Patterning of nanophotonic structures at optical fiber tip for refractive index sensing

Shawana Tabassum[1], Yifei Wang[1], Jikang Qu[1], Qiugu Wang[1], Seval Oren[1], Robert J. Weber[1], Meng Lu[1,2], Ratnesh Kumar[1], and Liang Dong[1]
[1]Department of Electrical and Computer Engineering
[2]Department of Mechanical Engineering
Iowa State University, Ames, Iowa, USA

***Abstract*—This paper reports on an efficient and convenient method of patterning nanostructures on the cleaved facet of an optical fiber. The fabrication method utilizes ultraviolet (UV) assisted nanoimprint lithography in which the fiber tip is pressed against a stamp carrying nanoscale patterns, and then is exposed to UV radiation. The novelty of this work lies in utilizing simpler fabrication steps with better control over angle of contact at the fiber tip, which leads to rapid formation of nanostructures with well-defined features. An array of nanoposts are patterned at fiber tip and coated with titanium oxide to work as a guided mode resonant (GMR) device. The sensitivity of the fiber-tip GMR device to surrounding refractive index is 183.3 nm per refractive index unit. The proposed nanofabrication method offers a promising approach to develop remote fiber-optic sensors with intrinsic optical beam alignment for detecting the presence of subtle concentration of analytes at the fiber tip.**

Keywords—nanostructure; fiber; nanoimprint lithography; guided mode resonance.

I. INTRODUCTION

The ability of creating high-resolution nanopatterns on the tip of optical fiber has a great potential to open up many possibilities of realizing applications involving remote sensing with different detection devices such as diffraction gratings, photonic crystals, and nanophotonic resonators. Yet, there are a small set of reports [1, 2] on patterning the tips of optical fibers and utilizing them as a sensing platform. The main techniques of forming nanostructures at the fiber tip include nanoskiving [1], focused ion beam milling [2] and nanoimprint lithography technique requiring non-trivial inclined ultraviolet (UV) incidence [3]. However, these methods are relatively tedious and often involve multiple processing steps.

In this paper, we demonstrate a simple and efficient method to inscribe high-resolution nanophotonic patterns on the cleaved facets of optical fibers using UV assisted nanoimprinting lithography (NIL) [3, 4]. The nanopatterns are made of SU8 photoresist and coated by a thin layer of titanium oxide (TiO_2) to form a fiber optic index sensor utilizing guided mode resonance (GMR). The resonance is due to the leaky modes of the GMR structure. Incident light energy is coupled to these radiated leaky modes. As the deposited TiO_2 at the fiber tip acts as a light confinement layer, the device works as a high contrast grating in which the electric field associated with the GMR modes is evanescently confined to the surface. The successful transfer of different nanostructures to the fiber tip is confirmed by scanning electron microscopy (SEM) and optical spectroscopy. Optical detection of changes in surrounding refractive index is performed at the fiber tip to validate the workability of the nanostructures as a fiber-optic sensor. In a nutshell, the contributions of this work are as follows:

- A simplified and efficient process to fabricate nanopatterns on optical fiber tip.
- Utilization of the GMR structure to monitor surrounding refractive index changes.

II. DEVICE FABRICATION

The process flow starts from preparing a flat-cleaved fiber tip and a transparent master mold with patterns made on a glass wafer. The first step of the fabrication process was to strip the polymer jacket with a fiber stripper and cleave the stripped multimode fiber (FT200EMT, Thorlabs) to obtain a flat fiber tip. Subsequently, an array of nanoholes was formed in polydimethylsiloxane (PDMS) by using a silicon mold (Figs. 1a and 1b). After that, a UV curable polymer (ZIPCONE™ UA or ZPUA) was used to imprint the nanopatterns from the PDMS mold to the glass wafer (Figs. 1c and 1d). The glass wafer carried the patterns to be transferred to the fiber tip. Next, the formed ZPUA mold was treated with an anti-adhesion coating by salinization in vacuum (10^{-5} mTorr) using trichloro(1H,1H,2H,2H-perfluoro-octyl) silane. This anti-adhesion treatment minimized the adhesion between the glass wafer and the UV-curable resist, thus facilitating easy release of the fiber tip from the mold. The next step was to use a low-viscous UV curable resist (SU8-2000) to transfer the patterns from the ZPUA mold to the fiber tip. The fiber was first dipped into SU8-2000, and then mounted on an XYZ stage (Fig. 1e). It was then gradually approached towards the mold until the tip touched the mold, resulting in filling the grating cavities with the resist (Fig. 1f). Subsequently, the fiber tip was exposed to UV light with the intensity of 14 mW/cm^2 for 15 min. After the UV irradiation, the fiber tip was lifted from the mold (Fig. 1g). The critical steps of the process flow include carefully selecting a low viscous UV curable resist and finding the optimum UV intensity and exposure time. Lastly, to form a GMR device, a 160 nm-thick TiO_2 layer was deposited using e-beam evaporation at the fiber tip.

Other reports [3] used an opaque substrate such as silicon wafer to form the master mold which required an oblique UV

978-1-4799-8287-5/16/$31.00 ©2016 IEEE

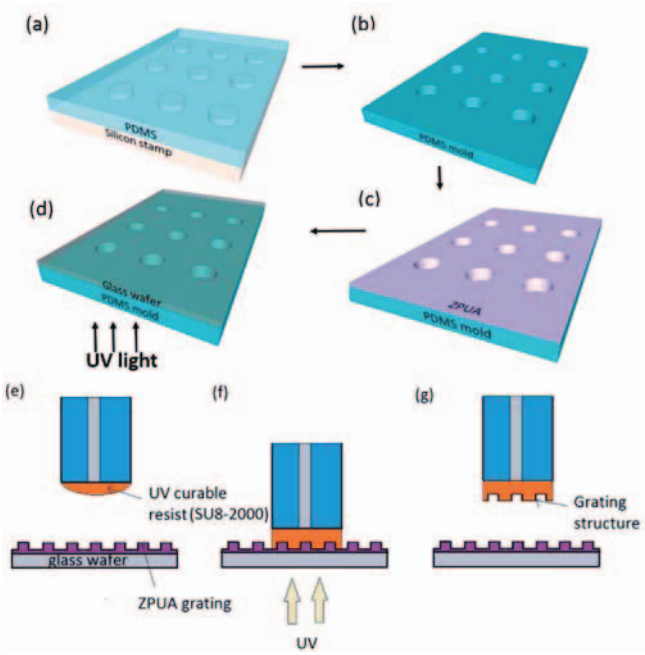

Fig. 1: Fabrication processes. (a) PDMS is poured on the silicon stamp and then thermally cured. (b) PDMS is peeled off the stamp. (c) ZPUA is poured on the PDMS mold. (d) The PDMS mold is pressed against the glass wafer and exposed to UV radiation. (e) The fiber tip is dipped into SU8-2000. (f) The fiber is pressed against the grating structure and is subject to UV irradiation. (g) The mold is released from the fiber tip.

incidence to polymerize the photoresist. As the UV exposure energy needed is sensitive to the angle between the mold and the fiber tip, the control over energy is relatively poor. In contrast, in our case with a transparent mold and a normal incidence the polymerization energy is more controllable.

III. Results and Discussion

The obtained nanoholes at the fiber tip has the period of 500 nm, the hole diameter of 250 nm, and the hole height of 210 nm. The nanoholes coated with the 160 nm-thick TiO_2 layer acts as a GMR device owing to the high refractive index of TiO_2 (η_{TiO2}= 2.49). Resonance occurs when there is a phase matching of excitation light with a GMR mode. This significantly enhances the near-field intensity associated with the GMR modes and is also sensitive to the changes in surrounding refractive index. For a dielectric slab waveguide, the mode angle θ_n is a function of core and cladding refractive indices as shown in the equation below [5].

$$\tan\left(\frac{2\pi}{\lambda_0}\eta_{eff}.a.cos\theta_n - m_w.\frac{\pi}{2}\right) = \frac{\sqrt{sin^2\theta_n-(\frac{\eta_{eff}}{\eta_c})^2}}{cos\theta_n} \quad (1)$$

where, λ_0 is wavelength of light in the air, a is half of the width of the waveguide, η_{eff} , η_c are the effective refractive index of the nanopatterned-core and refractive index of the cladding (fiber on one side and air on another), respectively, and m_w is the mode number of waveguide. For the transmission region of a grating structure [5],

$$\eta_{eff}sin\theta_n = \eta_f sin\theta_f + m_g.\frac{\lambda_0}{\Pi} \quad (2)$$

where, η_f is the refractive index at the incident (fiber) side, η_{eff} is the effective refractive index at the transmission (nanopatterned-waveguide) side, θ_f is the angle of incident light, from fiber side, with respect to the normal to the grating plane, θ_n is the mode angle at the transmission (nanopatterned-waveguide) side, m_g is grating mode number, and Π is the grating period.

When the diffraction grating and waveguide are unified, the subwavelength grating couples the incident light into a strongly confined mode of the waveguide structure and we get guided mode resonance. This happens when the mode angle in the first equation of GMR corresponds to the one in the second equation corresponding to the grating structure. So substituting

$$sin\theta_n = 1/\eta_{eff}[\eta_f sin\theta_f + m_g.\frac{\lambda_0}{\Pi}] \quad (3)$$

into the first equation leads to a final equation, constraining the resonant wavelength. It is evident that any changes in the surrounding refractive index will lead to a change in η_{eff} which in turn will shift the resonant wavelength.

A. Confirming Transfer of Nanopatterns to Fiber Tip

The fiber tip was observed under a stereomicroscope (Leica, 205FA). Reflective color patterns from the grating patterned at the fiber tip for different incident angles were observed (Fig. 2). SEM analysis was also performed to verify the transfer of nanopatterns to the fiber tip (Fig. 3).

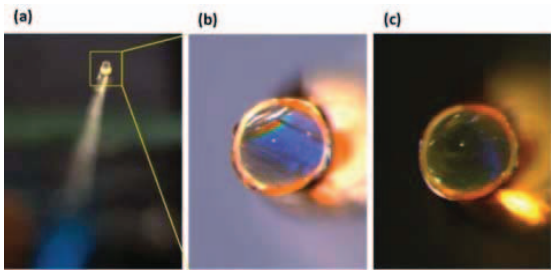

Fig. 2: (a) Optical image of a multimode fiber with the tip patterned with nanostructures. (b, c) Reflective colors from the 2D GMR patterns at the fiber tip for different incidence angles of light.

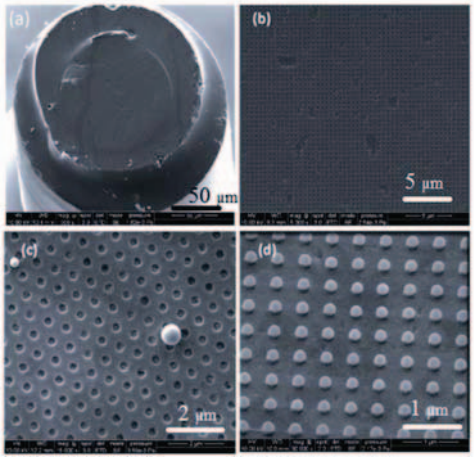

Fig. 3: SEM analysis of the fiber tip: (a) patterned fiber tip, (b) zoomed in fiber tip. Different nanopatterns are formed at the fiber tip: (c) nanoholes with a triangular lattice, (d) nanoposts with square lattice.

B. Optical Simulations

We conducted electromagnetic simulations using commercial software DiffractMOD (RSoft Synopsis) with a view to analyze the optical properties of the fabricated nanopatterns at the fiber tip (Fig. 4a). The change in resonance with changing surrounding refractive index was simulated. The simulated result suggests zero transmission at the GMR resonance wavelength of 810 nm. From the simulation results of Fig. 4a, a red-shift in resonance wavelength is evident from an increase in the surrounding refractive index. Moreover, the electric field enhancement of the TiO_2 coated GMR structure at this resonant wavelength is illustrated in the inset of Fig. 4a. The enhancement accounts for the strong confinement of GMR mode by the high-index TiO_2 layer.

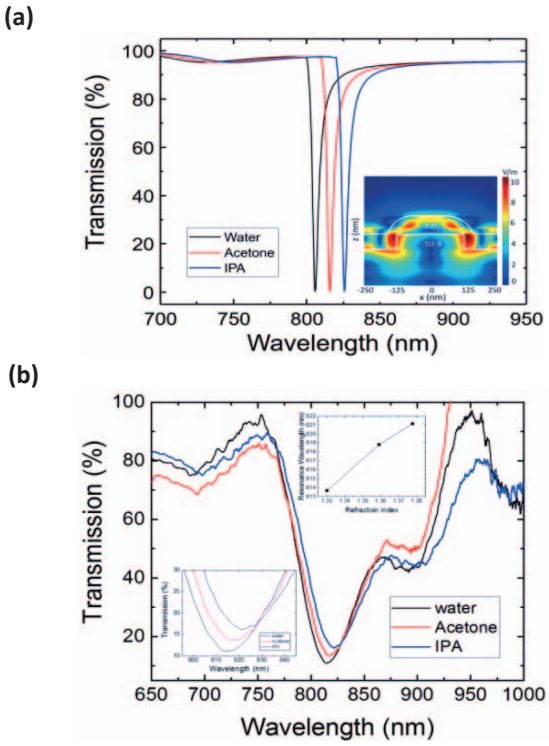

Fig. 4: (a) Simulated transmittance with different surrounding media (water, acetone, and IPA). Inset shows field distribution at the resonance mode of the GMR structure. (b) Experimental transmittance of the device with surrounding water, acetone and IPA. Insets show the close-up of the resonance shift (lower left corner) and refractive index sensitivity (upper right corner).

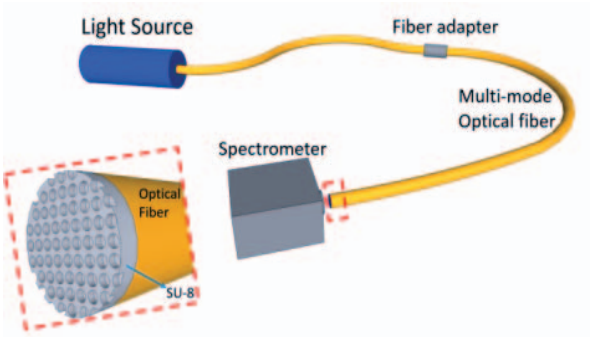

Fig. 5: Optical setup for transmission measurement.

C. Bulk Refractive Index Change Characterizations

The fiber tip was characterized after depositing a 160 nm thick TiO_2 layer. The optical properties of the GMR structure at the fiber tip were measured by shining white light from a halogen light into the multimode fiber through a collimator. The transmitted light was then collected into a spectrometer (USB4000, Ocean Optics) from the other end of the fiber where the nanostructures were formed (Fig. 5). The measured transmission spectrum is shown in Fig. 4b, where the interaction of light with the grating structure results in a dip, matching the one obtained from simulation, confirming the resonant mode. However, it was also observed that the measured spectra appeared broader compared to the simulated ones. This may be mainly due to the use of the total internal reflection based fiber coupling which results in multiple-angle light incidence at the fiber tip. As a result, instead of getting a distinct resonance at a well-defined angle as is the case in free-space coupling, an average resonance dip was obtained.

As the surrounding medium of the fiber tip was changed by introducing water, acetone and isopropyl alcohol (IPA) on the fiber tip, a shift in resonance was observed. The higher the surrounding refractive index, the larger the observed resonance shift. Based on these measurements, the device exhibited an index sensitivity of 183.3 nm/RIU.

Conclusion

In summary, through this work we have simplified the fabrication steps of transferring nanopatterns to optical fiber tip. We have also demonstrated a TiO_2 coated GMR structure which is sensitive to changes in surrounding refractive index and provides shifts in its resonant wavelength. This simplified and rapid nanostructuring at fiber tip can contribute to remote sensing applications through the insertion of the nanopatterned fiber tips into aqueous and gaseous analytes in regions otherwise inaccessible.

Acknowledgement

This work was supported by US National Science Foundation under grants CCF-1331390 and DBI-1331390, US Agriculture Department's NIFA under grant 2013-68004-20374, Iowa Corn Promotion Board, and Iowa State University's Plant Sciences Institute Faculty Scholar Program.

References

[1] D. J. Lipomi, R.V. Martinez, M.A. Kats, S.H. Kang, P. Kim, J. Aizenberg, F. Capasso, and G.M. Whitesides, "Patterning the tips of optical fibers with metallic nanostructures using nanoskiving", Nano Lett., 11, 2011, pp. 632-636.

[2] A. Micco, A. Ricciardi, M. Pisco, V. La Ferrara and A. Cusano, "Optical fiber tip templating using direct focused ion beam milling", Nature, 2015.

[3] S. Scheerlinck, P. Bienstman, E. Schacht, and D.V. Thourhout, "Metal grating patterning on fiber facets by UV-based nano imprint and transfer lithography using optical alignment", IEEE Journal of Lightwave Technology, 27, 10, 2009.

[4] S. Scheerlinck, D.V. Thourhout, and R. Baets, "Nano imprint lithography for photonic structure patterning", Proceedings Symposium IEEE/LEOS Benelux Chapter, 2005.

[5] S. O. Kasap, "Optoelectronics and photonics, principles and practices", Pearson; 2 edition, October 25, 2012.