Organic amorphous fluoropolymer membrane for variable optical attenuator applications

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Abstract

The paper describes the design, fabrication and testing of a MEMS (micro-electro-mechanical systems) variable optical attenuator (VOA) made from an organic fluoropolymer thin film. The optical attenuation is achieved by changing the radius of curvature of the organic thin film by actuating a pneumatic force. The size of the organic polymer membrane is $4\text{ mm} \times 4\text{ mm}$ and the measured centre displacement of the organic membrane is as large as $57\text{ }\mu\text{m}$ without any plastic deformation. The mechanical deformation of the fluoropolymer membrane can be simulated by finite element method (FEM) and the optical coupling efficiency is calculated based on the coherent optical transfer function (OTF) of the deformed membrane. The experimental results show that the attenuation range can achieve 25 dB at the wavelength of 1550 nm, which agrees well with the theoretical calculation. The measured wavelength dependence loss is less than 0.5 dB.

Keywords: MEMS, variable optical attenuator, amorphous fluoropolymer membrane, organic materials

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The variable optical attenuator is a critical optical component for next generation dynamic wavelength division multiplexing (WDM) optical networks [1]. It has a wide range of applications in optical fibre communications, including dynamic gain equalizing, optical blocking, and overload protection. Due to recent fast progress in micromachining fabrication, VOAs made by MEMS (micro-electro-mechanical systems) technology show high reliability and compact size, which make MEMS VOAs promising components for telecommunication applications [2–8]. Traditionally, the structure layers of MEMS devices are made of inorganic materials, such as single crystalline silicon, polysilicon, and silicon nitride. In the last decade, organic materials, however, have found broad applications in the electrical and optical fields [9, 10]. Organic materials provide wide selectivity in

terms of fracture toughness against Young's modulus [11] and they usually can be applied at room temperature either by spin coating or injection printing, which require less complicated fabrication processes as compared with standard semiconductor production lines.

Most MEMS VOA devices make use of rotation micromirrors to either reflect the incident light away from the optimized coupling spot [2, 3] or rigid shutters to block the incoming light intensity [4–7] to achieve the desired attenuation. Both approaches, however, are not suitable for organic materials due to their compliant characteristics. On the other hand, the optical attenuation can be realized by deforming the mirror surface to defocus the optical system to adjust the optical signal intensity [8]. Since a micromirror made of brittle semiconductor materials is generally limited to deflections of less than $10\text{ }\mu\text{m}$, the highest attenuation is restricted ($<5\text{ dB}$). As a result, organic polymers with high

Figure 1. A MEMS variable optical attenuator consisting of an organic membrane and a dual fibre collimator.

yield stain and low Young's modulus are desired. It is reported that the yield strain of an organic polymer is around 5%, which far exceeds the breaking limit of the semiconductor materials, and the Young's modulus is about two orders of magnitude lower than that of most inorganic materials [12, 13].

In this paper, we report a novel MEMS VOA consisting of a deformable organic thin film aligned with a dual fibre collimator in a free-space configuration. Due to the compliant structure of the organic thin film, the deformation of the thin film can attenuate the light intensity up to 25 dB at a wavelength of 1550 nm. An organic thin film of size 4 mm × 4 mm has been successfully fabricated and tested. First we will discuss the design principle of the devices with theoretical calculations in both the mechanical and optical domains. In the following sections, we will describe the fabrication processes and experimental measurements. Finally, we will summarize the paper in the conclusion.

2. Device design and theoretical calculation

Considering the compliant characteristics and high yield strain of organic polymer materials, we decided to adopt the design of a deformable membrane structure [14]. Figure 1 shows the proposed MEMS VOA, which consists of a dual fibre collimator and a deformable mirror made of an organic polymer thin film coated with aluminium to reflect the incident light. The deformable mirror is stretched over a silicon substrate with an opening etched by low-cost anisotropic wet etching. The optical input signal from the single mode fibre is collimated by the GRIN lens and is incident onto the mirror surface. The optical output intensity is optimized when the mirror is flat and the reflected optical signal is collected by the same GRIN lens to the output port of the fibre. When the polymer membrane is deformed by an external force, the light coupling efficiency is decreased accordingly.

To estimate the necessary centre displacement for achieving the desired optical attenuation, we need to calculate the fibre coupling efficiency of the single mode fibre. This computation is based on computation of the overlap integral of the far-field source fibre amplitude distribution times the coherent OTF (optical transfer function) of the coupling system, and times the receiver fibre amplitude distribution [15], as given below:

$$T = \left| \int \Psi'_S L \Psi'_R da \right|^2, \quad (1)$$

Figure 2. Optical simulation of (a) attenuation versus radius of curvature for different beam waist, and (b) optical 3D model from ZEMAX.

where T is the power coupling efficiency, Ψ'_S the far-field distribution of the source fibre in the exit pupil plane, Ψ'_R the far-field distribution of the receiving fibre in the exit pupil plane, and L the coherent transfer function of the optical system. The coherent OTF is a function of aberration in the exit pupil plane, which can be expressed in the following way:

$$L = \exp \left[-ik W(\bar{X}_e) \right], \quad (2)$$

where W is the aberration of the optical coupling system and the $\bar{X}_e$ is the coordinate vector for the exit pupil. The most significant approximation made in this computation is that the diffraction within the optics is neglected. In many cases this approximation is sufficiently accurate, but in special cases, such as when the beam is extremely small, diffraction within the optics must be considered. The beam waist from the dual fibre collimator is of the order of few hundred micrometres and the computation method described above can meet the optical system configuration in our design. By incorporating with ZEMAX®, the coherent OTF can be calculated in the geometrical optics approximation by using equation (2). The output of the GRIN lens fibre in free space is specified to be a Gaussian distribution, so the relationship between optical attenuation and radius of curvature of the deformable mirror is calculated by a Gaussian shape model for a single mode fibre. The simulation results of the optical attenuation and three-dimensional (3D) optical model are plotted in figures 2(a) and (b), respectively. By deforming the shape of the organic membrane, the optical attenuation is in inverse proportion to the radius of the curvature of the mirror membrane. In other words, more deformation of the organic thin film causes more optical attenuation because the optical rays are not collimated, as shown in figure 2(b). Besides, it is advantageous to use larger beam waist to reach higher attenuation at the same radius

Figure 3. Mechanical simulation of (a) pressure versus centre displacement for the 4 mm × 4 mm membrane with different residual stress, and (b) ANSYS model at pressure of 2 kPa to achieve 57 μm centre displacement.

of the curvature. Given a fixed radius of curvature of 80 mm, the attenuation can be increased from 1 to 8 dB when the beam diameter is enlarged from 280 to 600 μm. These results suggest that a large beam size could increase the dynamic range of the VOA. Therefore, a deformable mirror with large surface area is preferred to accommodate larger beam diameter, which improves the attenuation efficiency. In our optical coupling system, we use a commercially available dual fibre collimator with 280 μm beam diameter. The relation between the centre displacement and the radius of curvature of the membrane mirror can be calculated by formula shown below:

$$D = A \tan \left(\frac{\sin^{-1}(A/R)}{2} \right), \quad (3)$$

where D is the centre displacement, A the effective aperture radius of the mirror and R the radius of curvature. Equation (3) is only valid for a circular shape and the effective aperture size is smaller than the square membrane size. For example, the square membrane size is 4 mm × 4 mm, but the effective aperture size is about 3 mm in diameter based on the mechanical modelling described below. The 57 μm centre displacement will change the radius of curvature from infinity to 20 mm. To the best of our knowledge, no inorganic semiconductor materials can achieve such large displacement without breaking or permanent plastic deformation.

Before the fabrication of the organic membrane, a structural FEM (finite element method) was done by ANSYS®. As discussed in the previous paragraph, a displacement of at least tens of micrometres at the centre of the organic membrane is needed to achieve more than 20 dB attenuation. We supposed that the organic membrane still remains in the elastic region and behaves as a linear material. The stress related to the strain

Figure 4. Fabrication processes of a MEMS VOA made of organic polymer membrane.

for a 3D anisotropic element can be modelled by [16]:

$$\{\sigma\} = [D] \{\varepsilon\}$$

$$\{\sigma\} = [\sigma_x \sigma_y \sigma_z \sigma_{xy} \sigma_{yz} \sigma_{xz}]^T \quad (4)$$

$$\{\varepsilon\} = [\varepsilon_x \varepsilon_y \varepsilon_z \varepsilon_{xy} \varepsilon_{yz} \varepsilon_{xz}]^T,$$

where $\{\sigma\}$ is a 6 × 1 stress vector, $[D]$ a 6 × 6 elastic stiffness matrix or stress–strain matrix, and $\{\varepsilon^{el}\}$ a 6 × 1 elastic strain vector. The elastic stiffness matrix is a function of Young's modulus, Poisson's ratio and shear modulus. All the constants can be found from the data sheet of the polymer and the D matrix must be positive definite. Figure 3 shows the simulation results of an organic fluoropolymer membrane with an area of 4 mm × 4 mm square. It is noted that the deformation of a membrane is mainly determined by residual stress, instead of Young's modulus of the material [17]. The centre displacement of the membrane can increase from 19 to 55 μm when the residual stress is lowered from 25 to 5 MPa at a uniform pressure of 800 Pa, as shown in figure 3(a). The top view and side view of a fluoropolymer membrane with centre displacement of 57 μm are drawn in figure 3(b). The deformation contour at the centre is closed to a circular shape and is used to calculate the radius of the curvature of the membrane mirror, which can then be applied to compute the corresponding optical attenuation. The residual stress of the amorphous fluoropolymer is of the order of 15–20 MPa according to the specification sheet. To successfully actuate the membrane, we decided to use a pneumatic force with a micro vacuum pump to demonstrate our idea first. The polymer membrane mirror, however, can be actuated by other means, such as electrostatic force, once the residual stress can be reduced to less than 1 MPa or so.

3. Fabrication processes

It is important to find an organic material with high yield strain for large deformation applications and good chemical stability to resist severe etching processes. We selected an amorphous fluoropolymer, CYTOP™, from Asahi Glass to fabricate the membrane-based pneumatic-actuated MEMS VOA. CYTOP™ is in the field of fluoropolymers that have excellent chemical resistance during wet etching [18]. CYTOP™ is also a Teflon-like material with high optical

Figure 5. Photograph of fabricated device.

transmittance, which makes it a suitable material for a refractive lens as well. The adhesion of CYTOP™ to silicon and metals is excellent before high temperature curing, so we need to take extra care during the fabrication process flows. These properties make it ideally suited for the

integration of polymer membrane with silicon substrates. In addition, the yield strain of CYTOP™ is about 5%, which is considered high compared with traditional semiconductor membrane materials (e.g. silicon nitride). The high yield strain is critical for large deformation of the membrane.

Fabrication processes of MEMS VOA with an organic membrane are drawn in figure 4. Starting with a 4 inch (100) silicon wafer, 3000 Å silicon dioxide was thermally grown on the wafer as a wet etching protection mask. A 4 mm × 4 mm square opening was etched on thermal oxide by buffer HF at the backside of the silicon wafer, as shown in figure 4(c). The silicon was anisotropically etched in a solution of tetramethyl ammonium hydroxide (TMAH) at a temperature of 90 °C. The etching depth of the silicon was time-controlled to leave about 30 μm silicon membrane before etching through the wafer. The 2000 Å aluminium was then deposited by an e-beam evaporator on the front side of the

(a)

(b)

Figure 6. (a) Physical deformation and (b) side profiles measured by a white light interferometer.

Figure 7. Measured mechanical deformation versus applied pressure and its theoretical calculation.

silicon wafer with a 500 Å chromium seed layer. The 2 μm organic thin film, CYTOP™, was then spin-coated and baked in an oven at 150 °C to dry the solvents out, as shown in figure 4(f). The silicon wafer was etched again by TMAH for a short time to remove the remaining silicon membrane and the etching was stopped at the thermal oxide layer. Due to the excellent chemical resistance of the amorphous fluoropolymer, the aluminium is well protected in the final wet etching process. Finally, the thermal oxide layer in the membrane was removed by a pad etchant, which contains acetic acid, ammonium fluoride, surface tension, and water. The pad etchant could minimize the damage to the aluminium layer. Figure 5 shows a photograph of the fabricated device. The surface of the CYTOP™ membrane is smooth due to the tensile residual stress of the fluoropolymer; the surface roughness is measured to be around 60 nm. The fabricated membrane is a square shape, 4 mm $\times$ 4 mm in size. We found that the high yield strain of the fluoropolymer is advantageous during the fabrication because no special attention is needed to handle the large-area membrane.

4. Experimental data and discussion

The deformation of the fluoropolymer membrane is characterized by a white light interferometer from WYKO. Due to the field of view of the objective lens, only part of the membrane mirror is shown in figure 6(a). The deformation contour at the centre of the membrane mirror is close to circular shape, which is consistent with the FEM mechanical modelling discussed in the previous section. The side profiles of the *X* and *Y* axes are shown in figure 6(b). The shape of the deformed membrane mirror is assumed to be spherical. This spherical mirror hypothesis is good enough for the first-order approximation because the size of the fluoropolymer is larger than the optical beam waist. The centre displacement versus applied pressure is plotted in figure 7. For a 4 mm $\times$ 4 mm membrane mirror, the measured centre displacement is as high as 57 μm when the applied pressure is around 2 kPa. The centre displacement of the fluoropolymer membrane is almost linearly proportional to the pressure. Also of interest is that this linearity relationship between centre displacement and applied pressure implies that the membrane is still within the elastic region. These experimental data are in good agreement with the theoretical result made by ANSYS® as discussed in the previous section.

The optical attenuation measurement was performed in the setup shown in figure 8. A dual fibre collimator was aligned in front of the fluoropolymer membrane. The beam waist from the dual fibre collimator was 280 μm and the working distance was 5 mm, which means that the distance

Figure 8. Experimental setup for optical attenuation measurement.

Figure 9. Optical attenuation versus applied pressure and its theoretical calculation.

from the dual fibre collimator to the deformable membrane was 2.5 mm. A plastic chunk connected to a compact vacuum pump was placed under the organic membrane mirror to provide the necessary pneumatic force. A pressure sensor (Asia Pacific Microsystems, Inc LP030T0) was joined to the vacuum pump to measure the applied pressure. Before turning on the pump, the membrane mirror is flat and the measured insertion loss is 1.45 dB, including the loss from one pair of FC/PC-connectors. The high insertion loss can be partly attributed to reflectivity of aluminium at the wavelength of 1550 nm and surface roughness of the fluoropolymer membrane.

When the pump is turned on, the atmosphere pressure is applied to the fluoropolymer membrane and the pressure difference is directly measured by the *in situ* pressure sensor. The applied pressure is evenly disturbed over the entire membrane because the cavity on the plastic chunk covers all the organic membrane area. The pneumatic force will pull down the compliant organic thin film so that the radius of curvature of the deformable mirror can be changed accordingly. Figure 9 shows the experimental data of optical attenuation versus the applied pressure. The optical attenuation increases almost linearly with the applied pressure. The maximum optical attenuation is around 25 dB at 2.2 kPa. Compared with a similar silicon nitride membrane design [8], the attenuation range is improved from less than 5 dB to about 25 dB. By incorporating the mechanical modelling and optical simulation, the theoretical calculation is plotted along with the experimental data. There are some unfitted points; these might be due to the pump vibration during the operation and imperfect alignment of the dual fibre collimator to the centre of the deformed membrane.

In shutter-type VOA designs, the wavelength dependent loss (WDL) slightly increases as the optical attenuation increases [19, 20]. But we observed that the attenuation in our device did not show this trend, as shown in figure 10. The measurement was done in the C-band of the wavelength,

Table 1. Qualitative comparison between different MEMS VOAs.

Mechanisms/specifications	Blocking shutters [6]	Diffractive ribbons [21]	Reflective mirrors [2]	Polymer membrane
Input/output fibres	Two sides	One side	One side	One side
Package sizes	Small	Small	Small	Large
Fabrication complexity	Difficult	Easy	Medium	Easy
Insertion loss	Low	High	Medium	Medium
Attenuation range	Large	Large	Large	Medium
PDL	Low	High	Low	Low
WDL	Medium	High	Medium	Low
Power consumption	Medium	Small	Small	Large

Figure 10. C-band wavelength dependent loss for different attenuation ranges.

from 1520 to 1560 nm. The WDL shows the highest value of 0.5 dB in the attenuation range of 8 dB. Theoretically speaking, the WDL of this design is low because the coupling design in our configuration still remains symmetric as the attenuation increases. The optical simulation results showed that the WDL is around 0.25 dB through the whole attenuation range and this is caused mainly by the GRIN lens. Besides, the membrane mirror reflects the light back to the output port and the reflection is not wavelength dependent. We suspect that the peak in this measurement may be due to the optical alignment, i.e. that the dual fibre collimator is not perfectly aligned to the centre of the deformed membrane mirror. The polarization dependent loss (PDL) was measured by a lightwave polarization analyser (Hewlett-Packard co, HP 8509B) and is plotted in figure 11. The measured data show that the PDL is below 0.15 dB at its attenuation range. The repeatability is less than 0.05 dB at the attenuation of 15 dB because the deformation of the polymer membrane is still in the elastic region.

To the best of our knowledge, this is the first report of a deformable polymer membrane actuated by pneumatic force for variable optical attenuator applications. Due to the fast progress of MEMS technology, qualitative comparisons of different MEMS VOAs are summarized in table 1. We looked into the working mechanisms of each approach, instead of a particular device. A reference, however, is given for different approaches as an example. Please be reminded that listed characteristics of different approaches are intrinsic and some may be improved later by means of optical designs or device configurations. In our approach, we found good WDL and PDL performance due to concentric design, but the deformable membrane needs a large actuation force and this may limit its current package size.

5. Conclusion

In summary, we report a novel variable optical attenuator made of an organic fluoropolymer membrane by micromachining

Figure 11. Polarization dependent loss for different attenuation ranges.

techniques. The amorphous fluoropolymer has the advantages of good stability to resist chemical etchant and high yield strain for large displacement. The attenuation is achieved by varying the radius of curvature of the organic membrane to defocus the optical coupling efficiency by pneumatic force. An organic thin film as large as 4 mm × 4 mm has been demonstrated and operated without any cracking. The experimental results show that a displacement of 57 μm can be achieved by a pneumatic force of 2.2 kPa. The large displacement of the amorphous fluoropolymer could increase the dynamic range of optical attenuation up to 25 dB. The WDL is measured as low as 0.5 dB at the C-band for optical communication applications. The theoretical calculations based on FEM mechanical modelling and OTF optical simulation agree well with experimental results. A novel MEMS VOA made by the fluoropolymer membrane has been successfully designed, fabricated and tested.

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