with dielectric constant $\varepsilon_{\text{polymer}}$, the dielectric constant of the composite $\varepsilon_{\text{composite}}$ is in the range of: $\varepsilon_{\text{polymer}} < \varepsilon_{\text{composite}} < \varepsilon_{\text{filler}}$. The work
present in this article is to prepare fillers modified PDMS, which has enhanced dielectric constant, to reduce the driving voltage requirement.

Experiments:

As the host polymer, PDMS with three dimensional networks is formed by crosslinking linear vinyl-terminated PDMS with trimethylsiloxoy-terminated methyhydrosiloxane-dimethylsiloxane copolymer. TiO$_2$ nanoparticles are selected as fillers due to its high dielectric constant, chemical inertness, non-toxicity and easy dispersion in silicones [2]. The PDMS-TiO$_2$ nanocomposite is prepared by in-situ polymerization. Firstly, TiO$_2$ particles are mixed with linear PDMS in the presence of polyether-modified silicone, which works as dispersant. These components are mixed by high energy ball-milling for 24 hours. Secondly, the cross-linker and catalyst are added into the solution sequentially, followed by 2 minutes manual stirring after each step. Finally, samples are cured at room temperature for 30 minutes.

Results and discussion:

Inhomogeneous dispersion due to pronounced agglomeration tendency of nanoparticles is a common phenomenon for synthesizing polymer nanocomposites [27]. Two techniques have been applied to suppress the agglomeration. High-energy ball-milling is employed during mixing, providing high impact and shear energy to break agglomerates. Moreover, polyether-modified silicones, which is a good dispersant for dispersing TiO$_2$ into silicones, is used for homogenous dispersion and avoiding particles re-agglomeration.

The size distribution of the dispersed particles in PDMS solution is characterized by particle size analyser and SEM. The results are given in Figure 18 and Figure 19 respectively. Both experiments indicate that the particles in PDMS solutions have size around 500 nm.
Figure 18. Particle size distribution of nanoparticles in PDMS solution with and without the dispersant, measured by particle size analyser.

Figure 19. SEM image of TiO$_2$ nanoparticles.

Light transmittance spectra for the nanocomposites films (after curing) with different particle concentrations are plotted in Figure 20. The transmittance decreases with particle concentration. At the UV range (300 nm – 400 nm), the light loss is dramatic for all films, due to the absorption of TiO$_2$ fillers at this wavelength range [16]. When it comes to the visible wavelength (400nm – 800 nm) the light loss is mostly due to the Mie scattering.
Figure 20. The transmittance spectra of 10 µm nanocomposite films with varied TiO$_2$ concentrations.

The dependence of nanocomposite elastic modulus on TiO$_2$ particle concentration is plotted in Figure 21. The influence of particles to the elastic modulus is attributed to two factors: softening effects due to the interfering of cross-linking (major effect for TiO$_2$ concentration lower than 5 wt%) and hardening effects due to the particle-polymer interaction (major effect for TiO$_2$ concentration higher than 5 wt%). At 5 wt% particle concentration, the two effects are balanced with each other, and the elastic modulus is more or less the same as neat PDMS elastomer.

Figure 21. The elastic modulus of nanocomposites with varied TiO$_2$ concentrations.

The effect of particle concentration on the response time is given in Figure 22. With increase of the particle concentration, the PDMS response time increase and then
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decrease. An optimization point is found at 5 wt% particle concentration. Comparing with neat PDMS, the response time of PDMS with 5 wt% fillers improves from 9 µs to 6 µs, while the elastic modulus is more or less the same.

Figure 22. The response time of nanocomposites with varied TiO$_2$ concentrations.

The dependence of the dielectric constant on particle concentration is shown in Figure 23. A sharp increase of the dielectric constant from 2.97 to 3.85 is observed when the concentration of TiO$_2$ particles increases from 0 wt% to 5 wt%. Thereafter, the dielectric constant gradually increased to 4.4 with particles concentration reaching to 30 wt%. The increasing of dielectric constant is attributed to the high dielectric constant of TiO$_2$.

The measured dielectric constant of nanocomposite is compared with theoretical values calculated from several mixing rules: Maxwell-Wagner equation [78, 79], Sillars equation [80], Looyenga equation [81], and Lichtenecker equation [82]. As seen from Figure 23, none of the theoretical model predicts the dielectric constant change of nanocomposite well. The reason could be due to: these mixing rules hold for the dielectric constant at high frequency range, while in this work the dielectric constant has been measured at 100 Hz. At low frequency, the Maxwell-Wagner relaxation process [83] arises and influences the dielectric constant.
Motivation:

This work is performed after the study in Article I. Motivation of the work is to design and fabricate a novel SLM with improved reliability. Beside the air-gap structure as reported in Article II, a SLM, in which transparent a conductive polymer is utilized as electrode, is proposed. Attributing to the stability and compatibility with other polymer materials, conductive polymer PEDOT: PSS is employed as the top electrode. Moreover, PEDOT: PSS is a cheap material and gives opportunity for easy deposition by screen printing [84], spin coating [85], roll-to-roll coating [86].

Another motivation is to investigate the conductive polymer. Optical and electrical properties of the PEDOT: PSS as well as its processing technique is studied. The knowledge of conductive polymer is not only useful for SLMs but for all MEMS modulators, especially in some biological applications where an all-organic modulator is desired.
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Experiments:

In the SLM, PDMS, working as actuation material, is sandwiched between rigid glass substrate and conductive polymer PEDOT: PSS. The transmission and sheet resistance of the conductive polymer are measured for different thickness of PEDOT: PSS films.

The device is fabricated using micro-machining technology. The fabrication process is simple and straightforward. PDMS is an originally hydrophobic material exhibiting a static contact angle of 110° [87]. A surface treatment of PDMS to make it hydrophilic is necessary for the subsequent PEDOT: PSS deposition. Plasma treatment is commonly applied to change the wettability of polymers [88-90]. SF₆, Ar and O₂ plasmas are tried one after another for PDMS surface modification. The wettability is evaluated by measuring the contact angle between water drops and the modified surface. The surface morphology of PDMS after the plasma treatment is also characterized.

Results and discussion:

Unlike the SLM reported in Article I where the illumination light is reflected at the top metal surface, the device proposed in this work has transparent top electrodes. If no voltage is applied, the polymer surface is flat. Since both PEDOT: PSS and PDMS are transparent, incoming light goes through these layers with the same optical path and reflects at the underlying gold electrode. The reflected light is mainly in the 0th diffraction order. If the driving voltage is applied, the polymer surface deforms into a sinusoidal shape. When incoming light penetrates the transparent layers, which has varied thickness at different location, a spatially varying optical path of the light beam is obtained. The polymer layers act like a phase grating and diffract light into higher diffraction orders.

A prototype of the SLM has been fabricated as shown in Figure 24. PEDOT: PSS films with thickness of 100 nm are deposited on PDMS surface. As a preliminary test, the modulator has interdigital bottom electrodes and it works for one pixel. Hence there are only two signal voltages which are applied through the left and right bottom electrodes, respectively. The grating profile on PEDOT: PSS surface under 250 V driving voltage is measured by interferometer and shown in Figure 25(a). The value of the peak-to-peak deformation is approximately 200 nm.
Figure 24. A prototype of the SLM. The centre of the chip is covered by PDMS and PEDOT: PSS. The underlying interdigital electrode is zoomed in and shown in the bottom-right corner.

Figure 25. (a) Grating profile on PEDOT: PSS surface measured by an interferometer. The relief depth is exaggerated for observation; (b) Simulation results of surface grating from COMSOL. The colour grade represents the magnitude of the electric potential.

A 3D model simulation is performed by coupling electrical domain and mechanical domain in COMSOL Multiphysics [91]. The simulation results are obtained by solving the Maxwell’s equations and the Hook’s law in electrical domain and mechanical domain, respectively. The simulated PDMS grating under applied voltage is shown in Figure 25(b). The simulation results are compared with experimental results in terms of PDMS surface relief depth. As shown in Figure 26, the experiments agree with the simulations.
The response time of the device is measured as rise time 240 μs and fall time 250 μs. The response speed is determined both by the time needed for polymer deformation, and by the time constant of the RC circuit. In this work, the PDMS is synthesized to have response time of as 10 μs, while the retardation time of the RC circuit, which is calculated by $\tau = RC$, is 230 μs. The slow RC charging process is originated from the high resistance of the thin conductive polymer film. If the PEDOT: PSS is tuned to have high conductivity, as reported in [86, 92, 93], the RC charging time should be in the range of nanoseconds.

The stability of the device is tested by continuously driving the device by 200 V and 1 kHz rectangular wave for eight hours. The test shows that the modulator works well after millions times of actuation. No breakdown or reduction in the relief depth is observed. Eight hours continuously laser exposure does not bring any degradation of the modulator. The modulator works well after two months stored at room temperature.

2.5 Article V


Motivation:
As described in the introduction part, laser display has many advantages (e.g. colour performance, brightness, contrast and lifetime) comparing with conventional lamp
displays. However, the speckle phenomenon significantly degrades the imaging quality and need to be suppressed. Considerable efforts have been made to solve the problem. However, the proposed solutions are either expensive or not reliable.

A motionless diffractive optical element (DOE) is proposed in this work for speckle reduction. The key component in the device is dynamic polymer gratings, which is formed by DE material actuated under AC voltage. To achieve a satisfied de-speckle efficiency, the DE material with response speed in micro-seconds is necessary. The PDMS with optimized electro-mechanical properties using the reported techniques in Article I to III is a perfect candidate. Attributing to the merits of DE material, the de-speckle modulator have several advantages. The modulator is lightweight, compact, and therefore easy for implementation. The fabrication is simple, hence the cost is low. The reliability is improved since no mechanical vibration/rotation is used in the system.

**Experiments:**

The schematic of the modulator is shown in Figure 27(a). The de-speckle modulator has similar structure as the air-gap SLM, except in this case there are three separated polymer gratings. The polymer gratings have different orientations and spatial frequencies, which are determined by the shape of the underlying interdigital electrodes. Using micro-machining technology, a MOEMS de-speckle modulator based on DE material is fabricated and shown in Figure 27(b), where the modulator is assembled in a fixture for characterization.

![Figure 27. (a) Schematic of the dynamic DOE. Picture in the bottom shows the different electrodes in each grating. The dimensions are not to scale. (b) A fabricated DOE assembled in a fixture with electrical connection.](image-url)
The working principle of the de-speckle modulator for speckle reduction is creating \( N \) number of speckle patterns and reduce the speckle contrast to \( SC = I / N^{0.5} \) in the integration time of human eye. In the modulator, each grating can be switched “on” and “off” independently. In the “off” state, the PDMS surface is flat and the incident light is reflected at the angle of the total internal reflection (TIR); while in the “on” state, a phase grating is generated on the PDMS surface, splitting light into several diffraction orders. When one or several gratings are actuated, the incoming light is reflected sequentially and is split into a multitude of diffraction orders. There are totally \( N=2^m \) diffraction patterns for the modulator with \( m \) gratings. The diffraction patterns are scattered by a diffuser, homogenized by a light pipe and projected to the screen as speckle patterns. By actuating PDMS in high frequency, numbers of speckle patterns are generated fast and averaged out in human eye. As seen in this application, if \( N=1000 \) number of speckle patterns need to be created within the integration time of human eye (around 30 ms), the response speed of PDMS should be at least 30 \( \mu s \). It is important to optimize PDMS to achieve the response speed requirement. The PDMS used in this work has response time 10 \( \mu s \) and elastic modules 550 kPa. It is driving under 200 V DC bias voltage and 50 V AC signal voltage.

Results and discussion:

A DOE with two gratings is fabricated, and characterized for speckle reduction in the measurement setup as shown in Figure 28. A laser beam illuminates the modulator with an angle slightly larger than TIR-angles for the polymer/air and the glass/air interfaces. When voltage is applied, four diffraction patterns appeared sequentially on the first diffuser, corresponding to \( M=2^2 \) states. Photographs of these diffraction patterns are shown in Figure 29. Simulation of the modulator function to generate diffraction patterns is done in ZEMAX. As shown in Figure 29, the experimental results agree with simulations. Output diffraction spots of the modulator are scattered by the first diffuser, homogenised by the light pipe and illuminated at the second diffuser. The speckle field on the second diffuser is imaged by the CCD camera.
The speckle field registered by the CCD camera when all gratings are switched off is shown in Figure 30(a), and the speckle contrast is 0.73; while the speckle filed when four different diffraction patterns appear during the exposure time (1/32 s) is shown in Figure 30(b) with $C = 0.37$. Therefore, the speckle contrast reduction is $(0.37/0.73) \times 100\% \approx 51\%$. The original speckle contrast 0.73 is close to the expected value $1/2^{1/2}$ as it should be when the narrowband laser is scattered by a depolarizing screen. By tuning on the de-speckle modulator, $N=2^2$ number of speckle patterns are generated and detected by the CCD. According to simulations of the designed DOE, there is no overlapping between any of the four diffraction patterns, while the experiments demonstrate too that the overlapping is negligible. Thus the theoretical value of the reduced speckle contrast is $0.73 \times 1/4^{0.5} = 0.365$, which shows fair agreement with the experiments.
Figure 30. Images and sampling of intensity fluctuation of the original speckle (a) and the reduced speckle (b). The CCD level 256 corresponds to the brightest spot in the speckle pattern, while 0 corresponds to the darkest spot in the speckle pattern.

2.6 Article VI


Motivation:

Besides the DE based modulator, we also look for other speckle reduction techniques. Piezoelectric materials have been considered as good candidates, because it has stable performance, cheap and resistance to high temperature. Two piezoelectric benders have been employed in this work for speckle reduction. By dynamically changing the illumination angle of the laser beam on diffuser, different speckle patterns are generated sequentially and smoothed out in the integration time of human eye.

The measured speckle contrast depends on measurement conditions. Many parameters affect the measured speckle contrast, such as distance between camera and screen, F number of the lens, settings of the camera, etc. System calibration is necessary to fairly evaluate the speckle reduction efficiency. Examples of how to determine the measurement parameters are given both in free space geometry and imaging geometry.
Another motivation of this work is to investigate the “compound speckle” phenomenon for better understanding of de-speckle method in system level.

Experiments:

The experimental setup to implement speckle reduction in the free space propagation is shown in Figure 31. He-Ne laser (633 nm) with beam spot size 0.5 mm is employed as light source. The piezoelectric benders are deposited with thin gold film, which works as reflective mirrors. Two piezoelectric benders are placed perpendicularly to each other and driven by ±100 V AC voltage. Laser beam is reflected at two benders, and it is steered in both X and Y directions when the benders are actuated. The moving laser beam is collected by a condenser lens, and falls on a transmitting diffuser with different angles. After passing through the diffuser, laser beam propagates in free space and falls on a CCD sensor, which has pixel size of 5.6 μm × 5.6 μm.

![Figure 31. Speckle contrast measurement setup of free space geometry.](image)

Imaging geometry is constructed as shown in Figure 32. Unlike free space geometry, the scattered light after diffuser 1 is collected and homogenized by a light pipe. Diffuser 2 is placed at the output of the light pipe, to further homogenize the beam. The object, which is a transparent plastic sheet printed with a letter “S”, is placed right after diffuser 2. The CCD camera is equipped with an imaging lens.
Results and discussion:

When the piezoelectric benders are actuated, the moving laser beam is focused at a spot on diffuser via the condenser lens. The spatial position of the laser spots on diffuser remains the same while the illumination angle is changed. The laser with different illumination angle generates different speckle patterns, which are averaged out by the CCD camera during its integrating time. In order to find the suitable measurement parameters, the system calibration is done based on three criterions: 1). The speckle size detected in CCD sensor should be at least ten times bigger than with the CCD pixel size, to avoid the spatial averaging due to CCD pixel. 2). The CCD camera should be operated in its linear regime. 3). In free space geometry, ideally the original SC is equal to 1 without any de-speckle method applied. In practice, however, the SC should be $1/2^{0.5}$ (0.71) even without the motion of piezoelectric benders, due to the narrowband laser scattered at a depolarizing screen [46].

In free space geometry, the one dimensional “width of speckle” is given by $\lambda z/D$ [94], where $\lambda$ is the laser wavelength, $z$ is the propagation distance between diffuser and CCD sensor, $D$ is the diameter of the scattering spot. An approximation is for speckle size is $A_c = (\lambda z/D)^2$ [46]. The speckle size is calculated as $63.3 \times 63.3$ μm, which is big enough to avoid the CCD spatial averaging. The camera settings and light intensity are adjusted to make the camera operate in it linear regime and the obtained SC is close to 0.71. The captured speckle image with and without the actuation of the piezoelectric benders are shown in Figure 33(a) and Figure 33(b), respectively. The SC is reduced from 0.71 to 0.06.
For imaging geometry, the first two criterions as in free space geometry are employed. The third criterion is not applicable due to “compound speckle” phenomenon [46]. When light passes through diffuser 1, and falls on a finite-sized diffuser 2, there is a compounding of speckle statics. The SC of compound speckle can be bigger than 1. The speckle generated from diffuser 1 has bigger size, or “coarse speckle”; while the speckle generated from diffuser 2 has smaller size, or “fine speckle”. The fine speckle size is calculated by \( [(1+M)\times \lambda \times F\#]^2 \) [94], where \( M = f_1/f_2 \) is the optical magnification. To obtain sufficiently large fine speckle, \( F\# \) and \( M \) are set as the maximum value 16 and 2, respectively. The speckle size is 30.4 μm × 30.4 μm, which is big enough to avoid the CCD spatial averaging. The captured speckle image with and without the actuation of the piezoelectric benders are shown in Figure 33(c) and Figure 33(d). The SC is reduced from 0.87 to 0.16. The original SC is 0.87 rather than 0.71, which is due to the compound speckle phenomenon. In this case, both the fine and coarse speckle is detected by the CCD sensor. However, the coarse speckle is too big to distinguish. The size of coarse speckle is calculated size by \( [(\lambda z/D)\times M]^2 \), where \( z \) is the propagation distance within the light pipe. We assume that \( z \) is three times longer than the length of light pipe. To observe the coarse speckle clearly, the optical configuration is adjusted to: \( M = 6/25 \). The coarse speckle size is calculated as 159.5 μm × 159.5 μm. It is clear that the coarse speckle, as shown in Figure 33(e), is much bigger than the fine speckle, since the letter “S” is the same as in Figure 33(c). The coarse speckle is reduced from 0.72 to 0.09 by piezoelectric benders in imaging geometry.
Figure 33. Speckle reduction in free space geometry: (a) original speckle SC=0.71; (b) reduced speckle SC=0.06. Speckle reduction in imaging geometry with both fine and coarse speckle: (c) original speckle SC=0.87; (d) reduced speckle SC=0.16. Speckle reduction in imaging geometry with only coarse speckle: (e) original speckle SC=0.71; reduced speckle SC=0.09.
3 Conclusions

Two properties, which are the fast response time and the low driving voltages, have been focused in PDMS material investigation. By modifying the chain length of linear PDMS, the cross-linker density and the functionality of cross-linkers, it is found out that PDMS with highly cross-linked network and minimum residual groups shows fast response time, but requires high voltage to actuate (Article I). The synthesized PDMS has response time 9 µs and elastic modulus 601 kPa. The SLM, which is based on this type of PDMS, show response time of 9 µs and it is driven by 250V DC and 100 V AC. In order to reduce the driving voltage requirement of PDMS without substantial increase of the response time, PDMS network is modified via network swelling (Article II). The ease of chain movement results in reduced driving voltage requirement. PDMS with 50% solvent have response time 34 µs and elastic modulus 200 kPa. The SLM based on this PDMS has response time of 35 µs and driven by 200 V DC and 60 V AC. In the next step, the optimization of PDMS is carried out by filling PDMS with TiO$_2$ nanoparticles (Article III). The dielectric constant of PDMS-TiO$_2$ composite increases from 3.0 (neat PDMS) to 4.4 (PDMS with 30 wt% TiO$_2$). PDMS modified by adding 5 wt% TiO$_2$ particles has response time 6 µs, elastic modulus 567 kPa and dielectric constant 3.8. The fabricated SLM shows response time 6 µs and driven by 200 V DC voltage.

A SLM with sandwich structure, that PDMS film is between two metal electrodes, is proposed (Article I). This SLM shows advantages in light weight and easy fabrication, but may have reliability issue. An improved SLM with air-gap structure is designed and demonstrated (Article II). It has better reliability attributed to the absence of the contact between deformable PDMS and metal top electrodes. An alternate strategy for improving the reliability of SLM is replacing the metal top electrodes with conductive polymer (Article IV). The device reliability is achieved due to the improved compatibility between PDMS and electrodes.

PDMS based de-speckle modulator consists of many dynamic polymer gratings (Article V). An air-gap structure, similar as the SLM reported in Article II, is applied and ensures reliability of the modulator. Speckle noise is successfully suppressed to 50% when two dynamic gratings are used. Another de-speckle device investigated in this work is piezoelectric benders (Article VI). By varying the incident angle of the illumination beam with two piezoelectric benders, the speckle noise is reduced to 6%.
The investigation and exploring of this research work is valuable from both the DE material and MEMS modulator points of view. Firstly, measurement setups for polymer response time and elastic modulus characterization have been constructed. The setups are possible to re-construct in other labs as substitutes for sophisticated/expensive equipment. Secondly, the understanding of PDMS electro-mechanical properties with regard to its micro-structure has been obtained. This is very useful for tuning PDMS to obtain desired physical properties via chemical methods. Thirdly, the techniques for synthesizing polymer-particle composite and suppressing particle agglomeration have been described. This is a guide for further PDMS properties tuning by mixing with other particles. Fourthly, three SLM with different structures and working principles have been reported. It gives ideas about how to design a polymer based SLM and how to solve the consequent issues. Last but not the least, a de-speckle modulator by dynamic polymer gratings have been demonstrated. It shows advantages in compactness, reliability, lightweight and easy processing, comparing with existing de-speckle technologies. This point out a new way to design and manufacture de-speckle modulators by DE technology and MEMS technology.
References


Article I

Optimization of PDMS network for a fast response and sensitive actuation material applied in a MEMS spatial light modulator

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Abstract The cross-linked networks of linear vinyl-terminated poly(dimethylsiloxane) (PDMS) with trimethylsiloxy-terminated methyhydroxysiloxane–dimethylsiloxane copolymer (cross-linker) were investigated by tuning the cross-linker concentration, the chain length of linear PDMS and the functionality of the cross-linker. Response time and elastic modulus of the cross-linked PDMS elastomer were characterized by home-made measurement systems and analyzed based on their network topologies. An optimized PDMS elastomer, which has response time of 9 µs and elastic modulus of 601 kPa, was utilized as the actuation material in a MEMS spatial light modulator (SLM). The fabrication processes were described. This polymer based SLM has shown fast response time (9 µs) and successfully diffracted light into higher orders with 84% first-order diffraction efficiency.

1 Introduction

Polymer has promising features in applications such as MEMS actuators and modulators, attributed to its lightweight, easy fabrication and low production cost. In these applications, the most important performance of the polymer is the mechanical deformation under electric force, which is characterized by the response time and the sensitivity. When the polymer is applied in a spatial light modulator (SLM) as actuation material, fast response time and high sensitivity are always preferred to achieve high modulation efficiency of light. Several polymers have been investigated as candidate materials in the SLMs, for example, polymethylmethacrylate (PMMA) [1], SU-8 [2] and P(VDF-TrFE) based terpolymer [3]. However, the slow response is the biggest technical obstacle which limits the practical application of polymer based modulators.

Poly(dimethylsiloxane) (PDMS) is one of the most important polymers with unique properties, such as elasticity, durability, and resistance to high temperature, UV radiation and chemical attack [4]. These properties make the cross-linked PDMS suitable for a wide range of applications, such as in mechanic devices [5], in electrical/optical devices [6–8] and in biomedical devices [9–11]. More importantly, the response time and sensitivity of the PDMS elastomer (cross-linked PDMS) can be tuned by modifying its network topology. Therefore it is a promising candidate for SLMs. The theory of PDMS elasticity has been well established [12–14]. Normally, the PDMS elastomer has three-dimensional networks, which are formed by hydrosilylation reaction. The physical-mechanical properties of the elastomer depend on the cross-linked network structure and the residual chemical groups. Therefore, it is of great interest to understand and control polymer network topology for PDMS material engineering.
In this work, vinyl-terminated linear PDMS were cross-linked through hydrosilylation reaction by multifunctional cross-linkers in the presence of platinum complex catalyst. The aim is to synthesis PDMS material which has fast response time and high sensitivity. The sensitivity was indicated by the elastic modulus for this application. PDMS with different network topologies were prepared, by changing the concentration of the cross-linker, the chain length of the linear PDMS, and the cross-linker functionality, one at a time, with other parameters fixed. A PDMS elastomer with optimized network structure was successfully synthesized and further fabricated as the actuation material in a SLM. Comparing with other polymers [1–3], this modulator had similar sensitivity under applied electric force while the response time was significantly improved.

2 Experimental

2.1 Materials

Linear vinyl-terminated poly(dimethylsiloxane) with molecular weight from 800 g/mol to 62,700 g/mol and cross-linkers, which are trimethylsiloxy-terminated methyldimethyldichlorosilane–dimethylsiloxane copolymer, were purchased from Gelest, Inc. The cross-linking process was catalyzed by platinum complex previously dissolved in xylene, which were from UCT Specialties, LLC, at room temperature.

Hydrosilylation reaction has been commonly used to prepare PDMS elastomer [15], in which two vinyl groups of the linear PDMS react with silane groups of the cross-linker forming a three-dimensional cross-linked network. This reaction is expressed in Scheme 1.

The rate of the reaction and properties of the formed PDMS elastomer depend on several parameters, e.g. the functionality and concentration of the cross-linker, the molecular weight of the linear PDMS, the curing temperature and the catalyst. In this work, methyldimethylsiloxane–dimethylsiloxane copolymer was added to vinyl-terminated linear PDMS. After stirring for approximately 2 min, 0.1 wt% platinum complex catalyst was added. Then the mixture was intensively stirred for 30 s and cured in air at room temperature.

2.2 Measurement setups

Two properties of the PDMS elastomer, which are the response time and the elastic modulus, were focused in this work and characterized by home-made measuring systems.

The response time is in a range of micro-seconds, which was measured by a system equipped with a laser and a photo-detector [16], as shown in Fig. 1. In this measurement setup, the testing PDMS (20 µm thin film) was deposited on a prism coated with a transparent indium tin oxide (ITO) layer. A metal needle was suspended 5 µm above the PDMS film and its position was controlled precisely by a control stage. During measurements, a laser illuminated the PDMS on the prism. If no voltage was applied, the PDMS had a flat surface and the incident laser was totally reflected from PDMS/air interface, which was further blocked by a stopper. Once the voltage was applied between the ITO layer and the needle, a small spot on the PDMS (the area under the needle) experienced an electric force and started to deform. The deformation led to light diffraction and scattering, which was detected by the photo-detector. Using this method, the dynamic deformation of the PDMS was represented as the changing light intensity detected by the photo-detector. The plots in Fig. 1 show how the detected signal changed with regard to the applied 300 V plus voltage with 1 ms width.
When the pulse front came, the PDMS had a rapid deformation and then moved slowly to the maximum value. The similar behavior was observed when the pulse was released. The response time can be then extracted from the profile of detected light intensity. This measurement setup has been proved to be very effective and accurate in the evaluation of the response time of polymers [16]. It provides rich information on the response behavior of polymer material over a wide range of frequencies (1 Hz–1 GHz). However, it should be kept in mind that several factors may influence the measurement accuracy, e.g. capacitance between the needle and PDMS surface, the resistance of the ITO layer and the rise/fall time of the function generator. The time lag introduced by these factors was calculated in a range of nanoseconds in this work, which is therefore neglected.

An accurate and convenient measurement system was constructed to measure the elastic modulus of the synthesized PDMS, as shown in Fig. 2. In this setup, a metal probe with sphere indenter was fixed with a high precision load cell. The probe was controlled to move perpendicular to the PDMS surface by a control stage. The elastic modulus was obtained based on Hertz equations [17]:

\[
\frac{1 - \nu_p^2}{E_p} + \frac{1 - \nu_i^2}{E_i} = \frac{4h^2}{3F}\left(\frac{1}{R_p} - \frac{1}{R_i}\right)^{-\frac{1}{2}}
\]

where \(E_p, E_i, \nu_p, \nu_i, R_p, R_i\) are the elastic modulus, Poisson’s ratio, radius of the contact surface of the testing polymer and the indenter, respectively; \(F\) is the contact force from the indenter; \(h\) is the indentation depth. In this case, a sphere indenter, which has \(R_i\) equal to 1 mm, is pressed onto a PDMS plane, which has \(R_p\) as infinity. The Poisson ratio \(\nu_p\) of PDMS is 0.5. The indenter is made of ruby, which has an elastic modulus \(E_i\) around 300 GPa. Since \(E_i\) is much bigger than \(E_p\), it is considered as infinity. Equation (1) is then rewritten as

\[
\frac{1}{E_p} = \frac{16}{9F}\frac{1}{R_i^\frac{1}{2}}h^\frac{3}{2}
\]

In (2), there was a linear relationship between \(h^{3/2}\) and \(F\). By moving the probe and recording the contact force, the relationship between the indentation depth and the force can be found, as plotted in Fig. 2. The gradient \(K\), which is obtained by linear fitting the plots using least square method, was equal to \(9/(16R_i^{1/2}E_p)\), from which the \(E_p\) can be calculated.

3 Results and discussion

3.1 Influence of the cross-linker concentration

The influence of the cross-linker concentration on PDMS response time and elastic modulus was investigated. Linear PDMS with molecular weight equal to 9400 g/mol, was mixed with the cross-linker, which has functionality 4.8, molecular weight 1950 g/mol. The response time and elastic modulus of synthesized PDMS elastomer with different cross-linker concentrations are shown in Table 1.

It is observed that a gel-like elastomer can be formed within 4% and 65% weight percent of cross-linker, which are defined as the upper and lower critical gel point, respectively. With increase of the cross-linker concentration, the response time of the PDMS elastomer decreases (A2\(\rightarrow\)A4), reaches the minimum point (A5), and then increases (A6\(\rightarrow\)A8). The change of the response time is attributed to the change of network topology. While cross-linker concentration was 10%, a fastest PDMS elastomer (9 µs) was obtained, indicating that an ideal three-dimensional cross-linked network was formed, with minimum dangling or pendant chains. This network can respond to the applied force rapidly. Besides this point, less or more cross-linker lead to defectiveness of the network, therefore slow down the response. According to the experiments, a perfect network was not formed when the number of function groups of cross-linker (Si–H) were equal to that of the linear PDMS (C=C), but was achieved in the presence of extra Si–H groups. This is attributed to oxidation/hydrolysis side reactions of Si–H groups (the reaction formula is expressed as (3) and (4)), via reaction with other
compounds such as oxygen and moisture \[18\].

\[2\text{R–Si–H} + \text{O}_2 \xrightarrow{\text{Catalyst}} 2\text{R–Si–O–H} \]  \hspace{1cm} (3)

\[\text{R–Si–H} + \text{H}_2\text{O} \xrightarrow{\text{Catalyst}} \text{R–Si–O–H} + \text{H}_2 \]  \hspace{1cm} (4)

From Table 1, the response time increases significantly with the presence of extra linear PDMS (A2, A3), while the increase rate of the response time with extra cross-linker (A6, A7, A8) is slower as compare to the former. This is because the chain length of the linear PDMS (molecular weight = 9400 g/mol) is much longer than the cross-linker (molecular weight = 1950 g/mol). The dangling or pendant long chains respond slower to the applied force than that of shot chains, and thus significantly increase the response time.

The elastic modulus of the cross-linked polymer is also changed with the concentration of the cross-linker, due to the changed network topology. A hardest elastomer is obtained when a perfect three-dimensional network is formed, while any defectiveness of the network decreases the elastic modulus. From Table 1, the elastic modulus is inversely proportional to the response time. The results agree with the “Voigt–Kelvin model” \[19\].

The curing time of the cross-linked PDMS decreases with the increase of the cross-linker concentration, indicating that no matter the perfectness of the formed network, additional cross-linker always increase the curing speed.

### 3.2 Influence of the linear PDMS chain length

The influence of the linear PDMS chain length to the physical-mechanical properties of the PDMS elastomer was studied. Linear PDMS with molecular weight from 800 g/mol (short chain) to 62,700 g/mol (long chain) were mixed by cross-linker with molecular weight 1950 g/mol and functionality 4.8. The molar ratio of function groups between linear PDMS (C=C) and cross-linker (Si–H) was fixed at 1:1.2 to ensure an ideal network. The response time and elastic modulus of the formed PDMS elastomers are shown in Table 2.

It can be observed in Table 2 that the response time increases from 5 to 500 µs with increasing molecular weight. It is attributed to the increased chain lengths between the cross-linking sites. In another words, the cross-link density is lower with increased chain length of linear PDMS (the cross-link density is defined as the averaged number of cross-links per unit volume), and polymer with lower cross-link density is slower.

It is worth to mention that when long chain linear PDMS mixed with cross-linker, the long-range chain-chain interactions, called “chain entanglements”, dominated the polymer network. The consequence of the entanglements domination (B4, B5) is the significantly increase response time. It is explained thus: the entanglements forms a “tube” that restricts the lateral movement of chains and allows one dimensional diffusion in the “tube” as a mechanism for relaxation. The relaxation of these trapped entanglements is a relative slow process via a sliding motion of the chains along each other \[20\]. In applications, where a fast response time is desired, the linear PDMS with short chains is a better choice to form a cross-linking dominated PDMS network.

### 3.3 Influence of the cross-linker functionality

Trimethylsiloxy-terminated methyhydroxiloxane–dimethylsiloxane copolymer with different number of Si–H groups per chain was mixed with vinyl-terminated linear PDMS with molecular weight 9400 g/mol. The molar ratio of C=C and Si–H was fixed at 1:1.2 to form an ideal network. The corresponding response time and elastic modulus of the cross-linked PDMS are listed in Table 3.

With the decrease of cross-linker functionality (C1→C4), the cross-link density is smaller, therefore a slower and
soft PDMS was obtained. Moreover, the relationship between response time and elastic modulus show agreement with the “Voigt–Kelvin model”. The curing time of the cross-linked PDMS increases with the decreased functionality of the cross-linker, as expected. For sample C5, the cross-linker is nearly monofunctional. In this case, a three-dimensional network cannot be formed.

### 3.4 Influence of entanglements

Many efforts have been made to investigate the influence of the entanglements on physical-mechanical properties of the cross-linked PDMS [20–22]. In the case of small polymer deformation, a phenomenological equation, which was developed by Langley [21], Dossin and Graessley [22], can be used to calculate the contribution of entanglements to the elastic modulus [14].

\[
G = \left(1 - \frac{2}{f}\right) \frac{ρ}{M} RT + G_N^0 T_E
\]  

(5)

where \(G\) is the shear modulus equal to \(E/3\) in the case of the incompressible polymer, \(f\) is the functionality of the cross-linker, \(ρ\) is the density, \(M\) is the molecular weight, \(R\) is the gas constant, \(T\) is the temperature, \(G_N^0\) is the plateau modulus of the melt of uncross-linked polymer and \(T_E\) is the trapping factor. The first term in (5) is the modulus contributed from chemical cross-links, while the second term is from entanglements. Based on this model, the contribution of cross-links to the elastic modulus was calculated. Using the measured elastic modulus, the contribution of entanglements was obtained from (5), as shown in Table 4.

The contribution of entanglement to elastic modulus become obvious when long chain linear PDMS were cross-
For sample B2, B3(C3), C1, C2 and C4 the elastic modulus is mostly determined by chemical cross-links, while for sample B4 and B5, entanglements start to dominate the polymer network. Among all entanglements in polymer network, only the fraction of entanglements between elastically active chains, called “the trapped entanglements”, contributes to the elastic modulus [20]. The increased percentage of the entanglements contribution indicates an increased fraction of the trapped entanglements. These trapped entanglements slow down the polymer response to the applied force, as discussed previously. Therefore, a trapped entanglements dominated polymer is much slower than a cross-link dominated PDMS. These results agreed with the discussion in Sect. 3.2: an abrupt response time increase was observed when the molecular weight of linear PDMS reached 28,000 g/mol.

To conclude, PDMS elastomer formed by short chain vinyl-terminated PDMS cross-linking with high functionality cross-linker has fastest response under electric force. Hence such polymer is a good candidate for polymer based modulators. In the next section, the PDMS elastomer was applied as the actuation material in a SLM, by cross-linking the vinyl-terminated PDMS, which has molecular weight 9400 g/mol, with the cross-linker functionality 4.8.

4 Application of the optimized PDMS in spatial light modulator

Spatial light modulator is a widely used device for modifying the optical wavefront properties in projection displays, printing and optical communications. In this work, a fast and sensitive PDMS, which has intrinsic response time 9 µs and elastic modulus 601 kPa, was applied as the actuation material in a SLM.

The SLM was successfully fabricated using micromachining technology. First, a 250 nm thick titanium–tungsten adhesion layer was sputtered on a glass substrate. Afterwards, a 150 nm thick gold layer was sputtered on the titanium–tungsten layer. These two layers were then patterned as interdigital bottom electrodes by reactive ion etching and wet etching, respectively. Afterwards, the synthesized PDMS was deposited by spin coating to form a film with thickness of 4 µm. Finally, a 50 nm thick gold film was deposited on the PDMS by sputtering, which worked both as an electrode and reflective mirror. The schematic drawing as well as the fabricated SLM are shown in Figs. 3a, 3b. The top gold film had a continuous reflective surface. This mirror-like surface is necessary to ensure good light modulation efficiency.

The working principle of this SLM have been described in previous publication [23]. In brief, grating can be generated on polymer surface by applying voltage through the top gold film and bottom interdigital electrodes, as shown in Fig. 3c. Incident light illuminated at the grating and diffracted into higher orders. By selectively picking/blocking these orders, the intensity of the light can be modulated. Performances of the SLM depend on both PDMS properties and structure dimensions. The following design parameters of the SLM were obtained from finite element method simulations in COMSOL targeting a relatively big relief depth of PDMS: PDMS thickness 4 µm; period of gold electrodes in a range of 50 µm to 100 µm, size of the chip 20 × 12 mm.

When no voltage is applied, the polymer surface is flat, reflecting incoming light as a mirror; while the driving voltage is applied, a sinusoidal grating is formed on PDMS/Au surface, diffracting incoming light into many higher orders. Surface topographies of the SLM was measured and reconstructed by an interferometer in these two cases, as shown in Fig. 4. In order to achieve a large relief depth, 250 V DC voltage and ±100 V AC voltage was applied to the top and bottom electrodes, respectively. The peak-to-peak deformation was 170 nm, giving 84% first-order diffraction efficiency at 635 nm wavelength. Higher diffraction efficiency can be achieved by apply higher voltage or choose a softer
PDMS elastomer. By utilize the grating, incident light was diffracted into higher orders, as observed in Fig. 5. The response time was 9 µs, which was exactly the same as the intrinsic response time of the PDMS, indicating that the time lag in the circuit is negligible. Comparing with other polymer based SLMs, which have response time 4 ms [2], 2 ms [24], 1 ms [23], our SLM is much faster thanks to the optimized PDMS network. The faster response of the SLM gives many advantages in its practical applications. For example, the efficiency can be improved in data storage applications; the motion-blur of fast moving objects in action scenes can be eliminated in display applications.

5 Conclusions

A fast response and sensitive PDMS elastomer was synthesized by cross-linking vinyl-terminated linear PDMS with methyhydrosiloxane-dimethylsiloxane copolymer at the function group ratio $C=\text{C:Si-H}=1:1.2$. The presence of extra Si–H function group was necessary due to inevitable oxidation/hydrolysis side reactions. Linear PDMS with shorter chain length or cross-linker with more function groups per volume created a denser polymer network which showed faster response time and higher elastic modulus. The relationship between response time and elastic modulus can be roughly fitted to Voigt–Kelvin model. The influence of the entanglements became obvious in the polymer network when the molecular weight of linear PDMS reached 28,000 g/mol.

The optimized PDMS elastomer with intrinsic response time 9 µs and elastic modulus 601 kPa was utilized as the actuation material in a SLM. Under the applied electric force, the surface of elastomer was deformed, forming a sinusoidal grating. The grating successfully diffracted light into higher orders with 84% first-order diffraction efficiency. Comparing with other technologies, the SLM fabricated using our PDMS elastomer has shown significant improvement in response time.

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References

Article II

Electroactive polymer-based spatial light modulator with high reliability and fast response speed

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Abstract. An electroactive polymer (EAP)-based MOEMS spatial light modulator (SLM), which shows high reliability and fast response speed, is reported in this work. The reliability is achieved by designing the SLM without direct contact between electrodes and deformable EAP surface; while the fast response speed is obtained by optimizing the microstructure of the EAP material. The concept of SLM, material optimization approach, fabrication processes, as well as characterization methods, are described. The SLM is driven by relatively low voltage, which is 200 V dc and 60 V ac and the response time is 35 μs. The manufactured SLM shows no degradation or breakdown after millions of actuation cycles, indicating a good reliability of the device. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3659216]

Subject terms: spatial light modulators; polymers; micro-optics; diffractive optical elements.

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1 Introduction
A spatial light modulator (SLM) is a device that imposes spatially-varying modulation on a beam of light. Many different of SLMs have been commercialized, such as grating light valve, digital micromirror device, and spatial optical modulator. These devices are all based on silicon technology. Organic materials, for example electroactive polymers (EAPs), are promising alternates for SLMs. EAPs have many desirable features, e.g., lightweight, durability, easy fabrication, and low production cost. It has been utilized in many optical devices such as tunable gratings, micro-optical zoom lens, optical attenuators, and spatial light modulators. In EAP-based SLMs, gratings, which are formed by EAP material under electric field, are used to modulate the light. The electric field induced strain is either generated from Maxwell stress, arising from Coulomb electrostatic interactions among free charges on electrodes, or from the electrostrictive stress, arising from strain-induced permittivity change of the material, or both. Currently, several technical obstacles limit the practical applications of EAP-based SLMs. First, to drive the EAP under an electric field, a sandwich structure, in which the EAP is between two electrodes, is commonly employed. At least one of the electrodes has to comply with the deformation of the EAP. Such electrodes suffer from reliability problems due to fatigue and creep, not to mention that the electrodes themselves mechanically constrain the deformation of the EAP. Second, due to the viscoelastic property of polymers, the EAP-based devices normally have slow response speed (in the range of milliseconds to seconds). Finally, a high driving voltage, typically on the order of kilovolts, is required to drive the devices.

In order to improve the performance of an EAP-based spatial light modulator, the SLM structures were designed to avoid direct contact between the deformable EAP surface and electrodes. Polydimethylsiloxane (PDMS) was used as the EAP material and it was optimized to have a fast response speed and high sensitivity by swelling of its network. The fast response speed of the PDMS resulted in higher SLM modulation efficiency, while the high sensitivity of PDMS lowered the requirement of driving voltages.

2 PDMS Processing and Characterization
The property of the PDMS is determined by its microstructure. PDMS elastomer has a three-dimensional cross-linked network, formed by linear vinyl-terminated PDMS reacting with multifunctional cross-linker. To obtain both the response speed and sensitivity, the PDMS networks were swollen by solvents. First, the linear PDMS and the cross-linker were mixed by manual stirring for 3 min. The molar ratio between function groups of linear PDMS and cross-linkers were set as 1:1.2 to achieve a PDMS network with minimum dangling or pendant chains. Second, silicon oil (solvent) with molecular weight around 700 was added into the PDMS solution to swell the PDMS network. Samples with solvent concentration varying from 0% to 90% were prepared and characterized. Third, a catalyst was added into the mixture, followed by stirring thoroughly for 5 min. Finally, the samples were de-bubbled in room temperature and cured in an oven at 60°C.

The dependence of response time and elastic modulus of swollen PDMS on solvent concentration are plotted in Fig. 1. The unswellen (0% solvent concentration) PDMS had a response time of 9 μs and elastic modulus 601 kPa. This high elastic modulus and fast response time indicated a rigid structure which was formed by a tightly cross-linked network. Due to the high elastic modulus, the sensitivity of the PDMS was relatively low, i.e., high voltage was required to drive the EAP. By introducing a short chain miscible solvent into PDMS, the polymer network was swollen. Because the polymer chains were surrounded by highly mobile solvents, the chain movement was promoted. The ease of chain movement resulted in the decrease of elastic modulus, meaning a promoted sensitivity. Meanwhile, the response time of PDMS increased, but this effect was rather moderate. To show the advantage of this
optimization method, the properties of PDMS via network swelling were compared with Ref. 10, in which the PDMS properties were tuned by modifying the cross-link density. As shown in Fig. 2, in order to obtain a PDMS with similar response time, the PDMS tuned by network swelling had a much higher sensitivity. The improvement was attributed to less trapped entanglements between polymer networks.10

3 Electroactive Polymer-Based Spatial Light Modulator

The optimized PDMS, which had an intrinsic response time of 34 μs and elastic modulus 200 kPa, was applied to fabricate a SLM. The structure of the SLM as well as the electrical connections is shown in Fig. 3. The PDMS film is deposited on the transparent indium tin oxide (ITO) top electrode, which is coated on the prism. There is an air gap between the inter-

Fig. 1 Response time and elastic modulus of swollen PDMS with regard to solvent concentration.

Fig. 2 Comparison of response time and elastic modulus of PDMS between this work (PDMS tuned by network swelling) and Ref. 10 (PDMS tuned by cross-link density modifying).

Fig. 3 Schematic of (a) top and (b) cross-section view of the SLM.
μm is required to actuate EAP films.\cite{9} The technology, as described in Fig. 4. Typically, a driven electric chip 11 mm interdigital electrodes in a range of 60 to 80 PDMS: PDMS thickness 25 μm, air gap 5 μm, size of the chip 11 mm × 18 mm.

The modulator has been fabricated with micromachining technology, as described in Fig. 4. Typically, a driven electric field up to 150 V/μm is required to actuate EAP films.\cite{9} The SLM reported in this work is driven by 200 V dc voltage and 60 V ac voltages to the ITO and interdigital electrodes, respectively. The low driving voltage requirement (260 V on 25 μm thick PDMS film) is attributed to the high sensitivity of PDMS. When the SLM was not actuated, the incident light was not diffracted. i.e., only zeroth order of the light came out of the SLM, as shown in Fig. 5(a). The measured power of the output beam was 1.84 mW. When the SLM was actuated, the incident light was decomposed into several output beams, as shown in Fig. 5(b). The power distribution of the decomposed beams is shown in Table 1, and the sum of all orders was 1.78 mW. The small deviation from a nondiffracted beam (1.84 mW) could be due to scattering and higher orders which were not taken into account. Simulations in ZEMAX were done to obtain far-field diffraction patterns using scalar diffraction theory.\cite{10} The results were compared with experiments, as shown in Figs. 5(c) and 5(d) and Table 1. The deviation between experiments and theory, especially for high orders, is due to the shape of the gratings, which is not a perfect sinusoidal. The response time of the modulator was measured as 35 μs, which was close to the intrinsic response time of the PDMS. The divergence can be generated from the timing delay in the circuit. The fast response speed gives many advantages in practical applications of SLMs. For example, the motion-blur of fast moving objects in action scenes can be eliminated in display applications. The SLM shows no degradation or breakdown after millions of actuation cycles. It functioned well after storage in room temperature for a month, indicating good reliability of the device.

4 Conclusion

A MEMS spatial light modulator was fabricated using micromachining technology with swollen PDMS as the actuation material. The SLM is driven by 200 V dc voltage and 60 V ac voltage and the response time is 35 μs. Compared with other polymer-based SLMs,\cite{3,11,12,13,14} the advantages of the proposed SLM are: fast response speed, reliability, low driving voltage, and low light loss. The improved reliability of the SLM is achieved by designing the SLM without direct contact between electrodes and deformable EAP surface, while the fast response speed is attributed to the optimized PDMS network structure.

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References


Biographies and photographs of the authors are not available.
Article III

TiO$_2$ nanoparticles modified polydimethylsiloxane with fast response time and increased dielectric constant

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Abstract: Polymer nanocomposite has shown great potential and impact on broad range of techniques since its properties can be tailored by nano-fillers. This paper reports a polymer nanocomposite with enhanced electro-mechanical performance by mixing TiO$_2$ nanoparticles into polydimethylsiloxane. The nanocomposites with particle concentration up to 30 wt% were prepared. High energy ball milling and polyether-modified silicone dispersant was used to suppress the agglomeration and ensure a stable dispersion. Properties of the nanocomposites, i.e. elastic modulus, response time, dielectric constant and optical transmittance, were tuned by modifying the particles concentration. Optimized electro-mechanical properties were observed at 5 wt% TiO$_2$ particles. This nanocomposite was applied to a MEMS spatial light modulator, which was fabricated using micro-machining technology. The device was driven by 200 V DC voltage and had response time of 6 μs.

Keywords: Nanocomposite; Electroactive polymers; MEMS; Spatial light modulator.

1. Introduction

Electroactive polymers (EAPs) have recently attracted considerable interests in applications of electro-mechanical modulators and actuators, attribute to their lightweight, reliability, durability and easy processing [1]. They have been applied in various devices, such as eyeball actuators [2], tunable gratings [3], lighter-than-air vehicles [4], inchworm robots [5], tactile display [6], etc. Despite the listed advantages of EAPs, several technical obstacles need to be overcome for their wide applications. A high driving electric field up to 150 V/μm, is required to drive the EAPs [7]. This brings safety issues associated with high voltages. The response speed of EAPs is slow, typically in the range of millisecond. A number of approaches have been explored aiming at improving electro-mechanical performance of EAPs, by increasing their dielectric constant and/or decreasing their elastic modulus [8-12]. Under the applied electric field, EAPs deform either by Maxwell stress, arising from Coulomb electrostatic interactions among free charges on electrodes, or electrostriction, arising from strain-induced permittivity change of the material, or both. The Maxwell stress induced strain $S_{\text{Maxwell}}$ and the electrostriction induced strain $S_{\text{electrostriction}}$ is calculated by Equation. (1) and Equation. (2), respectively [13].

$$S_{\text{Maxwell}} = -\varepsilon_0\varepsilon_r E^2/Y$$  \hspace{1cm} (1)

$$S_{\text{electrostriction}} = -Q\varepsilon_0 (\varepsilon_r-1)E^2$$  \hspace{1cm} (2)

where the $\varepsilon_0=8.85$ pF/m is the dielectric constant of the vacuum, $\varepsilon_r$ is the relative permittivity, $E$ is the electrical field and equal to the applied voltage divided by the EAP films thickness, $Y$ is the elastic modulus and $Q$ is the electrostrictive coefficient. From the equations, in order to achieve a same strain, the material with lower elastic modulus or/and higher dielectric constant requires lower driving voltage. Therefore a reduced driving voltage requirement for EAPs is accomplished by increasing their dielectric constant and/or decreasing their elastic modulus. Reducing the elastic modulus of EAPs involves polymer network modification [8]. Increasing of the dielectric constant can be achieved by mixing fine particles into polymer host [9-12].

In this work, nano-sized TiO$_2$ particles were applied to modify the polymer microstructure. Polydimethylsiloxane (PDMS) was chosen as the host polymer because of its remarkable durability and resistance to temperature, UV radiation and weathering [21]. Titanium dioxide particles were used as fillers owing to its relatively high permittivity, chemical inertness, non-toxicity and easy dispersion in silicone [1]. Previous applications of TiO$_2$-polymer nanocomposite were mainly in photocatalytic and UV absorption. The material investigations focused on the mechanical properties [14, 15], thermal properties [14, 16], optical properties [16-19], and dielectric properties [1, 15, 20]. Investigations regarding the response time, when TiO$_2$-polymer nanocomposite is actuated under electric field, are limited. The presented work aims to broaden the application area of the material and to use it as electroactive polymers in compact and light weight MEMS devices, such as spatial light modulators (SLM), variable optical attenuators and optical switches. Fine TiO$_2$ particles were dispersed in PDMS with the help of polyether-modified silicone. The nanocomposites were characterized for their response time, elastic modulus, dielectric constant and optical transmittance. Comparing with pure PDMS, the nanocomposites with optimized TiO$_2$ concentration have faster response speed and increased dielectric constant. The nanocomposite was applied to a MEMS spatial light
modulator. The SLM was fabricated using micro-machining techniques. The device was driven by relatively low voltage and shown fast response time.

2. Experimental

As the host polymer, PDMS with three dimensional networks was formed by hydrosilylation reaction. Linear vinyl-terminated PDMS (molecular weight 9400 g/mol, from Gelest Inc.) reacted with cross-linkers, which were trimethylsiloxy-terminated methylhydrosiloxane-dimethylsiloxane copolymer (molecular weight 1950 g/mol, functionality 4.8, from Gelest Inc.). The ratio of function groups C=C:Si–H was 1:1.2. The presence of extra Si–H function groups is necessary because of the inevitable oxidation/hydrolysis side reactions [22]. The cross-linking process was catalyzed by platinum complex previously dissolved in xylene (from UCT Specialties, LLC). The reaction formula is given in figure 1, where the C=C groups in linear PDMS react with the Si–H groups in cross-linker. The fillers, which were titanium dioxide nanoparticles, have primary size of 25 nm (anatase, from Sigma-Aldrich Co.,).

There are many ways to disperse inorganic nanoparticles into organic polymers matrix. One can firstly modify the particles to change their surface properties and then disperse them into polymer solutions, as reported in [23, 24]. Or certain dispersant can be used to help the particle dispersion when mixing the particles with polymer solution, such as in [18, 19]. Surface modification of the particles is rather complicated and time consuming. After modification, a process to remove residual chemicals is necessary. This method is normally applied for high volume particle processing. Directly mixing the particles into solution with the help of dispersant, on the contrary, is simple and requires single processing step. If the correct dispersant is chosen, particles agglomeration is suppressed and a stable and evenly dispersed particles in solution can be obtained.

In this work, fine TiO₂ particles were dispersed in PDMS with the help of polyether-modified silicone. Firstly, TiO₂ particles (weight percentage from 1% to 30%) were mixed with linear PDMS in the presence of polyether-modified silicone (KF-6015 from ShinEtsu). The ratio between polyether-modified silicones and nanoparticles was 1:5 by weight. These components were mixed by high energy ball-milling for 24 hours. Secondly, the cross-linker and catalyst were added into the solution sequentially, followed by 2 minutes manual stirring after each step. The ratio between linear PDMS and cross-linker was 9:1 by weight and the catalyst was 100 ppm. Finally, samples were cured at room temperature for 30 minutes.

The size distribution of dispersed particles in PDMS solution was characterized by particle size analyzer Malvern ZetaSizer Nano S. The solution was diluted to 0.1 wt% to meet the requirement of the device. The particle distribution was also characterized by scanning electron microscope (SEM, Philips XL30). The nanocomposite solution, which was well mixed but without adding catalyst for cross-linking, was deposited on silicon wafers. The samples were placed in oven at 40°C overnight. The wafer with TiO₂ nanoparticles on its surface was used for SEM measurements.

The elastic modulus of the nanocomposite was obtained by Hertz equation using a mechanical measurement system, as shown in figure 2a. In this setup, a metal probe with sphere indenter is fixed with a load cell. The probe is controlled to move perpendicularly to the nanocomposite surface by a control stage. When the indenter touches the nanocomposite surface, the contacting force is detected by the load cell. According to Hertz equation, there is a linear relationship between indentation depth of power 3/2 and the force on indenter [8]. The elastic modulus is a function of the gradient and it is acquired by fitting indentation depth with regard to detected force, as plotted in figure 2b.

The response time of the nanocomposite was measured using an optical measurement system, as shown in figure 3a. In this setup, the testing nanocomposite is deposited on a prism coated with an indium tin oxide layer (works as one electrode). A metal needle (works as another electrode) is suspended close to the nanocomposite film. When the voltage is applied to the electrodes, a small spot on the
nanocomposite (the area under the needle) deforms. The deformation results in light diffraction and scattering, which is detected by the photo-detector. The response time is obtained by comparing the detected signal to applied voltage in an oscilloscope, as plotted in figure 3b. More details of the elastic modulus and response time measurement setups are referred to [8].

Figure 3. Diagram of the response time measurements. (a) Measurement setup; (b) Applied AC voltage and detected light intensity in oscilloscope. The response time is defined as the time required for the light intensity to rise (fall) from 10%(90%) to 90%(10%) of its peak value.

The dielectric constant was characterized by measuring the capacitance of nanocomposites using TTi LCR400 precision LCR meter. The testing samples were molded into cylinders with thickness of 5.7 mm and diameter of 26 mm. Both sides of the testing samples were sputtered with 50 nm gold film, to ensure a good electrical contact to the LCR meter.

Light transmittance was measured for 10 μm thick nanocomposite films which were deposited on glass plates. Hitachi U-1100 spectrophotometer was employed for the measurements. The characterized wavelength range was between 300 nm and 800 nm.

A nanocomposite with 5 wt% TiO$_2$ was applied in a MEMS spatial light modulator. The SLM was fabricated using micro-machining technologies. The fabrication process is shown in figure 4. A 250 nm thick titanium–tungsten adhesion layer was sputtered on a glass substrate. Afterwards, a 150 nm thick gold layer was sputtered on the TiW layer. Both TiW and Au layer were deposited by MRC 603 DC Sputter. These two layers were patterned as interdigital bottom electrodes by wet etching sequentially. The Au layer was etched by KI+I$_2$+H$_2$O at room temperature for 20 sec and the TiW layer was etched by H$_2$O$_2$ at 50°C for 60 sec. A photoresist layer (Microposit S1813, 2.2 μm thick) was patterned to protect the bonding pads. Afterwards, the synthesized nanocomposite was spin coated on the chip surface with spin speed of 1200 rpm. The thickness of nanocomposite layer was 4 μm, measured by Veeco Dektak Profilometer. A 50 nm thick gold film was sputtered on the nanocomposite at room temperature by Fisons SC500 sputter coater. The gold film together with the nanocomposite on the photoresist was lifted off by dissolving the photoresist in acetone. Finally, the chip was placed on a ceramic board with gold bonding pads. The electrodes on the SLM chip were wire-bonded to the ceramic board for electrical connection.

Figure 4. Fabrication process of the nanocomposite based spatial light modulator. (a) TiW, Au deposition; (b) TiW, Au patterning; (c)Photoresist deposition; (d) Nanocomposite spin coating and Au film sputtering; (e) Lift-off of Au and nanocomposite layer, wire-bonding.

3. Results and discussion

3.1 Particle dispersion

Inhomogeneous dispersion due to pronounced agglomeration tendency of nanoparticles is a common phenomenon for synthesizing a polymer nanocomposite [25]. However, a good dispersion is necessary to obtain a nanocomposite with optimized properties. Two techniques have been applied to suppress the agglomeration. Firstly, high-energy ball-milling was employed during mixing. It provided high impact and shear energy to break agglomerates. Secondly, polyether-modified silicone, which acts as a good dispersant for dispersing TiO$_2$ into silicones, was used for homogenous dispersion and avoiding the re-agglomeration. The dispersant has branched polyethylene chains which can bond to the -OH group on TiO$_2$ surface. The reaction formula is given in figure 5. The TiO$_2$-PDMS dispersion with or without using the dispersant are compared, and shown in figure 6. In this test, both mixtures have been left at room temperature for 24 hours after ball milling. The suspension without dispersant is found to quickly settle to the bottom of the bottle. In contrast, the one with dispersant shows no phase separation even after 24 hours. The stable and homogenized dispersion indicates that the polyether-modified silicone dispersant is bonded to the TiO$_2$ particle surface.
Figure 5. Chemical reaction between polyether-modified silicone dispersant and TiO$_2$ nanoparticles.

Figure 6. Comparison between 5 wt% TiO$_2$ in PDMS solution without (left) and with (right) the dispersant.

The size distribution of the dispersed particles in PDMS solution is characterized by particle size analyzer and SEM. The results are given in figure 7 and figure 8, respectively. As shown in figure 7, by using the polyether-modified silicone dispersant, the particle size decreases from around 1000 nm to 500 nm, indicating the function of the dispersant for suppressing the particle agglomeration. The SEM image in figure 8 shows agreement with the results in figure 7, that the particles exist in the PDMS as size around 500 nm. It is very difficult to further reduce the agglomerates size even with high energy ball milling, because of the strong agglomeration tendency of nanoparticles.

Figure 7. Particle size distribution of nanoparticles in PDMS solution with and without the dispersant, measured by particle size analyzer.

Figure 8. SEM image of TiO$_2$ nanoparticles.

3.2 Electro-mechanical properties

The dependence of nanocomposite elastic modulus on TiO$_2$ particle concentration is plotted in figure 9. The elastic modulus decreases from 600 kPa to 487 kPa, when the particle concentration increases from 0 wt% to 3 wt%. As more particles added into PDMS, elastic modulus increases to 872 kPa at 30 wt% concentration. The influence of particles to the elastic modulus is attributed to two factors: softening effects due to the interfering of cross-linking (major effect for TiO$_2$ concentration lower than 5 wt%) and hardening effects due to the particle-polymer interaction (major effect for TiO$_2$ concentration higher than 5 wt%). At 5 wt% particle concentration, the two effects are balanced with each other, and the elastic modulus is more or less the same as unloaded PDMS elastomer. The classical rule of mixture is frequently used to describe the relationship between elastic modulus and particle concentration. It predicts a linear increase of elastic modulus with volume fraction of particles. This is obviously not the case as it is observed in figure 9. The reason is that the classical rule of mixture describes a rather ideal situation. When nanoparticles are mixed with polymer, the polymer-particles interaction may result in the formation of an interfacial region with mechanical properties different to the bulk polymer. This effect is not taken into account in the classical rule of mixture. The change of elastic modulus with regard to particle concentration has been also investigated by other research groups [1, 12]. In these works, the elastic modulus increased continuously with TiO$_2$ concentration. The deterioration of the cross-linking process by particles was not mentioned. However, this work shows that the interfering of cross-linking is inevitable. At particles concentration above 5 wt%, strong particle-polymer interaction results in a reinforcement of the polymer network [26], i.e. particles acting as effective chemical “cross-links”. Chemical cross-linking leads to a decrease in mobility and increase the elastic modulus of nanocomposite.
The effect of response time on particle concentration is given in figure 10. The PDMS without any particles has response time of 9 μs. It increases to 11.5 μs at 2 wt% particle concentration and decrease to 3 μs at 30 wt% particle concentration. At low particle concentration, the cross-linking process is interfered by the particles. The polymer chains are less cross-linked and therefore there are high mobility chains existing in polymer network which can have large-scale chain relaxation. The result is prolonged response time. When the polymer network is enhanced by the polymer cross-linker and the particle-polymer interaction at high particle concentration, the chain motion is suppressed. The decreased chain mobility leads to a decreased response time. The relationship between elastic modulus and response time can be fitted to “Voigt-Kelvin model”. In brief, the elastic modulus is inversely proportional to the response time [27]. However, at 5 wt%, though the elastic modulus of nanocomposite (5 wt%) is more or less the same as neat PDMS (0 wt%), the response time improves from 9 μs to 6 μs. Possible explanation for the improvement of response time is due to the reduced moveable entanglements. When particles are added into polymer matrix, the particle-polymer interactions freeze the surrounding chain entanglements and reduce the amount of moveable entanglements. Since the movement of entanglements is a rather slow process, the reduced amount of entanglements improves the response time.

The dependence of the dielectric constant on particle concentration is shown in figure 11. A sharp increase of the dielectric constant from 2.97 to 3.85 is observed when the concentration of TiO$_2$ particles increases from 0 wt% to 5 wt%. Thereafter, the dielectric constant gradually increased to 4.4 with particles concentration reaching to 30 wt%. The increase in dielectric constant is attributed to the high dielectric constant of TiO$_2$. For a modulator based on the deformation of electroactive materials, the increased dielectric constant gives an advantage of increased electrostatic force, therefore reduce the requirement of the driving voltage. The measured dielectric constant of nanocomposite is compared with theoretical values calculated from several mixing rules: Maxwell-Wagner equation [28, 29], Sillars equation [30], Looyenga equation [31], and Lichtenecker equation [32]. The results are plotted in figure 11. As seen from figure 11, none of the theoretical model predicts the dielectric constant change of nanocomposite well. The reason could be due to: firstly, these mixing rules hold for the dielectric constant at high frequency range, while in this work the dielectric constant has been measured at 100 Hz. At low frequency, the Maxwell-Wagner relaxation process [33] arises and influences the dielectric constant. Secondly, the mixing rules assume that the particles have perfectly sphere shape, and have not taken account of the particles real geometry.

3.3 Optical properties

Light transmittance spectra for the nanocomposites films (after curing) with different particle concentrations is plotted in figure 12. The transmittance maintains around 80% at visible wavelength for TiO$_2$ concentration below 3 wt%. It decreases very fast when the TiO$_2$ concentration cross 10 wt%. At the UV range (300 nm – 400 nm), the light loss is dramatic for all nanocomposite films. This is because of the absorption of TiO$_2$ fillers at this wavelength range. The band gap for TiO$_2$ (anatase) is 3.2 eV, corresponding to the absorption edges 388 nm [34]. When TiO$_2$ is illuminated by light with energy higher than its band gap, i.e. with
wavelength shorter than the absorption edge, electrons will jump from valance band to conduction band by absorbing the energy from photons. When it comes to the visible wavelength (400nm – 800 nm), the light absorption of TiO$_2$ is negligible, since the electrons do not have enough energy to jump to the conduction band. The light loss in visible wavelength is mostly due to the Mie scattering when light illuminated on TiO$_2$ particles which has a size comparable with wavelength. In figure 13, a photograph of nanocomposite films prepared by spin coating is given. A high level of transparency is observed when the particle concentration is lower than 5 wt%.

![Figure 12. The transmittance spectra of 10 µm nanocomposite films with varied TiO$_2$ concentrations.](image)

![Figure 13. Comparison of 10 µm nanocomposite with varied TiO$_2$ concentrations on glass plates. a)1 wt% TiO$_2$; b) 5wt% TiO$_2$; c)10 wt% TiO$_2$.](image)

To conclude the investigation, the properties of nanocomposite can be tuned by modifying TiO$_2$ concentration in PDMS host material. The choice of particle concentration depends on the application demands. If a fast response speed is the top consideration, a nanocomposite with high particle concentration is a good candidate. 3 µs response speed is obtained with 30 wt% TiO$_2$ in PDMS. If a low driving voltage is mostly desired, a nanocomposite with 3 wt% TiO$_2$ particles is a wise choice, since this nanocomposite has the smallest elastic modulus. For a material with smaller elastic modulus, the strain is bigger under the same driving voltage. However, the cost is the prolonged response speed. In some optical applications, where a high transparency is necessary, the nanocomposite should have particle concentration lower than 5 wt%. From the electro-mechanical point of view, the optimal point or balanced point is found at 5 wt%. Comparing with the pure PDMS, nanocomposite with 5 wt% TiO$_2$ has faster response time. The driving voltage is also reduced, attributed to the smaller elastic modulus, and the increased dielectric constant.

3.4 Application in SLM

The nanocomposite with 5 wt% TiO$_2$ concentration is applied in MEMS spatial light modulators as the electroactive material. The elastic modulus of nanocomposite is 567 kPa, which is slightly smaller than the elastic modulus of pure PDMS. The response time and dielectric constant are 6 µs and 3.85, respectively. In this SLM, light is reflected at the gold film which is deposit on the surface of nanocomposite, therefore a high transmittance is not necessary. The schematic drawing of the SLM is given in figure 14a. The working principle has been described in previous publication [35]. In brief, when no voltage is applied, the surface of nanocomposite is flat. Incoming light is reflected at the gold film on nanocomposite surface. When the driving voltage is applied through the top gold electrode and bottom interdigital electrodes, a sinusoidal surface grating is formed on nanocomposite, diffracting incoming light into many higher orders. By selectively picking/blocking these orders, the intensity of the light is modulated. Performances of the SLM depend on both material properties and structure dimensions. The following design parameters of the SLM are obtained from finite element method simulations in COMSOL Multiphysics targeting maximum diffraction efficiency of gratings: nanocomposite thickness 4 μm; period of interdigital electrodes in a range of 50 μm to 100 μm.

![Figure 14. SLM chip with nanocomposite utilized as EAP to create the gratings. a) Schematic of the SLM. b) The fabricated SLM chip. The top gold electrode also works as a reflective mirror.](image)

Surface topographies of the SLM are measured by an optical interferometer (Wyko NT9100) when the gratings are non-actuated and actuated, as shown in figure 15. Sinusoidal gratings at the actuated SLM are observed. However, the surface of nanocomposite in a non-actuated SLM is not extremely flat. The relatively rough surface is
because of the TiO₂ nanoparticles inside the polymer host. The surface roughness Rₐ is measured as 15 nm. As the value much smaller than the wavelength of the incident light, the nanocomposite surface still works as a reflective mirror. In order to ensure the diffraction efficiency, 200V voltage is applied via the top and bottom electrodes. The peak-to-peak deformation of gratings in figure 15b is measured as 180 nm. The first order diffraction efficiency is calculated by \( J_q^{(m/2)} \), where \( J_q \) is the Bessel function of the \( q \)th order, and \( m \) is a parameter which are determined by the SLM structure and polymer relief depth. In the case of SLM with surface reflection, \( m \) is equal to \( 4d\pi/\lambda \), where \( d \) the the grating relief depth and \( \lambda \) is the wavelength of incident light. The calculated first order diffraction efficiency is 33% for the light with 633 nm wavelength. Typically, a driven electric field up to 150 V/µm is required to actuate EAP films [7]. The low driving voltage requirement in this work (200 V on 4 µm EAP film) is benefitted from low elastic modulus and high dielectric constant. The response time of the device is the same as the response time of the nanocomposite, which is 6 µs. This indicated that the time lag due to RC circuit in the device is negligible. Comparing with other EAP based SLMs, which have response time in the range of millisecond [36], 250 microseconds [3], 9 microseconds [8], the response time in this work is improved thanks to the modified PDMS network with nanoparticles. The fast response speed gives many advantages in its practical applications. For example, the motion-blur of fast moving objects in action scenes is eliminated in display applications.

Figure 15. The profile of nanocomposite gratings. a) When no voltage is applied, the surface is flat (Rₐ = 15 nm). b) When voltage is applied, the grating profile is observed. The dimension in z-direction is exaggerated for observation purpose.

5. Summary and conclusion

TiO₂ nanoparticles with concentration up to 30 wt% were dispersed into PDMS host material, forming nanocomposites. The agglomeration of nanoparticles was suppressed and TiO₂ particles are uniformly dispersed in PDMS with sizes below 500 nm. The nanocomposite with optimized electro-mechanical properties were found at 5 wt% particle concentration. The elastic modulus, response time, dielectric constant of the nanocomposite was 567 kPa, 6 µs and 3.85, respectively. Nanocomposite with 3 µs response time was obtained by dispersing 30 wt% nanoparticles into PDMS. Nanocomposite with 5 wt% particle concentration was utilized in a MEMS spatial light modulator. Comparing with traditional technology, where pure polymer is used as the electroactive material in SLMs, the requirement for driving voltage is reduced to 200 V and the response speed is improved to 6 µs.

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References

Article IV

A novel tunable grating fabricated with viscoelastic polymer (PDMS) and conductive polymer (PEDOT)

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1. Introduction

A spatial light modulator (SLM) is a device which is used to modify the optical wavefront properties, such as intensity, phase, and polarization, etc. Many different configurations of SLMs have been investigated during the past decade and applied in projection displays, printing and optical communications [1,2]. The grating light valve (GLV) [3], which was developed at Stanford University, is a spatial phase modulator made by an array of tiny movable ribbons mounted on a silicon substrate. The digital Micromirror Device (DMD) [4], which was invented by Texas Instruments, uses a two-dimensional array of tilting micromirrors. The spatial Optical Modulator (SOM) [5], invented by Samsung, uses an array of movable ribbons made of polarized lead zirconium titanate (PLZT). These successful modulators are primarily based on silicon technology, and complicated processing steps are required for the fabrication.

Organic materials, such as polymers, are an alternate for SLMs. Polymers have many desirable features, such as lightweight, easy fabrication and low production cost [6]. Poly(methylmethacrylate) (PMMA) [7], PVDF-TrFE terpolymer [8], PDMS [9–14] based modulators have been investigated and reported. In polymer based SLMs, gratings are used to modify the light and they are commonly generated by a sandwich structure (flexible metal film/polymer actuation layer/fixed electrodes). In such a structure, the flexible metal film is utilized as both the top electrode and the reflector, and it deforms with the polymer actuation layer underneath. This quite often leads to a stability problem. A wrinkle-like surface and cracks were observed on the flexible metal film [9,12,15] due to the large coefficient of thermal expansion (CTE) mismatch and the poor adhesion between the polymer and the metal layer.

In this work, a tunable grating is designed and fabricated using conductive polymer PEDOT: PSS as the flexible electrode instead of metals to improve the surface quality and the device stability. With minor electrodes modification, this tunable grating can be utilized as a spatial light modulator for high-resolution display. The choice of PEDOT: PSS is made based on its high stability and compatibility with other polymer materials such as PDMS. Moreover, PEDOT: PSS is a cheap material and gives opportunity to manufacture by screen printing [16], inject printing, spin coating [17], roll-to-roll coating [18], and chemical vapor deposition [19]. PDMS is chosen as the actuation material since it is soft, inert, and highly resistant towards oxidation and chemical attack [20]. Compared with other polymer based tunable gratings and SLMs, our device has several advantages. First, thanks for the small CTE mismatch and the good adhesion between PEDOT: PSS and PDMS, a smooth surface was obtained and the stability of the modulator was improved. Second, the fabrication method is simple and straightforward. All the processing is carried out at room temperature. No sophisticated equipments are required for the fabrication. At last, the device is light weight, low cost and compatible with laser display.
system. Using the techniques described in this paper, one can readily manufacture a spatial light modulator for high-resolution display applications.

2. Structure design and working principle

The structure of the modulator is shown in Fig. 1. A thin PDMS film was sandwiched between a PEDOT: PSS film and rigid bottom electrodes. Gold is chosen as the bottom electrodes for its high conductivity and reflectivity. It is compatible with the subsequent wire-bonding process. The shape of the bottom electrodes determines the eventual surface grating profile of PDMS. For simplification, interdigital bottom electrodes were used. Different from other polymer based modulators [7–15] in which incoming light penetrates the transparent layers, which has varied thickness at different location, a spatially varying optical path of the light beam is obtained. The polymer layers act like a phase grating and diffract light into higher diffraction orders.

When light passes through a grating area with dimension $L \times W$ and electrodes spatial frequency $f$ in $x$ direction (dimensions are indicated in Fig. 1 and Fig. 2), the amplitude transmission function can be expressed by Eq. (1). The light intensity distribution at the far-field output plane $(x_0, y_0)$ is determined by Eq. (2) [21].

$$T(x, y) = \exp \left[ \frac{m}{L} \sin(2\pi fx) \right] \text{rect} \left( \frac{x}{L} \right) \text{rect} \left( \frac{y}{W} \right)$$

$$I(x_0, y_0) = \left( \frac{LW}{\lambda^2} \right)^2 \sum_{q=\pm \infty}^{\infty} I_q^2 \left( \frac{m}{L} \right) \sin^2 \left( \frac{x_0 - qy_0W}{\lambda} \right)$$

where $f$ is the Bessel function of first kind order $q$, $\lambda$ is the wavelength, $z$ is the distance from the grating to the output plane, and $m$ is the phase modulation parameter, which is the function of the peak-to-peak relief depth $d$ and the refractive index $n$ of PDMS. The diffraction efficiency of the $q$th order can be obtained by the squared Bessel function $I_q^2(m/2)$. In this case, light is reflected at the bottom electrodes and the phase modulation parameter $m$ is calculated as [22]:

$$m = 2d(n - 1)2\pi/\lambda$$

By controlling the relief depth $d$ with applied voltage, the phase modulation parameter $m$ can be adjusted. Hence the amount of light diffracted into the 0th and higher orders can be manipulated. The relationship between diffraction efficiency of the $q$th order and phase modulation parameter $m$ is shown in Fig. 3. For light modulation efficiency, the grating depth is expected to be as big as possible with certain driving voltage. In this tunable grating, a relatively big relief depth is achieved by optimizing the structure dimension and the viscoelastic properties of the actuation layer, PDMS. The optimized dimension of each layer is determined based on simulations and experiments, which are: PDMS thickness = 3.5 nm, PEDOT: PSS thickness = 100 nm, linewidth of the gold electrodes = 30 μm and spacing between the electrodes = 3 μm.
3. Experiments

3.1. PDMS synthesis

Commercial PDMS-based elastomer (e.g., Sylgard) has been used as the electroactive material for optical modulator applications [9–12]. However, the experimental results from different research groups are inconsistent due to the unspecified chemical compositions. In this work, the PDMS is synthesized to satisfy the demand of deformability and fast response, by mixing vinyl-terminated monomer, cross-linker (PDMS that contains hydrides-sites in polymer chain), catalyst and certain amount of solvent. All the mixing and curing process were performed at room temperature. Young’s modulus and response time are characterized using home-built measurement systems. The details of the measurement set up are referred to [23].

3.2. Conductive polymers PEDOT: PSS characterization

CLEVIOSTM PEDOT: PSS is an aqueous dispersion of the conductive polymer PEDOT doped with PSS. The optical and electrical properties of the conductive polymer were characterized before applying it to the tunable grating. The transmission and sheet resistance were investigated for different thickness of PEDOT: PSS films. The transmission of PEDOT: PSS in UV light (385–405 nm) was measured using a UV power meter and the sheet resistance is characterized by four-probe method.

3.3. Device fabrication

A tunable grating was fabricated on a glass substrate. First, a 100 nm thick titanium–tungsten layer, which works as an adhesion layer between gold and glass, was sputtered on the glass substrate. Afterwards, a 150 nm thick gold layer was sputtered on a titanium–tungsten layer. These two layers were then patterned as interdigital electrodes by reactive ion etching (RIE) and wet etching, respectively. Afterwards, a 3.5 μm thick PDMS layer was deposited by spin coating to obtain a smooth PDMS surface. Finally, a 100 nm thick PEDOT: PSS film was spin coated on PDMS.

Since PDMS is an originally hydrophobic material exhibiting a static contact angle of 110° [20], a surface treatment of PDMS to make it hydrophilic is necessary for the subsequent PEDOT: PSS deposition. Oxygen plasma treatment is commonly applied to change the wettability of polymers [24,25]. However, it was reported in Ref. [20] that plasma treated PDMS surface gradually changed back to hydrophobic as hydrophobic groups slowly diffuse towards the surface and replace polar groups existing on the plasma treated surface. This aging effect can be slowed down using SF6 plasma followed by O2 plasma processes [26]. Thus SF6, Ar, O2 plasmas were tried out with several sets of processing parameters. The wettability was evaluated by measuring the contact angle between water drops and the modified surface, and the morphology after the plasma treatment was evaluated.

A prototype of the tunable grating has been fabricated as shown in Fig. 4. As a preliminary test, this modulator has interdigital bottom electrodes and it works for one pixel. Hence there are only two signal voltages which are applied through the left and right bottom electrodes, respectively. A SLM with many individually controlled electrodes for high-resolution display (e.g., 1080 pixels for HDTV) can be readily fabricated using the same techniques except different bottom electrodes. This part of work is still going on and will be reported in the future.

3.4. Device characterization

The electric field induced grating profile on the PEDOT surface was characterized by an optical interferometer (Wyko NT9100), and the diffraction efficiency of the modulator was calculated based upon the measured relief depth. The transmission of the modulator was obtained by comparing the incident and reflected light. A HeNe laser with 633 nm wavelength was illuminated at the modulator. The intensity of the incident and reflected light was measured using a photo detector (Photomultiplier Tube).

Theoretical analysis of the static electro-mechanical property of the device was carried out using a finite elements software COMSOL Multiphysics 3.4, and the simulation results are compared with the experiments.

The dynamic electro-mechanical properties of the tunable grating were characterized in terms of the response time. It was measured by a home-built measurement system. As shown in Fig. 5, a HeNe laser beam with 633 nm wavelength was directed onto the gratings. When no driving voltage was applied, only the 0th order of light was reflected from the bottom gold electrode and then blocked by a Schlieren stop. When driving voltage was applied, a grating appeared on the polymer surface, diffracting light into higher orders. These higher orders were detected by a photo detector (Photomultiplier Tube).

4. Results and discussions

4.1. Material properties

The Young’s modulus of the synthesized PDMS is measured as 600 kPa. The response time is characterized to be 10 μs. The mea-
Fig. 6. Transmission (*) and sheet resistance (Δ) with regard to PEDOT: PSS thickness.

measurement results prove that the synthesized PDMS has both good deformability and fast response speed.

The transmission of PEDOT: PSS in UV-visible wavelength is given in the product specification [27] that more than 80% transmission can be obtained for 200 nm PEDOT film. The transmission of PEDOT: PSS in UV light (385–405 nm) was measured using a UV power meter to verify the datasheet. The result is shown in Fig. 6.

With the film thickness below 250 nm, the transmission was in the range of 80–95%. This measurement results fit the data given in Ref. [27]. The sheet resistance of the PEDOT: PSS films were obtained using four-probe method as shown in Fig. 6. As expected, thinner film has better transmission but bigger resistance. In order to obtain the efficiency of the device, it is important to find the optimal balance between the transmission and resistance of the transparent conductive polymer. In this work, 100 nm PEDOT: PSS films were utilized since they have relatively high transmission and small resistance.

4.2. Surface morphology

In SLMs, the surface morphology has significant effects on the light modulation. Usually, a smooth surface is required so that the light scattered into random direction can be kept at the minimum. After PDMS spin coating, a smooth surface was obtained with surface roughness of approximately 7 nm, which was measured by an optical interferometer. However, the plasma processing, which is necessary before PEDOT: PSS deposition, may change the surface morphology of PDMS. Varied plasma sources were tried to change the wettability of PDMS without surface deterioration. The results are shown in Fig. 7. SF6 plasma created column-like structures due to the selective etching. These structures have height around several hundred nanometers and this phenomenon was also reported in Ref. [28]. Ar plasma gave smoother surface but slightly increased the surface roughness due to the physical impinging. A wrinkle-like surface was observed after 5 min O2 plasma treatment, which may be due to the elevated temperature caused by the long time plasma treatment. The O2 plasma treatment time was then optimized as 60 s which dramatically increased the surface wettability of PDMS (contact angle drops from 110° to 3°) without noticeable surface deterioration. After PEDOT: PSS deposition, the surface roughness of the device was further decreased to 3 nm. Meanwhile, the experiments indicated that if the PEDOT: PSS layer was deposited right after the plasma treatment on PDMS surface, it bonded to PDMS tightly. The adhesion between PDMS and PEDOT: PSS remained good after two months. The reason for the eliminated aging effect can be explained as follows: once the conductive polymer is bonded to the polar groups on PDMS surface, it stops the diffusion of polar groups towards bulk PDMS. In this work, PEDOT: PSS solution was spin coated on PDMS surface right after the oxygen plasma processing, and then baked in an oven at 60 °C for 1 h to evaporate the solvent in PEDOT: PSS. Thus the aging effect of PDMS surface wettability was avoided.

4.3. Static characterization of the device

When driving voltage was applied between the top conductive polymer layer and the bottom electrodes, electric field was generated in the PDMS layer and led to gratings on PDMS surface. The grating profile on PEDOT: PSS surface under 250 V driving voltage was measured by an interferometer and shown in Fig. 8. The value of the peak-to-peak deformation was approximately 200 nm.

Fig. 7. Surface morphology of plasma treated PDMS film, measured by an interferometer. The surface structures are exaggerated. (a) SF6 plasma treated PDMS. The surface roughness is $R_a = 250$ nm. (b) Ar plasma treated PDMS. The surface roughness is $R_a = 15$ nm. (c) 5 min O2 plasma treated PDMS. The surface roughness is $R_a = 35$ nm. (d) 60 s O2 plasma treated PDMS. The surface roughness is $R_a = 7$ nm.
The relief depth shows good uniformity across the whole device. From Eq. (2), the diffraction efficiency of the first order, defined as the amount of light diffracted in the first diffraction order, was calculated as 27%.

The optical transmission of the modulator was measured as 78% at 633 nm wavelength. It is not as good as the SLMs with a continuously reflective surface, but it is considered acceptable. The light loss is mainly due to the absorption in the polymer layers, the reflection in the media interface, and the light loss in the small spacing between bottom electrodes.

According to Refs. [30,31], the refractive index of PEDOT: PSS and PDMS is 1.51 and 1.47, respectively. This refractive index variation can influence the characteristic of the diffracted light. Based on the Snell’s law, the angular change at the PEDOT/PDMS interface is 0.01 radians). Hence the diffraction angle is mainly defined by the grating period and the relief depth of PDMS. Small amount of light will also reflect at the interface due to the refractive index change. From Eq. (3), where \( R \) is the reflectance, \( n_1 \) and \( n_2 \) are the refractive index of PEDOT: PSS and PDMS, respectively, the reflected light is calculated as 0.01% of the total incident light. In this case, the angular change and the reflection, which are originated from the refractive index variation, are considered negligible.

\[
R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}
\]  

(3)

The theoretical analysis of the electric field induced deformation was described in detail in Ref. [29], where the relief depth of the gratings was given as a function of the electric potential, the spatial frequency of bottom electrodes, the viscoelastic property and the thickness of the actuation layer. A 3D model was constructed by coupling electrical domain and mechanical domain in COMSOL Multiphysics 3.4. The electric field and the relief depth were calculated by solving the Maxwell’s equations and the Hook’s law respectively [32]. The simulation results are shown as Fig. 9, in which the grating profile is clear. To compare the experimental results with the simulation results, the relief depth of the PDMS surface with regard to the driving voltage was plotted. As shown in Fig. 10, the experiment results show fair agreement with the simulation results.

4.4. Dynamic characterization of the device

The results of the measured response time of the tunable grating are shown in Fig. 11. In this measurement, a 200 V, 1 kHz rectangular wave was applied. The rise/fall time, which is defined as the time required for the PDMS deformation to rise/fall from 10% (or 90%) to 90% (or 10%) of its peak value, was measured as 240 \( \mu \)s and 250 \( \mu \)s respectively.

The response speed of the device are determined both by the time needed for polymer deformation, which is determined by its viscoelastic property, and by the time constant of the RC circuit where the resistance is mainly originated from the conductive polymer and capacitance is from the PDMS layer. The response speed of the polymer based modulator is usually limited by the viscoelastic property of the polymer as the time constant of the RC circuit is relatively small. In this work, the PDMS was synthesized to have a short response time, which is measured as 10 \( \mu \)s, while the retardation time of the RC circuit, which is calculated as \( \tau = RC \), is 230 \( \mu \)s. In this calculation, the relative permittivity of PDMS is 2.5 [33]. The resistance of the wire bonds, the gold electrodes, the connecting
cables and the impedance of the generator were neglected. Comparing the RC retardation time with the measured rise time (240 μs) and fall time (250 μs), the response time of our modulator is mainly determined by the RC circuit. Therefore, to improve the response speed of the device, the best way is tuning PEDOT: PSS with high conductivity. It has been reported that the conductivity of PEDOT: PSS films can be dramatically increased by adding additives such as glycerol [18,34,35]. In Ref. [35], the PEDOT: PSS was modified to have conductivity approximately 750 S/cm. If this kind of PEDOT: PSS is used in our tunable grating, the time constant in electrical domain will dramatically decrease to 148 ns and the response time can reach 10 μs, which is limited by the intrinsic response time of the PDMS film.

Driving voltage of 200 V and 1 kHz rectangular wave was applied to the tunable grating for 8 h. The test showed that the modulator worked well after millions times of actuation. No breakdown or reduction in the relief depth was observed during this test. Eight hours continuously laser exposure did not bring any degradation of the modulator. The modulator works well after two months stored at room temperature.

5. Summary and conclusions

In conclusion, a tunable grating using conductive polymer PEDOT: PSS and viscoelastic PDMS was designed, fabricated and characterized. In contrast to other polymer/metal based modulators, our modulator uses PEDOT: PSS as the top electrode instead of metals in order to improve the surface quality and the stability. A smooth surface of PEDOT: PSS was obtained with roughness of approximately 3 nm, and it showed good adhesion to the underlying PDMS layer. To ensure a fast response time of the modulator, PDMS with 10 μs response time was successfully synthesized. The tunable grating was characterized with good static and dynamic performance. Under 250 V, 1 kHz driving voltage, a maximum 200 nm peak-to-peak relief depth on PDMS surface was obtained, giving 27% first order diffraction efficiency. The rise and the fall time of the modulator are 240 μs and 250 μs, respectively. Simulation model for the static electro-mechanical performance of the tunable grating was built. The simulation in COMSOL shows fair agreement with the experimental results with respect to the relief depth.

The technique reported in this paper can be easily applied to make a SLM for high-resolution display. Since the device shows no degradation after long time laser exposure, it can be adapted for line-scan laser display with low production cost.

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Biographies

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Article V

Speckle reduction using a motionless diffractive optical element

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Speckle reduction by moving diffuser has been previously studied in display systems with coherent light sources, such as lasers. In this Letter, we propose a motionless diffractive optical element (DOE) for speckle reduction. The DOE was designed based on finite-element method simulations, fabricated using micromachining technology, and characterized for despeckle efficiency. Experiments using a DOE with two gratings have indicated that the speckle was suppressed to 50%, which shows fair agreement with theoretical analysis. With some modification of this DOE, the speckle noise can be reduced to 10% according to the theory. © 2010 Optical Society of America

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Speckle is induced by the light scattering and interference of coherent radiation from a screen with roughness of optical wavelength. The fundamental theory of speckle formation, its statistical properties, and despeckle methods are described thoroughly in [1]. Considerable efforts have been made to minimize the speckle in display systems with coherent sources. The efforts use, to list a few, a moving diffuser placed at the image plane [2], dynamic Hadamard phase patterns inside each detector resolution pixel at the intermediate image plane [3], partially coherent beams [4], and a stationary phase plate based on the Barker or another binary phase code at the intermediate image plane [5]. When a mechanically vibrating element is used, such as those in [2,3], a motor is needed to provide fast vibration or rotation. This can be difficult for practical implementation and decreases the system’s reliability. When a laser array is used, as in [4], the illumination optics is complicated and the cost increases. The methods based on binary phase code [5] are only applicable in line-scan projectors.

A micro-opto-electromechanical-system-based motionless despeckle modulator, which consists of a dynamic diffractive optical element (DOE) and a static diffuser, is proposed in this work. It is applicable in a laser imaging system with a two-dimensional display chip, such as a digital micromirror device. An example of its implementation in a laser full frame projector is shown in Fig. 1. Compared with other techniques, the reliability is improved and the noise is minimized, since no mechanical vibration is needed for the modulator. Moreover, as fabricated with micromachining technologies, this modulator is compact; therefore, it is flexible for system implementation. Last but not least, the dynamic gratings are made of deformable polymer material, such as poly-dimethylsiloxane (PDMS), which is low cost, lightweight, reliable, and easily processed. According to the experiments, it can stand 80 °C, 80% humidity, and long-time laser exposure without any degradation [6], providing the capability to work in harsh environments.

The speckle contrast ratio can be suppressed to \( C = 1/M^{1/2} \) by sequentially creating a number of \( M \) uncorrelated speckle patterns and adding them together during the integration time of the detector, which is around 30 ms for human eyes [1]. In this work, different speckle patterns were created using a dynamic DOE together with a static diffuser. To explain the working principle, a dynamic DOE including three electrically controlled gratings is shown in Fig. 2. Each grating can be switched “on” and “off” independently by applying voltage between the indium–tin–oxide (ITO) electrode and the opposite gold interdigital electrodes. In the “off” state, the polymer (PDMS) surface is flat and the incident light is reflected at the angle of the total internal reflection (TIR), while in the “on” state a phase grating in the form of periodical relief is generated on the PDMS surface, splitting light into several diffraction orders. When one or several gratings are actuated, the incoming light is reflected sequentially from the areas of the polymer surface over the gold electrodes and is split into a multitude of diffraction orders. There are totally \( M = 2^m \) diffraction patterns for a DOE with \( m \) gratings, corresponding to different combinations of actuated gratings. Each diffraction pattern is scattered by the diffuser and then homogenized by the light pipe. Speckle fields created on the screen by these diffraction patterns are fully independent if there are no overlapping areas between different diffraction patterns on the diffuser. In this case, the speckle contrast can be reduced to

\[
C = \frac{1}{M^{1/2}}
\]

Fig. 1. General structure of the projection display with the laser light source and the motionless despeckle modulator for speckle reduction.
where $K$ is the number of resolution elements of the projection lens lying within one resolution element of the eye [1]. However, the despeckle efficiency will be reduced if there is overlapping of spots of different diffraction patterns [7]. An efficient way to minimize the overlapping is to use gratings with varied orientation angle and spatial frequency, which was done in this work by designing interdigital gold electrodes with varied patterns, as shown in Fig. 2.

The dynamic DOE has been fabricated with micromachining technology. First, gold layers were patterned in the form of interdigital signal electrodes on a glass substrate. Second, a flexible polymer, PDMS, was deposited on the prism that had a thin ITO layer on the surface, by compression molding [8]. Last, the prism was bonded to the glass substrate with spacers in between to set the air gap. Performance of the dynamic DOE is greatly dependent on the properties of the PDMS, which are the response speed and the elastic modulus. PDMS with $10 \mu s$ response speed and $550 \text{kPa}$ elastic modulus was synthesized by modifying its intrinsic network structure as described in [9]. The following design parameters of the DOE for practical implementation were obtained from finite element method simulations in COMSOL to ensure the diffraction efficiency: PDMS thickness, $30 \mu m$; air gap, $5 \mu m$; period of gold electrodes in a range of $50 \mu m$ to $100 \mu m$.

A DOE with two gratings was fabricated and tested for speckle reduction in the measurement setup, as shown in Fig. 3. A laser beam illuminated the DOE with $45^\circ$ incident angle, which was slightly larger than TIR angles for the polymer/air and the glass/air interfaces. By applying $50 \text{V}$ square-wave ac voltage with frequency of $100 \text{Hz}$ to the signal electrodes (Au interdigital electrodes) and $200 \text{V}$ dc voltage to the bias electrodes (ITO), four diffraction patterns appeared sequentially on the first diffruser, corresponding to $M = 2^2$ states (Fig. 4). The diffraction spots were scattered by the first diffruser, which has a $\pm 10^\circ$ divergent angle, and then passed through a 175-mm-long hexagonal light pipe, which was used to homogenize the intensity of the incoming light. In the experiments, the light pipe was placed adjacent to the first diffruser to avoid light loss. The second diffruser was illuminated by the homogenized light after the light pipe and imaged by the CCD camera approximately 600 mm away. The CCD camera was equipped with an imaging lens of focal length $f = 75 \text{mm}$ and $f$-number $= 16$ and operated in the linear regime. The integration time of the camera was set to $1/32 \text{s}$. The speckle contrast was calculated as $C = \sigma_I/I_{\text{mean}}$, where $\sigma_I$ was the standard deviation and $I_{\text{mean}}$ was the mean value of light intensity [1] all over the CCD sensor area ($640 \times 480$ pixels). The speckle field registered by the CCD camera when all gratings were switched off is shown in Fig. 5(a), and the speckle contrast was 0.73, while the speckle field when four different diffraction patterns (Fig. 4) appeared during the exposure time ($1/32 \text{s}$) is shown in Fig. 5(b) with $C = 0.37$. Therefore, the speckle contrast reduction was $(0.37/0.73) \times 100\% = 51\%$. The original speckle contrast of 0.73 was close to the expected value, $1/21/2$, as it should be when the narrowband laser is scattered by a depolarizing screen [1]. According to simulations of...
the designed DOE, there was no overlapping among any of the four diffraction patterns, while the experiments demonstrated, too, that the overlapping was negligible. In this case, Eq. (1) can be used. We assumed that $K$ in Eq. (1) is infinitely larger, because $C$ was calculated over the entire area of the CCD sensor with $640 \times 480$ pixels; one pixel had the approximate size of the projection lens resolution element. Then the speckle contrast $C = 1/M^{1/2}$, which gives $C = 0.5$, or 50% for $M = 2^2$. Thus, the experimental result shows fair agreement with the theory.

The proposed dynamic DOE provides an idea of using a motionless spatial light modulator to reduce the speckle noise, and it has been proved by preliminary measurements with 50% speckle suppression. Higher speckle reduction can be achieved by using a DOE with more gratings. Calculations based on [7] and simulations in ZEMAX have shown that the speckle contrast can be reduced to 25% for the dynamic DOE with four gratings [10]. However, one cannot arbitrarily increase the number of gratings to get higher speckle suppression, since the overlapping of different diffraction patterns will increase, as well. To further reduce the speckle, one can use a laser beam with a smaller diameter or introduce a lens between the dynamic DOE and the static diffuser. This will provide smaller diffraction spots and, therefore, less overlapping. Further speckle suppression can be achieved by using gratings with dynamic periods. In that case, the grating period is varied during the integration time. The speckle noise can be suppressed down to 10% for the dynamic DOE with four gratings, with each grating having three grating periods during the integration time [10].

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References
Article VI

Laser Speckle Reduction Based on Angular Diversity Induced by Piezoelectric Benders

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Abstract—Speckle reduction techniques have been investigated in display systems with coherent light sources. We propose a simple but efficient method to reduce speckle via two fast vibrating piezoelectric benders. The concept is modulating laser beams to have angle diversity and reducing speckle by temporal averaging in the integration time of the detector. Experiments demonstrate that the speckle contrast is suppressed down to 0.06. Both free space and imaging geometry are considered. In order to fairly evaluate the speckle reduction, the optical configuration as well as the camera settings, which largely affect the speckle contrast, is discussed.

Index Terms— Angular diversity, Laser imaging, Projection display, Speckle.

I. INTRODUCTION

In comparison with conventional lamps, the use of lasers in projection displays gives unrivaled imaging quality with extensive color coverage. However, one major technique obstacle, which limits its applications, is the speckle phenomenon. Speckle is induced by the light scattering and interference of coherent radiation from a screen with roughness in the scale of optical wavelength. The presence of speckle masks the image information and therefore its reduction is highly desirable in projection displays. The fundamental theory of speckle formation, its statistical properties and de-speckle methods are described thoroughly in [1]. Considerable efforts have been made to minimize the speckle noise. A moving diffuser is placed at the image plane [2] and dynamic Hadamard phase patterns are employed at the intermediate image plane [3] for speckle reduction. However, a motor is needed in these cases, to provide fast vibration or rotation. This can be difficult for practical implementation and decreases the system reliability. Partially coherent laser beams are applied in laser projections [4]. The illumination optics is complicated. A stationary phase plate based on Barker code located at the intermediate image plane [5] is only applicable in line-scan projectors. A polymer dynamic diffractive optical element [6] is not suitable for high power lasers.

Two piezoelectric benders have been employed in this work for speckle reduction. The incoming laser beam is steered by the two piezoelectric benders. The moving beam is collected by a condenser lens, and falls on a transmitting diffuser at different angles. Speckle reduction is achieved by angular diversity of laser beams. Experiments are performed both for free space propagation geometry and imaging geometry. The speckle reduction technique proposed in this work is reliable, low cost and efficient. The integration in laser TVs or projectors is simple and straight forward. It is a good candidate in the case when high laser power is requested, since the piezoelectric ceramic is reliable under high temperature.

II. EXPERIMENTAL SETUP

The experimental setup to implement speckle reduction in the free space propagation is shown in Fig. 1. In free space geometry, no imaging lens is mounted on the charged coupled-device (CCD). He-Ne laser is employed with power of 4 mW, wavelength of 633 nm, and beam spot size of 0.5 mm. The laser beam has a fixed polarization and passes through two polarizers. Polarizer 1 is rotated to adjust the beam intensity, and polarizer 2 maintains a fixed polarization of the transmitted beam. The piezoelectric benders are based on lead zirconate titanate material and are purchased from Noliac AS. The dimension is 50 mm x 7.8 mm x 0.7 mm (L x W x H). The surface of piezoelectric benders is deposited with thin gold film, which works as reflective mirrors. Two piezoelectric benders are placed perpendicularly to each other and both of them are fixed at one end. The maximum deflection range of the benders is characterized as ±1 mm at ±100 V 167 Hz square wave voltage. Laser beam is reflected at two benders and it is steered in both X and Y directions, creating a 2D scanning. The moving laser beam is collected by the condenser lens with focal length 25 mm, and falls on a transmitting diffuser with different angles. The diffuser is very rough on the optical wavelength scale to ensure a sufficient phase modification. After passing through the diffuser, the beam propagates in free space and falls on the CCD sensor. The CCD has a resolution of 640 × 480 pixels, and each pixel has a dimension of 5.6 μm × 5.6 μm.

In order to demonstrate the application of the piezoelectric benders for speckle reduction in full frame laser display, an imaging geometry is constructed as shown in Fig. 2. Unlike...
free space geometry, after passing through diffuser 1, the scattered light is collected and homogenized by a 175 mm long hexagonal light pipe. Diffuser 2 is placed at the output of the light pipe, to further homogenize the beam. The object, which is a transparent plastic sheet printed with a letter “S”, is placed right after diffuser 2. The CCD camera is equipped with an imaging lens of focal length 50 mm. Lens extenders are employed to adjust the distance between imaging lens and the CCD sensor, which is f1 in Fig. 2.

**Fig. 1.** Speckle contrast measurement setup of free space geometry.

**Fig. 2.** Speckle contrast measurement setup of imaging geometry.

### III. RESULTS AND DISCUSSION

When the piezoelectric benders are actuated, laser beam is steered. The moving beam is focused at a spot on diffuser 1 by the condenser lens. The spatial position of the laser spots on diffuser 1 remains the same while the illumination angle is changed. The laser spots with different illumination angle generate different speckle patterns, which are averaged by the CCD camera during its integrating time. The speckle is evaluated by speckle contrast (SC) which is defined as the standard deviation divided by the mean value of light intensity in the speckle pattern [1]. Many measurement parameters will influence the value of SC. In order to fairly evaluate the speckle reduction, it is important to perform the calibration and find the suitable measurement parameters. The calibration process is based on three criterions: 1). The speckle size detected in CCD sensor should be big enough compared with the CCD pixel size. According to [1], the ratio between the speckle size and CCD pixel size affects the value of SC, by:

\[
SC = \sqrt{k} \times \text{erf}(\pi/\sqrt{k}) - 1/\pi \times \left[1 - \exp(-\pi^2k)\right]
\]

where \(k\) is equal to \(A_c/A_m\), \(A_c\) is the “coherent area” or “speckle size” and \(A_m\) is the CCD pixel size. By plotting parameter \(k\) with regard to SC, it is seen that \(k\) should be at least above 10, to avoid the speckle reduction introduced by the spatial averaging of CCD pixel. 2). The CCD camera should be operated in the linear regime. The detected light intensity distribution should be neither over-saturated nor under-saturated. 3). In free space geometry, ideally the original SC is equal to 1 without any de-speckle method applied. In practice, however, the SC should be 1/2^(0.5) (0.71) even without the motion of piezoelectric benders, due to the narrowband laser scattered at a depolarizing screen [1].

In free space geometry, the center-to-center spacing of adjacent dark spots or of adjacent light spots in speckle pattern is given by \(\lambda z/D\) [7], where \(\lambda\) is the laser wavelength, \(z\) is the propagation distance between diffuser 1 and CCD sensor, \(D\) is the diameter of the scattering spot. This is the one dimensional “width of speckle”. A reasonable approximation is that \(A_c = (\lambda z/D)^2\) [1]. In this case, \(\lambda\) is 633 nm, \(z\) is 50 mm and \(D\) is 0.5 mm. Therefore the speckle size at the CCD sensor is 63.3 × 63.3 μm, which is big enough to avoid the spatial averaging due to the CCD pixel. To ensure that the CCD camera is operated in the linear regime, the camera parameters are set as: Gamma=100, Brightness=0, Gain=550, Exposure time=1/34 sec (to simulate the averaging time of human eyes). The light intensity is adjusted by the polarizer 1 to avoid over-saturation and under-saturation of the detected speckle in CCD. In this calibrated system, when laser illuminated at the diffuser, which works as a depolarizing screen, the SC is 0.71.

The captured speckle image with and without the actuation of the piezoelectric benders are shown in Fig. 3 (a) and (b), respectively. As expected, without the actuating of benders, the speckle is significant. As benders actuated, the speckle is averaged by angular diversity of beams and the image becomes smooth. The minimal SC is 0.06, which is obtained when piezoelectric benders are driven under ±100 V, 167 Hz square wave voltage. From Fig. 3 (b), the speckle pattern almost can not be perceived.

**Fig. 3.** Speckle reduction in free space geometry: (a) original speckle SC=0.71; (b) reduced speckle SC=0.06. Speckle reduction in imaging geometry with both fine and coarse speckle: (c) original speckle SC=0.87; (d) reduced speckle SC=0.16. Speckle reduction in imaging geometry with only coarse speckle: (e) original speckle SC=0.71; (f) reduced speckle SC=0.09.
For imaging geometry, in order to determine the measurement parameters, the first two criteria as in free space geometry are employed. The third criterion is not applicable in this case, due to “compound speckle” phenomena. In imaging geometry, when light passes through diffuser 1, and falls on a finite-sized diffuser 2, there can be a compounding of speckle statics. The speckle generated from diffuser 1 has bigger size, or “coarse speckle”; while the speckle generated from diffuser 2 has smaller size, or “fine speckle”. The SC of compound speckle can be bigger than 1.

Due to the dimension difference of the coarse and fine speckle, it is difficult to measure and evaluate them in a single setup. The optical configuration has to be adjusted in order to observer one or the other. The fine speckle size is calculated by \( (1+M) \times \lambda \times F\# \) [7], where \( M \) is the magnification of the optical configuration, which is \( f_1/f_2 \) as shown in Fig. 2. In order to obtain sufficiently large fine speckle size, \( F\# \) of the imaging lens is set as the maximum value 16. The lens is mounted 150 mm away from the CCD sensor and placed 75 mm away from diffuser 2. Hence, the speckle size is 30.4 \( \mu m \) \( \times 30.4 \mu m \), which is big enough to avoid the spatial averaging from CCD.

The original SC is 0.87 rather than 0.71, which is due to the compound speckle phenomena. In this case, both the fine and coarse speckle is detected by the CCD sensor. However, the coarse speckle is big and difficult to distinguish from the CCD sensor. The size of coarse speckle is calculated by two steps. From diffuser 1, the scattered beam propagates in the light pipe with multiple reflections. This is free space propagation and the speckle size is \( (\lambda z/D)^2 \). The speckle pattern at the output of light pipe is magnified into the CCD sensor by magnification \( M \). Therefore the final coarse speckle size is \[ (1+M) \times \lambda \times F\# \times M \] where \( z \) is the propagation distance within the light pipe. We assume that \( z \) is three times longer than the length of light pipe. To observe the coarse speckle clearly, the optical configuration is adjusted to: \( f_1=60 \) mm, \( f_2=250 \) mm, \( F\# = 1.4 \). Hence, the coarse speckle size is 159.5 \( \mu m \) \( \times 159.5 \mu m \). Please note that the coarse speckle size calculation is just an approximation because the light propagated inside light pipe in a complicated manner and it is difficult to predict the light path. Moreover, unlike the free space propagation, in light pipe propagation the speckle pattern is folded many times by multiple reflections from the side walls and this may affect the speckle size. The coarse speckle is shown in Fig. 3(e). It is clear that the coarse speckle is much bigger than the fine speckle, since the letter “S” is the same as in Fig. 3(c). The height of the letter “S” is approximately 0.5 mm, indicating that the calculated coarse speckle size 159.5 \( \mu m \) \( \times 159.5 \mu m \) agrees with the experiments. In this measurement setup, the fine speckle size is \[ (1+M) \times \lambda \times F\# \times M \] = 1.1 \( \mu m \) \( \times 1.1 \mu m \). The speckle size is much smaller than the CCD pixel size therefore it is not perceived by CCD sensor. The coarse speckle is reduced from 0.72 to 0.09 by piezoelectric benders in imaging geometry. From Fig. 3 (e) (f), the masked letter “S” becomes quite distinct after speckle reduction. In practice the \( f_1/f_2 \) ratio is usually much smaller than 1, since \( f_1 \) is normally the distance between the eye lens and retina. Therefore, the fine speckle is difficult to be observed due to the small size.

In conclusion, by using two fast vibrating piezoelectric benders, the speckle contrast is efficiently reduced from 0.71 to 0.06 and 0.09, in free space geometry and imaging geometry, respectively. It demonstrated that the proposed method can be implemented into full frame laser display for speckle reduction. The method is simple to construct with low cost and shows good reliability and stability. It is especially suitable for large display screen where a high power laser is needed.

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