

Optically 3D μ -Printed Ferrule-Top Polymer Suspended-Mirror Devices

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Abstract—We present a novel optical microfabrication technology to directly print polymer suspended-mirror devices (SMDs) on the end face of fiber-optic ferrules. With an own-established optical 3D μ -printing platform, three kinds of ferrule-top SMDs were rapidly fabricated by using SU-8 photoresist. Optical reflection spectra of the fabricated SMDs were measured and then analyzed by using fast Fourier transform (FFT). The application of the ferrule-top SMD as a miniature displacement sensor was experimentally demonstrated.

Index Terms—optical microfabrication, suspended-mirror device, 3D printed sensor

I. INTRODUCTION

SUSPENDED mirror devices (SMDs) have become one of the most commonly used components in optomechanics [1] for many ground-breaking researches in the fields of optical bistability [2], optical spring effect [3], and optical cooling [4]. For instance, in the early research of gravitational wave detections using laser interferometry, the optomechanical coupling between the suspended mirror and the radiation pressure of light was observed in which mechanical motion modulated the length of an optical cavity and shift its resonant frequency [5].

The end face of an optical fiber provides an ideal platform for the development of compact and highly integrated photonic devices because it is an inherently light-coupled structure [6]. In case that SMDs are fabricated on the end face of an optical fiber, probe light can be directly coupled into the resonant cavity, and the same optical fiber provides an easy access for the collection of the reflected signal for the interrogation of the weak signal or perturbation applied on the suspended mirror. However, the challenge is that the small cross-section and the large aspect-ratio of optical fibers make the fabrication of SMDs difficult by using conventional microfabrication technologies. Although a number of potential solutions have

been proposed such as photolithography [7], nanoimprinting [8], interference lithography [9], electron-beam lithography [10], focused ion-beam milling [11], and two-photon polymerization [12], there are still some drawbacks such as inconvenient fabrication process and low throughput. In order to achieve a cost-effective process, G. Gruca et al. demonstrated a fiber-top-like device, i. e. ferrule-top device, to simplify fabrication and meanwhile keep the advantages of fiber-top technology [13]. Thereafter, various ferrule-top devices were reported for e.g. pressure and humidity sensing [14], photoacoustic spectroscopy [15], and local dynamic mechanical analysis for heterogeneous soft matter [16].

In this paper, we present a novel optical microfabrication technology to directly and rapidly print SMDs on the end face of an optical fiber ferrule. As shown in Fig. 1(a), the optical 3D μ -printing platform consists of a high-power UV source (365 nm), a UV grade digital mirror device (DMD) for the generation of optical patterns, projection optics for scaling down the optical images and a digital camera for machine vision metrology [17, 18]. Three kinds of SMDs with different

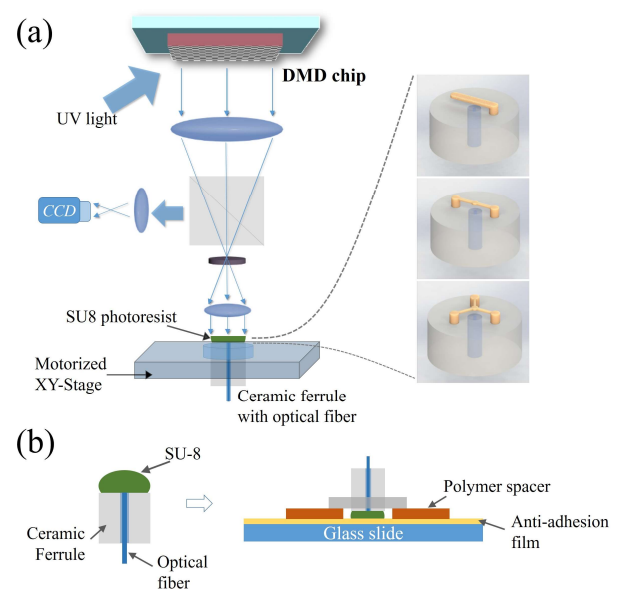


Figure 1 (a) Schematic diagram of the optical 3D μ -Printing technology. (b) The preparation of SU-8 photoresist on the end face of a ceramic ferrule of optical fiber.

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3D architectures are designed by using commercial CAD software, as shown in Fig. 1(a). Then, the 3D models were sliced into 200 layers by using in-house developed add-on software to generate the image data, with which the DMD chip can dynamically generate optical patterns frame-by-frame. After passing through projection optics, UV light patterns are projected upon the photoresist on the end-face of an optical fiber ferrule. A digital camera is used to capture images of the substrate, and a two-axis translation stage is utilized to move the optical fiber ferrule to the desired location. Based on the monotonically additive light-absorption property of the photoresist, the predefined SMDs can be rapidly fabricated through photo-polymerization. The DMD chip can quickly refresh patterns within 1 millisecond, which enables accurate control of exposure dose.

II. FABRICATION

A. Materials

SU-8 photoresist is widely used for polymer optical devices because of its good properties including highly transparent in both visible and near infrared band range, chemical resistance, and good mechanical strength. EPON resin SU-8 from Momentive Ltd. was used in the fabrication of SMDs.

Octoxyphenylphenyliodonium hexafluoroantimonate (OPPI) (Hampford Research Inc.) and tributylamine (Meryer Chemical Technology Co., Ltd.) were used as photoacid generator and inhibitor, respectively. 2-(2H-Benzotriazol-2-yl)-4,6-bis(1-methyl-1-phenylethyl)phenol (known as Tinuvin 234) (Sigma-Aldrich Inc.) is a UV-absorbing agent which can reduce light penetration depth and enhance the vertical distinguishability in the experiments.

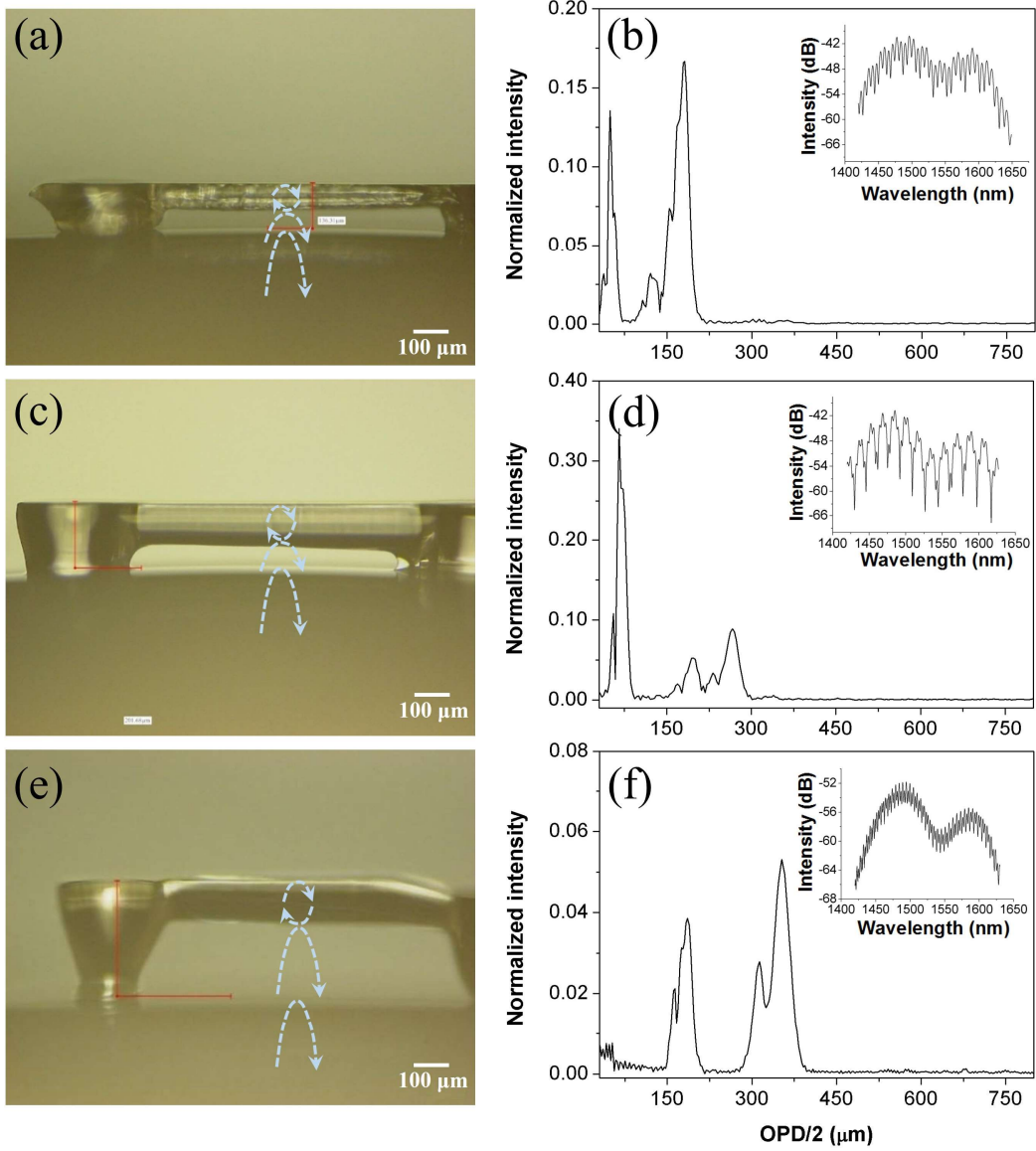


Figure 2 (a), (c) and (e) Optical images of three ferrule-top SMDs with different cavity lengths. (b), (d) and (f) FFT results of the reflection spectra of the corresponding SMDs shown in (a), (c) and (e), respectively. The insets are their measured reflection spectra.

These compositions were dissolved by cyclopentanone (Sigma-Aldrich Inc.) in a weight ratio of OPPI/tributylamine/Tinuvin 234/SU-8 = 2:0.014:0.2:100. Propyleneglycol monomethylether acetate (PGMEA) (Sigma-Aldrich Inc.) was used as developer.

B. Deposition of SU-8 on the end face of a fiber-optic ferrule

Depositing the substrate with a uniform layer of photoresist is a vitally important step for critical dimension control of SMDs. Although spinning coating is well established process for wafer scale substrates, it is not suitable for the coating on ferrule end-face due to the limited area of ferrule end-face. Here we use a simple method to coat a uniform layer of SU-8 on the ferrule end-face. As shown in Fig. 1(b), a small amount of SU-8 solution was firstly dropped upon the end face of fiber ferrule. Then, a glass slide coated with anti-adhesion layer made in polydimethylsiloxane (PDMS) is used to press the SU-8 droplet, where a polymer spacer with specific thickness is employed to precisely control the thickness.

The whole device will be placed on a digital hotplate for a soft bake. The optimal soft-bake time depends on both the concentration of SU-8 solution and the objective thickness of SU-8 film. For example, when the concentration of SU-8 solution is 70% (in weight ratio) and the designed film thickness is 70 μm , the sample was soft baked at 65 $^{\circ}\text{C}$ for 5 minutes, and then 95 $^{\circ}\text{C}$ for 20 minutes to remove the solvent. Thereafter, the SU-8 coated fiber ferrule can be peeled off from the glass slide. Compared with other methods as spinning coating, spray coating and thermal evaporation, this method is particularly suitable for the preparation of thick film (from ~ 10 μm to ~ 500 μm). It is noteworthy that such a spacer-based thickness control method is not convenient in case that the SMDs with different thicknesses need fabricated. For such a case, a high-precision motorized vertical stage mounted with the glass slide with anti-adhesion layer can be used to precisely press SU-8 droplet and thereby tailor the thickness of the device.

C. Optical 3D μ -Printing processes

With the digital camera based machine vision metrology, the sample was precisely aligned to the target location before optical exposure. Thereafter, a dynamic optical exposure process was applied with the sliced image data of the SMD models, which typically takes about 15~20 seconds under the power density of 35.86 mW/cm^2 . After exposure, the sample was post-baked at 65 $^{\circ}\text{C}$ for 5 minutes and 95 $^{\circ}\text{C}$ for 15 minutes. It was then developed by using PGMEA and the developing time is about 15 minutes.

The optical exposure dose is a key parameter for the fabrication of SMDs. It needs optimized to meet the fabrication conditions for the supporting pillar and the suspended beam of the designed SMD, respectively. In the experiments, the fabrication conditions like exposure doses for SMDs with different thicknesses were optimized. The thickness of the whole device was customized by changing the polymer spacers.

Figure 2(a), (c) and (e) show the optical images of three ferrule-top SMDs with different thicknesses. In order to

characterize the optical properties of the devices, a broadband light source, a circulator and an optical spectrum analyzer (OSA) were used to measure their reflection spectra. Fast Fourier transform (FFT) was applied to retrieve the cavity information from the measured optical spectra. Fig. 2(b), (d) and (f) depict the FFT's results of the reflection spectra of the SMDs with different cavity lengths. Three major peaks can be found in the FFT spectrum, which indicate the interferences between the light waves reflected from the three interfaces, i.e. the interface between fiber end-face and air, and the interfaces between air and bottom-/top-faces of the suspended structures. The locations of the peaks agreed well with that the cavity lengths of the SMDs measured by using optical microscope.

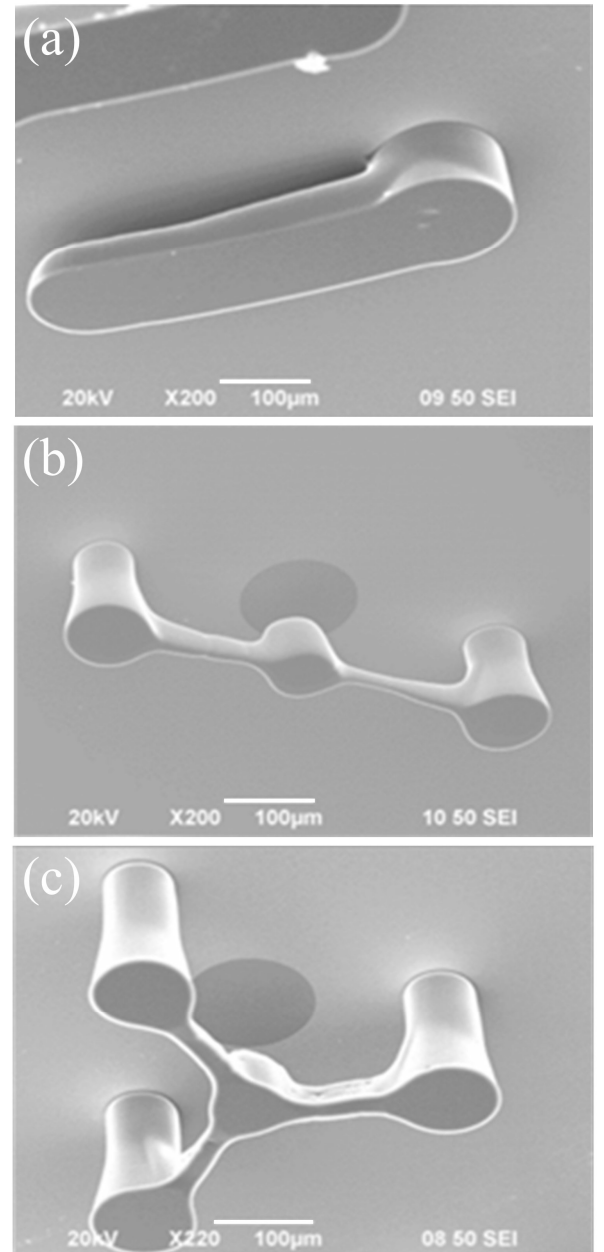


Figure 3 Scanning electron microscope images of the suspended mirrors on the end surface of ferrule of optical fiber connector.

III. RESULTS AND DISCUSSION

A. Fabrication results

Based on the optimized fabrication conditions, we fabricated three kinds of SMDs of different geometries shown in Fig. 1(a). Scanning electron microscope (SEM) images of the fabricated SMDs on the end-faces of optical fiber ferrules are shown in Fig. 3. The surfaces of these suspended mirrors are very smooth, which is important for improving the reflectivity of the suspended mirror. The root-mean-square surface roughness measured by using an atomic force microscope (MultiMode 8, Bruker, Germany) is about 5.11 nm.

Fig. 4 shows the optical microscope image and the reflection spectrum of the cantilever-beam like SMD shown in Fig. 3(a). The length, width, and thickness of the cantilever beam of the SMD are about 430, 84, and 62 μm , respectively. By using the finite-element analysis with the measured geometric parameters, the natural frequency of the fabricated cantilever-beam device was estimated as 86 KHz. The resonant frequency can be tuned through adjusting the geometric parameters such as beam length, width and thickness. Considering that the Young's modulus of SU-8 is relatively low (around one fiftieth of that of silicon), the optical 3D μ -printing technology is promising to fabricate the SMDs with low resonant frequencies.

B. Displacement sensor

The cantilever-beam SMD was tested as a displacement

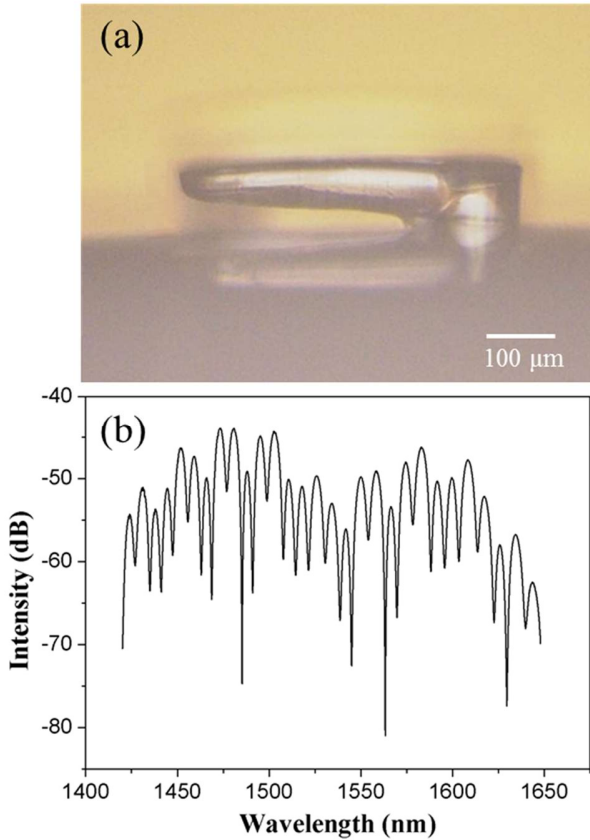


Figure 4 (a) Optical microscope image of the cantilever-beam SMDs for displacement sensing. (b) The measured reflection spectra of the SMD.

sensor. It is known that the wavelength of a resonance dip in the spectrum of the interference between co-directional two light waves can be expressed as

$$\lambda_m = 2n_r L_c / m, \quad (1)$$

where n_r is the refractive index of the medium between the two interfaces, L_c is the cavity length and m is the order of the resonant dip. When the suspended end of the SMD is pressed under a small displacement Δz , the spectral shift of the SMD is thus

$$\Delta\lambda \cong (\lambda_m / L_c) K(x) \Delta z, \quad (2)$$

where $K(x)$ is the ratio of the cavity change ΔL to the displacement Δz and depends on the position of the SMD over the optical fiber as described by the cantilever-beam deflection equation.

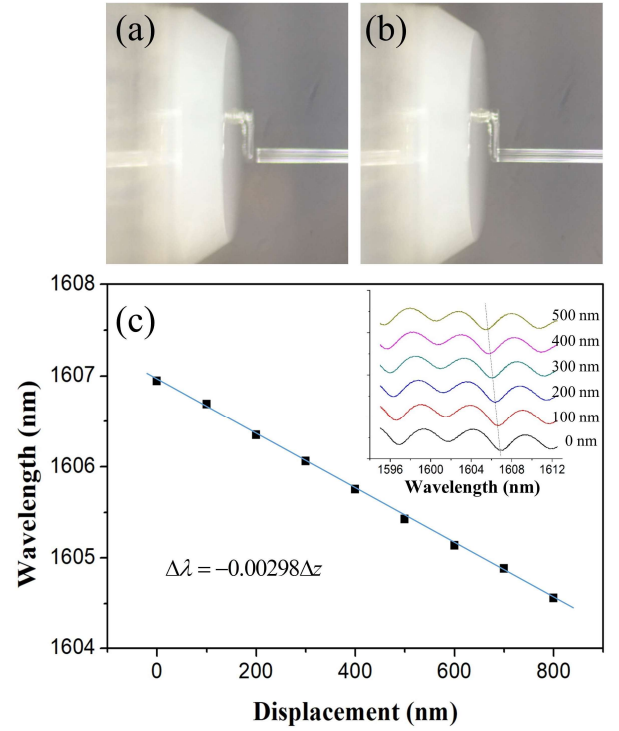


Figure 5 (a, b) Optical microscope images of a ferrule-top SMD under test. (c) Spectral response of the ferrule-top SMD under pressing. Inset shows the measured reflection spectra under different displacements.

Figure 5 (a) and (b) shows a SMD displacement sensor under testing. A cleaved optical fiber mounted on a PZT nanopositioner was utilized to precisely press the SMD displacement sensor. The measured reflection response was shown in Fig. 5 (c). A blue shift of the spectra was observed and the measured spectral sensitivity of the SMD sensor over a small displacement is 2.98 nm/ μm , which agrees well with the theoretical value 2.61 nm/ μm predicted by using Eqn. (2).

It is notable that the fabricated SMD shows good adhesion on the end face of fiber ferrule in the experiments. No detachment was observed in spite of that the device was pressed forward and back in the tests as a displacement sensor. Thermal testing

experiments showed that the device can sustain at high temperature up to 170 °C, and its reflection spectrum can recover back to the original one after cycling tests.

IV. CONCLUSION

An optical 3D μ -printing technology has been presented to directly print different kinds of SMDs on the end faces of optical fiber ferrules. The reflection spectra of the ferrule-top SMDs have been measured and then numerical analyzed by using fast Fourier transform to characterize the SMDs. The application of the fabricated ferrule-top SMD as a displacement microsensor has been experimentally demonstrated. The optical microfabrication technology can rapidly print complex 3D SMDs on the end faces of optical fiber ferrules, which is promising for the development of miniature photonic sensors and applications.

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