行政院國家科學委員會專題研究計畫　成果報告

可形變高分子薄膜材料之光學特性研究

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（一）中、英文摘要及關鍵詞

中文摘要

有別於傳統以矽為主的微機電技術，本計畫研究開發新的製程使用柔軟的高分子聚合物—無結晶性氟基化合物 (amorphous fluorocarbinate polymer)。此方法和傳統的矽製程最大的差異在於除了堅硬的材質使用外，還需加入可相容於傳統矽製程的高分子物質。比起以矽為主的化合物，這些高分子物質通常 1000 倍的柔軟並且可產生 10 倍以上的形變. 除此之外，高分子聚合物可長成的厚度可從數奈米（nanometer）到數厘米（millimeter）更增加此方法的應用彈性. 而這些將使設計人員有著更多可使用資源. 其他的優點還包括：需要較少能量產生形變、機械阻尼可減少高頻率雜訊、光學系統需較少光學元件以及緊緻封裝。

經由此計畫，對這方面應用的高分子聚合物有系統的分析及如何改善皆有基本了解。因此本計畫將經由實驗及模擬的方式來研究經由微機電製造出來的高分子聚合物之光學特性，包含了 1)表面光滑度和分子聚合及製程間的關係及 2)在高形變下之耐用性。

最後總結，本計畫以研究高分子聚合物之物質特性為主，對這些高分子聚合物的了解將有助於未來對此一物質在微光機電上的應用。

英文摘要

In order to overcome difficulties mentioned above and explore the new territory of optical MEMS, a new class of MEMS devices has begun to surface -- components made with highly compliant polymeric materials as a principal design element. This platform differs from conventional MEMS by adding a set of softer, more compliant, polymeric materials to the list of conventional rigid silicon-based materials used in traditional MEMS. In this project, we explore the possibility of using amorphous fluoroplymer, also known as CYTOP®. The compliant materials used in this new class of MEMS devices are as much as three orders of magnitude less stiff and can easily be tailored over a range of three orders of magnitude. Additionally, they can be deposited in a much broader range of layer thicknesses. This very wide range of flexibility expands the design space for MEMS devices far beyond what is possible with traditional silicon-based materials. There are several other advantages that compliant polymers enjoys over silicon-based MEMS, including mechanical deflection requires much lower energy, mechanical damping can be included to avoid high frequency noise, fewer discrete components provide better reliability at lower cost, and compact package design permits superior integration.

Through this project, we have systematic studies and fundamental understandings on how compliant polymers can be improved and be optimized. In this project, we explored this not-yet-well-known field and conduct both simulation and experiments on how the polymer material can be used to make deformable surface and its compatibilities with existing MEMS technology. The project will focus on the optical properties of polymer material fabricated by MEMS technology in the following areas, surface roughness and its relation to polymer structures/fabrication process and environmental resistance of various polymers.

To conclude, this is the initial efforts to study the material properties of amorphous fluorcarbinate polymer for the application in Optical MEMS. The results will provide deep understandings of compliant polymer materials and form the foundation of future development for micro optics.

關鍵詞（Keywords）

微光機電、高分子聚合物、表面粗糙、大形變量、耐用度

Optical Micro-Electro-Mechanical Systems, Polymer, Surface Roughness, Large Deformation, Reliability

（二）報告內容

研究目的

It has been optical scientists' dream to make mirrors, which can change the shape arbitrary to accommodate different optical designs, i.e. deformable mirrors. There are many potential applications of such devices such as optical signal processing, variable focal depth microscope, free space communications and bio-imaging instruments etc. Traditionally, such deformable mirrors are hand-made by gluing individual piezoelectric actuators to membranes or mirror pixels. They are inherent bulky and expensive and can only be applied to very limited applications, such as observatory telescopes. Recently, micro-electro-mechanical technology emerges as a promising method to fabricate deformable mirrors due to the intrinsic batch fabrication processes. Three types of deformable mirrors are currently being pursued by MEMS researchers: 1) membrane mirrors, 2) continuous face sheet mirrors backed by individual actuating elements, and 3) segmented mirrors. The microfabricated mirror membranes have high optical efficiency and allow several deformation modes of the membrane. On the other hand, segmented mirrors designs have lower optical efficiency and suffer diffraction effects from mirror gaps, but provide fast response time in the order of microseconds.

In order to achieve higher optical efficiency, the project will adopt membrane approaches. However, the deformation of membrane mirrors made by silicon based MEMS technology is limited to several microns due to rigid silicon-based materials. Recently, a new class of MEMS devices has begun to surface -- components made with highly compliant polymeric materials as a principal design element. Stiffer materials require higher voltages to achieve a given mechanical deflection, and traditional silicon-based materials are all extraordinarily stiff. The Compliant MEMS (CMEMS) technology platform differs from conventional MEMS by adding a set of softer, more compliant, polymeric materials to the list of conventional rigid silicon-based materials used in MEMS. Adding these compliant materials to the list of materials that can be deposited, patterned and etched greatly widens the design space. The compliant materials used in this new class of MEMS devices are as much as six orders of magnitude less stiff and can easily be tailored over a range of three orders of magnitude. Additionally, they can be deposited in a much broader range of layer thicknesses. This very wide range of flexibility expands the design space for MEMS devices far beyond what is possible with traditional silicon-based materials. This CMEMS platform enables the development of components and assemblies that demonstrate superior performance and lower costs than what can be achieved using the silicon-based MEMS solutions currently available. Its unique architecture is ideal for a broad range of high-performance deformable mirrors, where it offers several significant benefits over traditional MEMS-based designs.

As of a result, polymer materials combined with silicon-based MEMS technology will offer much wider flexibility to existing platforms. This project will further explore the optical characteristics of amorphous fluorocarbinate polymer, also known as CYTOP®, under different synthesis fabrication processes to fully understand the fundamental limits of such materials in the application of optical MEMS components. We fabricated a variable optical attenuator (VOA) as our test bench to understand its optical quality.

文獻探討

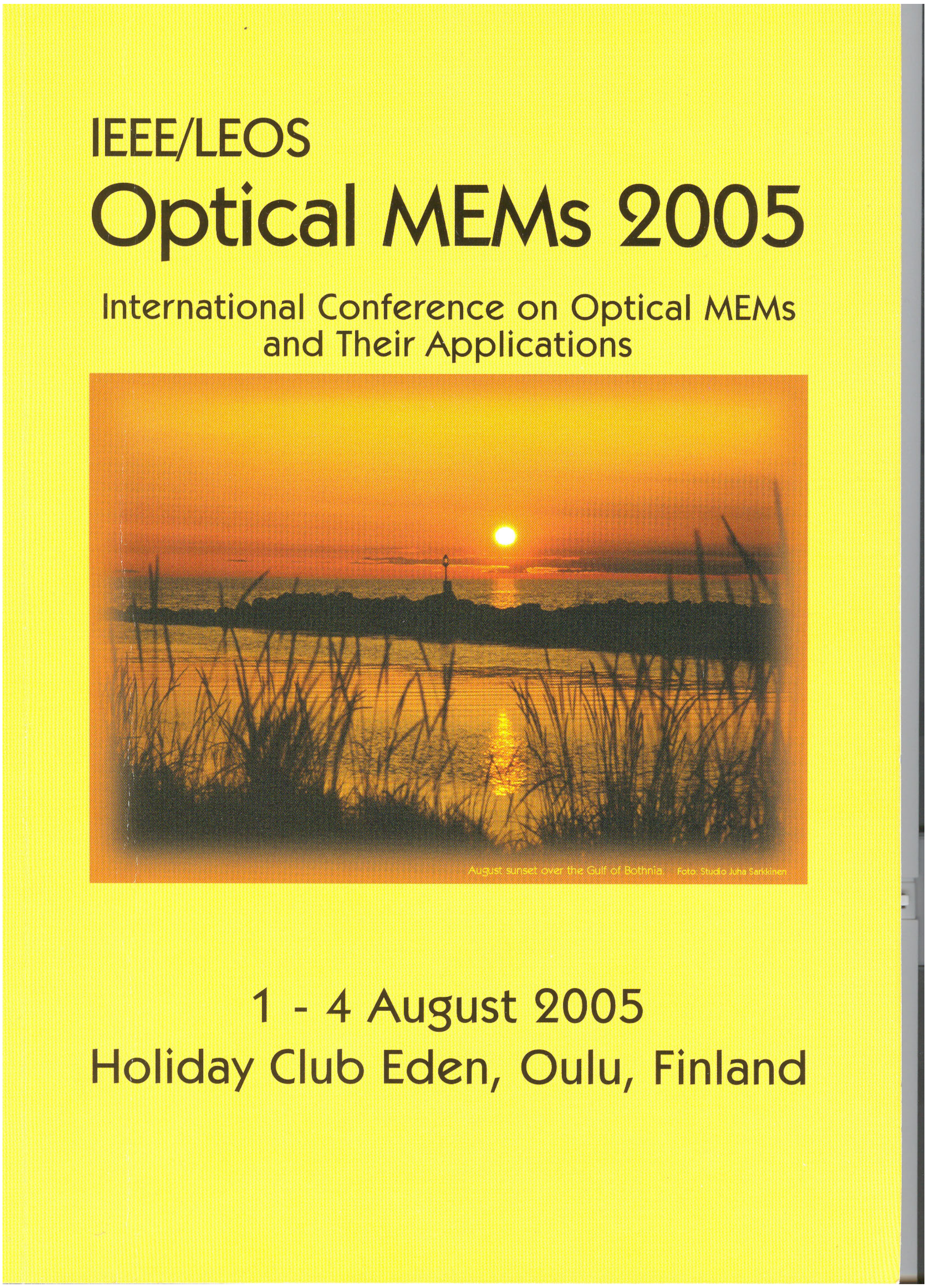
The variable optical attenuator is a critical optical component for the next generation dynamic wavelength division multiplexing (WDM) optical network [1]. It has a wide range of applications in the optical fiber communications, including dynamic gain equalizing, optical blocking, and overload protection. Due to 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, etc. In the last decade, organic materials, however, have found broad applications in the electrical and optical fields [9- 10]. Organic materials provide wide selectivity and they usually can be applied at room temperature either by spin coating or inject 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 desired attenuation. Both approaches, however, are not suitable for organic materials, which are usually compliant. 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 μm, the dynamic range is small (< 5dB). As a result, organic polymers with high yield stain and low Young’s modulus are desired. It is reported that the yield strain of organic polymer is around 5%, which far exceed the breaking limit of the semiconductor materials and the Young’s modulus is about two orders of magnitude lower than most inorganic materials [11-12].

In this report, we describe a novel MEMS VOA consisting of a deformable organic thin film aligned with a dual fiber 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 the wavelength of 1550 nm. An organic thin film with the size of 4 mm × 4 mm has been successfully fabricated and tested.

研究結果

The results are submitted to the international conference: IEEE/LEOS Optical MEMS 2005 International Conference on Optical MEMS and Their Applications. Photocopies of the conference proceeding cover page and papers are attached in this report as the research results.



IEEE/LEOS
Optical MEMs 2005
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August sunset over the Gulf of Bothnia. Foto: Studio Juha Sarkkinen

1 - 4 August 2005
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15:30 – 17:00

Organic Variable Optical Attenuator Made by Compliant Fluoropolymer Membrane

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***Abstract*- The paper describes the design and fabrication of micro-electro-mechanical systems (MEMS) variable optical attenuator (VOA) made by a compliant organic thin film. The optical attenuation is achieved by changing the radius of curvature of the organic thin film actuated by the electrostatic force. The simulation results show that the attenuation range can achieve 20 dB at the wavelength of 1550 nm.**

I. INTRODUCTION

The variable optical attenuator is a critical optical component for the next generation dynamic wavelength division multiplexing (WDM) optical network. It has a wide range of applications in the optical fiber communications, including dynamic gain equalizing, optical blocking, and overload protection. VOA made by MEMS technology shows high reliability and compact size, which make MEMS VOA a promising product for telecommunication applications [1-2]. Traditionally, the structure layers of MEMS device are made of inorganic materials, such as polysilicon, silicon nitride, etc. In the last decade, organic materials, however, have found broad application in the electrical and optical fields [3-4]. Organic materials provide wide selectivity and they usually can be applied at room temperature either by spin coating or inject printing, which requires less complicated fabrication processes as compared with standard IC production lines .

In this paper, we report a novel MEMS VOA consisting of a deformable organic thin film aligned with a dual fiber collimator in the 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 20 dB at the wavelength of 1550 nm. An organic thin film with the size of 3 mm × 3 mm has been successfully fabricated.

II. DEVICE DESIGN

Fig.1 shows the schematic drawing of a MEMS VOA. It consists of a dual fiber collimator and a deformable mirror made of an organic thin film coated with gold to reflect the incident light. The optical input signal from the single mode fiber is collimated by the GRIN lens and is incident onto the mirror surface. The maximum 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 fiber.

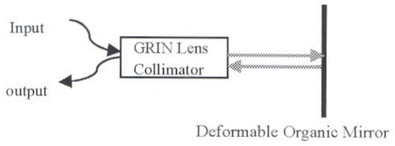

Fig. 1. The schematic drawing of an organic thin film VOA.

A bottom electrode is attached to the organic thin film with a spacer of 100 um thick. When the voltage difference is applied between the organic thin film and the bottom electrode, the electrostatic force will pull down the compliant organic thin film so that the radius of curvature of the deformable mirror can be changed accordingly. We assume the deformation of the organic membrane is close to spherical shape. The relation between the center displacement of the thin film and the radius of curvature of the mirror can be calculated by

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

, where D the center displacement, A the radius of the mirror and R the radius of curvature. For example, the mirror aperture of 3 mm, the 15 um center displacement will change the radius of curvature from 50 mm to 150 mm. In other words, a small deformation of the organic thin film can cause three order changes in the radius of curvature.

The relationship between optical attenuation and radius of curvature of the deformable mirror is calculated by Gaussian shape model for single mode fiber [5]. Fig. 2(a) shows that the attenuation increases up to 20 dB as the radius of curvature of mirror becomes smaller (i.e. more deformation at the center of the organic thin film) for a beam diameter of 200 um. We also found that the attenuation efficiency could be further improved at a given radius of curvature by increasing the size of the optical beam diameter, as shown in Fig. 2 (b). Given a fixed radius of curvature of 100 mm, the attenuation can be increased from 2 dB to 8 dB as the beam diameter is enlarged from 200 um to 500 um. These results suggests that large deformation of the mirror could increase the dynamic range of the VOA. In addition, a deformable mirror with large surface area is preferred to accommodate larger beam diameter, which improves attenuation efficiency.

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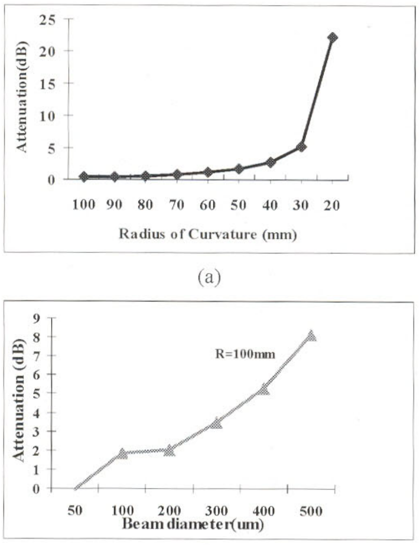


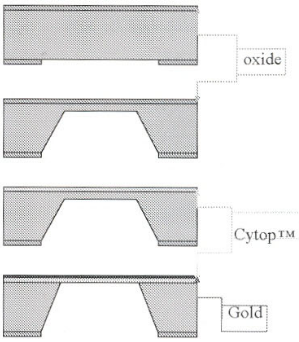
(a)

(b)

Fig. 2 The calculated optical attenuation versus (a) different mirror curvature and (b) beam diameter.

III. Fabrication Processes and Discussion

The fabrication processes of MEMS VOA with an organic membrane are presented in Fig.3. First the (100) silicon wafer was grown with thermal oxide as a wet etching protection layer. An opening was etched on thermal oxide at the backside of the silicon wafer. The silicon was etched in the solution of Tetramethyl Ammonium Hydroxide (TMAH) at the temperature of 90 °C. The etching depth of the silicon was time controlled to left about 100 um silicon membrane. Then, the front side oxide is removed by dipping the BHF at the top surface. The organic thin film, CYTOP^{TM}, is then spin-coat and baked at the oven of 150 °C to dry the solvents out. The silicon wafer is etched again by TMAH for a short time to remove the remaining silicon membrane. The wet etching stopped at the organic thin film. Finally, the gold of 2000 Å is coated on the organic thin film as the reflection layer for infrared light.



1. Oxidation for 5000Å. Pattern and etch backside oxide with openings.
2. TMAH etches silicon with a thin Si membrane left.
3. Remove frontside oxide. Spin-coat Cytop™, and bake solvents out.
4. Short time TMAH etch to release Si membrane. Deposit Gold 2000Å as reflecting layer.

Fig. 3. Micromachining fabrication processes of an organic thin film.

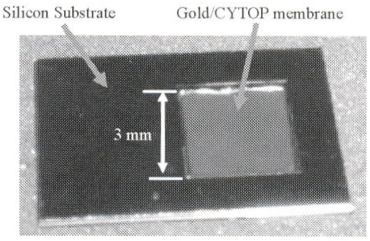


Fig. 4. Picture of a fabricated organic thin film for VOA application.

The organic thin film, CYTOP^{TM}, is from Asahi Glass. It is in the field of fluoro-polymers that have excellent chemical resistance during the wet etching. The size of the fabricated organic membrane is 3 mm × 3 mm without any cracking. In addition, it is highly optical transparent so that a metal coating to reflect the light is necessary. The Young's modulus of the CYTOP^{TM} is around 1.2 GPa, which is two orders less than the typical membrane materials, such as silicon nitride. This compliant characteristic makes the organic thin film suitable for large deflection. A bottom electrode is attached to the membrane with a 100-um thick spacer. The simulation results show a deflection of 15 um can be achieved with the applied voltage of 60 V. This corresponds to about 10 dB optical attenuation for 500 um beam diameter.

IV. Conclusion

We report a novel variable optical attenuator made of an organic membrane by micromachining techniques. The organic thin film as large as 3 mm × 3 mm has been demonstrated without any cracking. The mechanical simulation result shows tens of micrometer displacement can be achieved by electrostatic force with reasonable voltage. The large displacement of the organic thin film could increase the dynamic range of optical attenuation. The attenuation is achieved by varying the radius of curvature of the organic membrane with attenuation range up to 20dB.

Acknowledgement

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（三）計畫成果自評

In conclusion, we report a novel variable optical attenuator made of an organic fluoropolymer membrane by micromachining techniques. The amorphous fluoropolymer has the advantages of good stability to resist chemical etchant and high yield stain 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. The organic thin film as large as 4 mm × 4 mm has been demonstrated and operated without any cracking. The experimental results show displacement of 57 μm can be achieved by pneumatic force with 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 the optical communication applications. The theoretical calculations based on the FEM mechanical modeling 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.

Besides the internal conference paper we showed, we are currently summarizing our results and are submitting a paper to SCI journal. The journal title is "Journal of Optics A". We will keep updated any results to NSC website.

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