Highly Birefringent Slot-Microfiber

Jun-long Kou, Fei Xu, and Yan-qing Lu

***Abstract*—We propose a possible approach to realize a highly birefringent slot microfiber by postprocessing a circular microfiber (CMF). The shape can be fabricated with very high repeatability, reliability, and accuracy. Light field can be enhanced and confined in the nanometer-wide low index slot, and the birefringence achieves as high as 4×10^{-2}. The slot-microfiber has the advantages both of a microfiber and a slot waveguide. It is perfect for miniature fiberized polarization manipulation devices and its unique geometry can also greatly enhance the refractive index sensitivity (nearly ten times higher than that of CMFs) for evanescent-field-based gas sensors.**

***Index Terms*—High birefringence, microfiber, slot waveguide.**

I. INTRODUCTION

HIGHLY birefringent (Hi-Bi) fibers are those maintain the polarization state of the propagating mode along their length. Previously, Hi-Bi fibers have been intensively investigated over the years and have found extensive applications in sensing (e.g., torsion measurement) and optical fiber communication systems (e.g., polarization-sensitive optical modulators). One kind of Hi-Bi fiber working on stress-induced birefringence is Bow-Tie [1] and Panda [2] fibers; another category is Hi-Bi photonic crystal fibers breaking the circular symmetry [3]. In most of the cases mentioned above, the birefringence is on the order of $10^{-4}\sim10^{-3}$, the size is above 100 μm and the compatibility with conventional fiberized components is a serious issue.

With recent advances in microphotonics based on optical microfibers [4]–[6], Hi-Bi microfibers have attracted considerable interest as one of the key topics for a variety of microphotonic applications. A Hi-Bi microfiber with its diameter in wavelength span may greatly reduce the component's size while still keeping the desired large evanescent field for sensing and coupling applications. Several approaches have been reported to fabricate Hi-Bi microfibers: such as adiabatically tapering conventional polarization maintaining (PM) fibers [7], rectangular-shaped fibers [8], [9]. However, it presents great challenges to keep these asymmetric geometries during tapering which is serious concern.

In this letter, we propose another possible approach to realize a Hi-Bi microfiber with a slot inside by postprocessing a circular microfiber (CMF). The shape can be fabricated with high repeatability, reliability, and accuracy. It is a fiberized slot waveguide [10] and the light field can be enhanced and confined in the nanometer-wide low index slot. Simulation results show that the birefringence reaches a high level of 4×10^{-2}, which is much higher than previous works [7]–[9]. By controlling the shape of the slot, light can be confined in the slot or not. A slot-microfiber is a hybrid of a microfiber and a slot waveguide including larger evanescent field, high birefringence, and compact size, flexible design, and simplified fabrication. It shows great potentials for miniature fiberized polarization manipulation devices, for example in-line microfiber wave plates. Its unique geometry can also enhance the refractive index sensitivity and offers opportunities for dispersion-related applications.

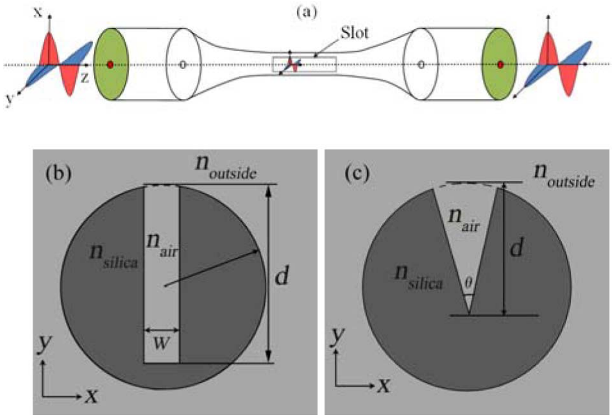

Fig. 1. (a) Schematic of the slot-microfiber; (b) cross section of a straight slot-microfiber with W denoting the width of the straight slot; (c) cross section of a V-groove slot-microfiber with θ denoting the V-groove angle; r and d are the radius of the microfiber and depth of the slot, respectively.

II. SCHEMATIC OF SLOT-MICROFIBERS

A slot-microfiber can be fabricated by introducing a slot in a microfiber as illustrated in Fig. 1(a). The microfiber can be obtained by adiabatically tapering a standard single mode fiber with current mature heat-and-drawing technology [6]; the slot can be formed with high accuracy by several kinds of typical micro-machining technologies, such as focused ion beam milling [11] or deep-UV lithography. These methods are time-saving and can achieve good sharpness of the slot edge. Of course, it can also be fabricated by retapering a thick slot microfiber. It is very flexible to design different slot shapes. Here, we investigate two kinds of typical geometries as shown in Fig. 1(b) and (c), which are called straight slot-microfiber (SSMF) and V-groove slot-microfiber (VSMF), respectively. In our work, n_{silica}, n_{air}, and $n_{outside}$ are set to be the indices of the microfiber, air, and outside environment. Other parameters are presented in Fig. 1(b) and (c). All the simulation in this work is performed using the commercial finite element method

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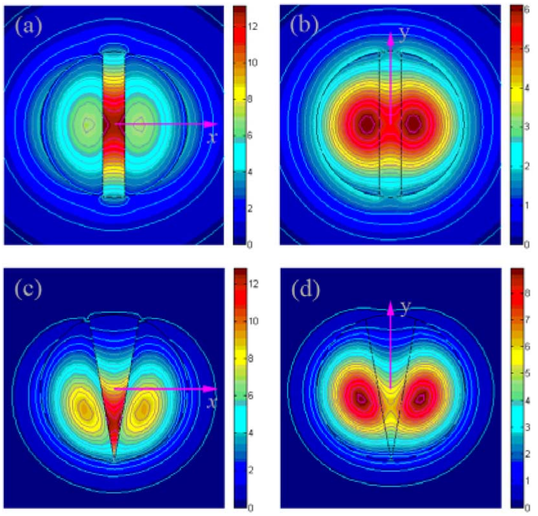

Fig. 2. Power flow distribution of the fundamental HE_{11} modes with both x- and y-polarizations of an SSMF [(a) and (b)] at $r = 500$ nm, $W = 150$ nm and a VSMF [(c) and (d)] at $r = 500$ nm, $\theta = 20^\circ$ in air. In all the figures, $d = 1000$ nm and $\lambda = 1550$ nm.

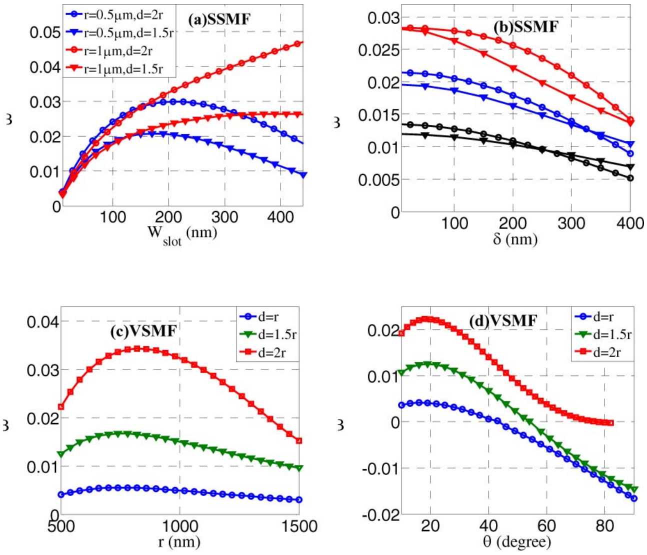

Fig. 3. (a) Birefringence of an SSMF as a function of W and d. (b) Influence of slot shift on birefringence of an SSMF. The red, blue, and black lines are plotted under $W = 150, 80, 40$ nm, respectively, and lines with circle (or triangular) are obtained when $r = 500$ (or 1000) nm and $d = 2r$. (c) Birefringence of a VSMF as a function of the radius of microfiber at V-groove angle of 20°. (d) Birefringence dependence on V-groove angle of a VSMF with $r = 500$ nm. All the results are obtained at $\lambda = 1550$ nm.

(FEM) software package COMSOL Multiphysics 3.4. In this letter, we assume $n_{outside} = n_{air} \approx 1.00027$.

III. BIREFRINGENCE OF SLOT-MICROFIBERS

We only consider the HE_{11} mode with two different polarizations in SSMF and VSMF. The nondegeneracy of HE_{11} mode is known as phase birefringence B of the slot-microfiber, and is defined as: $B = n^y_{eff} - n^x_{eff}$, where n^x_{eff} and n^y_{eff} are effective refractive indices of HE^x_{11} and HE^y_{11} modes, respectively. As can be deduced from Fig. 2, in order to satisfy the continuity of the normal component of electric flux density D (i.e., $D_{1n} = D_{2n}$), the corresponding electric field (E-field) must experience a large discontinuity with much higher amplitude in the slot side (the low index air) in the case of HE^x_{11} mode. Due to the high-index-contrast interface of silica and air ($n_{silica}/n_{air} = 1.444$), much field power will be strongly confined in the slot region which possesses a far lower refractive index (Fig. 2(a) for SSMF and (c) for VSMF). When the light wave is polarized in y-direction, $D_{1n} = D_{2n}$ is naturally satisfied and light is mostly confined in the high index medium (Fig. 2(b) for SSMF and (d) for VSMF). Same as planar slot waveguides, these modes (HE^x_{11} and HE^y_{11}) in slot-microfibers are true guided modes and there are no confinement losses. The HE^x_{11} mode has very different properties and undergoes a different effective index compared with the HE^x_{11} mode of both SSMF and VSMF. However, the slot shape has more impact on HE^y_{11} than on HE^x_{11}. As shown in Fig. 2, much less y-polarized light field is confined in the slot of VSMF than SSMF, but the x-polarized light field is confined similarly in the slot of VSMF and SSMF.

As the key parameter of slot microfibers, birefringence at $\lambda = 1550$ nm is calculated and shown in Fig. 3 ((a) & (b) for SSMF, (c) & (d) for VSMF). Fig. 3(a) shows the birefringence as a function of slot width and the radius of the microfiber. When the radius is small (such as $r = 500$ nm), the mode field diameter is larger compared to that of the microfiber. So evanescent field which propagates outside the microfiber contributes a big part of the total power flow. Thus, birefringence is relatively small. As the microfiber radius increases, birefringence becomes larger and can reach a very high level of $> 4 \times 10^{-2}$ at $r = 1$ μm with $W = 400$ nm and $d = 2r$. However, when the diameter of the microfiber is comparable to or bigger than the wavelength, birefringence decreases according to our calculation. In this case, the light field is well confined in two D-shaped silica rods, resulting in a low birefringence. $d = 2r$ is an extreme case and it is possible but maybe a little difficult to fabricate and handle. For practical application, it is more preferred at $r < d < 2r$. Fig. 3(a) also shows the birefringence at different depth of the slot. B decreases with smaller d, but can be as high as 0.02 when d decreases to $1.5r$. In fact, our calculation results show that even at $d = r$, B can still maintain a high level of 0.01.

Considering the fabrication feasibility of the SSMF, we study the influence of slot shift on birefringence. Slot shift (δ) is defined as the shifted distance of the slot center with respect to the center of the microfiber along x-direction as shown in Fig. 1. As can be deduced from Fig. 3(b), little change of birefringence is observed with slot shift smaller than 100 nm compared to that of the slot located at the center of the microfiber. Thus we can easily fabricate SSMFs with birefringence as large as 10^{-2} using microfibers of different radius.

As for the VSMF, we find the birefringence is on the order of 10^{-2} and changes slowly with the VSMF radius at V-groove angle of 20°, as shown in Fig. 3(c). However, birefringence changes rapidly with V-groove angle. Bigger groove depth (d in Fig. 1(c)) results in a larger birefringence as shown in Fig. 3(d). The birefringence can be not only positive but also negative. There exists an angle where birefringence becomes zero in different conditions. It is very different from SSMF and has promising applications in polarization independent sensing applications with a fluidic or gas channel inside.

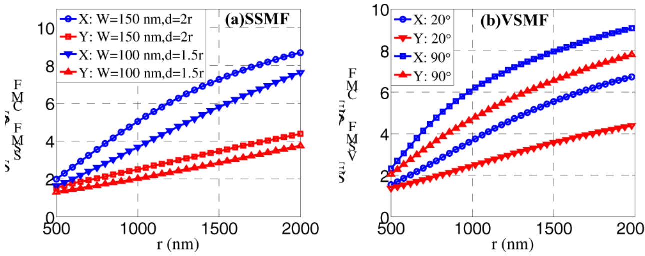

Fig. 4. SE ratios with both x- (blue line) and y-polarization (red line) of (a) an SSMF sensor and (b) a VSMF sensor as compared to that of a CMF sensor in air $(n_{outside} = n_{air})$.

IV. ENHANCED SENSING PROPERTIES OF SLOT-MICROFIBERS

Subwavelength-diameter optical microfibers are ideal sensor elements because of low cost, low loss, and very large evanescent fields. CMF devices in the form of resonators, interferometers, and gratings have been under intensive investigation for deployment as biological and/or chemical sensors [4], [11], [12]. Due to the presence of the slot where optical field is strongly confined, it provides an excellent channel for refractive index sensing applications. And the sensitivity of slot-microfiber sensors is possibly much larger than that of CMF sensors. In all these homogeneous evanescent-field-based sensing, the sensitivity (S) obtained by monitoring the shift of the resonant/interference wavelength λ_0 corresponding to the outside index change can be defined as

$$S = \frac{\partial \lambda_0}{\partial n_{outside}} = \frac{\partial \lambda_0}{\partial n_{eff}} \frac{\partial n_{eff}}{\partial n_{outside}} \infty \frac{\partial n_{eff}}{\partial n_{outside}}.$$

For our evanescent-field-based slot-microfiber and CMF sensors, the main difference on sensitivity comes from sensor efficiency SE $= \partial n_{eff}/\partial n_{outside}$ [13] which depends on the geometry. So we can only consider the SE ratios of slot-microfiber and CMF sensors at the same radius.

Fig. 4 gives the SE ratios with both x- and y-polarizations of (a) an SSMF sensor and (b) a VSMF sensor compared to that of a CMF sensor. The sensitivity of both the x-polarization and y-polarization modes can be much higher with a slot-microfiber than with a CMF. The ratio is about two at $r = 500$ nm and increases quickly with the radius. The sensitivity of the x-polarization mode can even be nearly ten times higher with an SSMF/VSMF than with a CMF. For an SSMF, a high SE ratio of four can still be achieved at $d = 1.5r$ with both polarizations. And for a VSSM, the sensitivity is also strongly dependent on the V-groove angle.

V. CONCLUSION

A possible approach to realize a Hi-Bi microfiber with a slot inside is proposed and discussed. It is a fiberized slot waveguide and the light field can be enhanced and confined in the nanometer-wide low index slot. The birefringence can be as high as 4×10^{-2}. Two kinds of typical cases are investigated and compared. The slot shapes have very important influence on the birefringence, propagation modes and so on. In particular, the birefringence of VSMFs changes quickly with the V-groove angle from positive to negative. Combining the advantages both of microfibers and slot waveguides, slot-microfibers possess larger evanescent field, high birefringence, flexible design, and convenient connection with standard single mode fibers. It is perfect for compact fiberized polarization manipulation devices, such as in-line microfiber wave plates. Due to the existence of the low index slot region, much enhanced gas sensitivity is reached with both polarizations. Its unique geometry can also provide a promising platform for dispersion-related applications.

REFERENCES

[1] M. P. Varnham, D. N. Payne, R. D. Birch, and E. J. Tarbox, "Single-polarization operation of highly birefringent bow-tie optical fibers," *Electron. Lett.*, vol. 19, pp. 246–247, 1983.

[2] T. Hosaka, K. Okamoto, T. Miya, Y. Sasaki, and T. Edahiro, "Low-loss single polarization fibers with asymmetrical strain birefringence," *Electron. Lett.*, vol. 17, pp. 530–531, 1981.

[3] M. Delgado-Pinar, A. Diez, S. Torres-Peiro, M. V. Andres, T. Pinheiro-Ortega, and E. Silvestre, "Waveguiding properties of a photonic crystal fiber with a solid core surrounded by four large air holes," *Opt. Express*, vol. 17, pp. 6931–6938, 2009.

[4] G. Brambilla, "Optical fibre nanowires and microwires: A review," *J. Opt.*, vol. 12, p. 043001, 2010.

[5] L. M. Tong, R. R. Gattass, J. B. Ashcom, S. L. He, J. Y. Lou, M. Y. Shen, I. Maxwell, and E. Mazur, "Subwavelength-diameter silica wires for low-loss optical wave guiding," *Nature*, vol. 426, pp. 816–819, 2003.

[6] G. Brambilla, V. Finazzi, and D. J. Richardson, "Ultra-low-loss optical fiber nanotapers," *Opt. Express*, vol. 12, pp. 2258–2263, 2004.

[7] Y. Jung, G. Brambilla, and D. J. Richardson, "Polarization-maintaining optical microfiber," *Opt. Lett.*, vol. 35, pp. 2034–2036, 2010.

[8] Y. Jung, G. Brambilla, K. Oh, and D. J. Richardson, "Highly birefringent silica microfiber," *Opt. Lett.*, vol. 35, pp. 378–380, 2010.

[9] H. Xuan, J. Ju, and W. Jin, "Highly birefringent optical microfibers," *Opt. Express*, vol. 18, pp. 3828–3839, 2010.

[10] R. Almeida, Q. F. Xu, C. A. Barrios, and M. Lipson, "Guiding and confining light in void nanostructure," *Opt. Lett.*, vol. 29, pp. 1209–1211, 2004.

[11] J.-L. Kou, J. Feng, L. Ye, F. Xu, and Y.-Q. Lu, "Miniaturized fiber taper reflective interferometer for high temperature measurement," *Opt. Express*, vol. 18, pp. 14245–14250, 2010.

[12] J.-L. Kou, J. Feng, Q.-J. Wang, F. Xu, and Y.-Q. Lu, "Microfiber-probe-based ultrasmall interferometric sensor," *Opt. Lett.*, vol. 35, pp. 2308–2310, 2010.

[13] S. Kerstin *et al.*, "A fibre Bragg grating refractometer," *Meas. Sci. Technol.*, vol. 12, pp. 757–764, 2001.