Diamond ring fiber for evanescent field exposure

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Letter

Diamond ring Fiber (DRF) is proposed to allow a high percentage of evanescent field exposure while maintaining low confinement loss. It provides a long and protected medium for light-matter interaction and large cavities to ease the infiltration of sensing elements. DRFs with different waveguide parameters have been analyzed theoretically and fabricated using a stack-and-draw fiber drawing technique. Mode analysis has been performed experimentally on the fabricated fibers, while the confinement loss and the percentage of evanescent field exposure are examined by simulation. DRF allows evanescent field exposure as high as 39.56% with negligible confinement loss at a wavelength of 1550 nm. © 2017 Optical Society of America

OCIS codes: (060.2280) Fiber design and fabrication; (280.4788) Optical sensing and sensors; (060.2370) Fiber optics sensors.

https://doi.org/10.1364/OL.99.099999

Fast, sensitive, and portable tools are highly demanded by numerous applications in health, environment, agriculture, and national security for detecting specific chemicals and biomolecules [1–3]. Gas detection, for example, is becoming important since, today, global warming is thought by many to be threatening human health. Fiber optic sensing has been one of the most successful and impressive applications of both fiber optics and sensing technology in the past 50 years [4]. The comprehensive research in fiber optic sensors leads to many advances in sensing technology such as immunity to the electromagnetic interference, low cost, resistance to high temperatures, and the possibility to perform safe, remote, and distributed measurements [5–8]. Fiber optic sensors can be based on fiber gratings, interferometers, scattering/reflecting, Faraday rotation, fiber-optic gyroscopes, fluorescence, luminescence, and the interaction of evanescent electromagnetic field structures [9].

The simplest way to use an optical fiber for sensing is by transporting light to and from the sensing region. In such a configuration, the interaction between the light and the environment such as scattering, absorption, and fluorescence occurs in the fiber [1]. Light is primarily confined within the core of a waveguide when the size of the core is notably larger than the wavelength of the light, with only the tails of the guided mode extending into the surrounding medium. This is usually defined as the evanescent field. Sensors based on the interaction of this tail of the guide mode with a sensing object, i.e., analyte or gas, are named as evanescent field sensors.

Various evanescent field exposed structures have been studied in recent years. Comparing to D-shaped fibers [10] which are environmentally sensitive, microstructured fibers provide enclosed interaction path and are more durable due to the fact that the coating or cladding of the fibers do not need to be removed [11]. A defect-core photonic crystal fiber (PCF) [12–14], a PCF with a hollow high-index ring defect at the center [6,15], a microstructured-core PCF [16,17], and a suspended-core holey fiber [1,18,19] have been reported to improve the evanescent field exposure of microstructured fibers.

In fact, scaling down the core size can effectively facilitate access to the evanescent field, since the guided light is no longer predominantly confined to the core. Conceptually, the simplest form of such a waveguide is microfiber [1]. Tapered fiber [20], for example, has been proposed to be one of the evanescent field exposed structures that can provide a high percentage of evanescent field exposure. The percentage of evanescent field exposure can be altered by varying the diameter of microfiber. However, when the diameter becomes too small, it will be too fragile for handling. Besides the issue in durability, compared to a microstructured fiber, the interaction path provided by a microfiber is short and environmentally sensitive.

In this Letter, we propose a new kind of evanescent field exposed structure, named diamond ring fiber (DRF). It is having criterion from both the microfiber and microstructured fiber, i.e., allowing a high exposure of the evanescent field with low confinement loss, high durability, and providing a long enclosed interaction path. Besides the aforementioned advantages, DRF comes with large cavities that can ease the analyte flow and material coating in some sensing applications.

The proposed DRF, shown in Fig. 1(a), is an all-silica optical fiber. The structure is mainly formed by a micro-sized silica core and a fiber-sized capillary shield to realize the concept of a protected microfiber which is able to provide a durable and
The fabrication of DRF is based on the conventional stack-and-draw method. Two glass tubes with different wall thicknesses have been used for fabricating DRF, one with an inner to outer diameter of 17.5 mm/25 mm and the thinner one measuring 18 mm/20 mm. The thicker glass tube is used as the jacket tube, while the thin tube is drawn into capillaries with a smaller outer diameter of 8.12 mm. Three capillaries are then stacked inside the jacket tube, and a silica rod is inserted in the central space between them as the DRF core, as shown in Fig. 2. Two capillaries stacked at the beginning and end parts of the jacket tube are in short length, used for the purpose of holding and positioning of the central core during a fiber drawing process. The long capillary stacked in the jacket is meant to be joined with the central core along the fiber length.

Prior to pulling, the DRF preform is annealed at 1800°C to introduce a mild surface joining between the long capillary and the central rod. Then, the preform is pulled based on the conservation of a mass equation to determine pulling parameters such as preform feed and drawing rates to produce the desired output diameter. The preform is drawn into a cane measuring 1 mm in diameter at a temperature of 1930°C with a drawing speed of 1.6 m/min. The structure, particularly the core position, is carefully controlled by controlling the applied pressure in the long capillary. The fabricated cane structure is frequently checked under a microscope throughout the whole drawing process. First, few meters of the cane are discarded because these canes have a three-ring structure resulting from the short supporting capillaries in the initial part of the preform.

The DRF cane is then pulled into a fiber form measuring 125 μm in diameter at a temperature of 1820°C and 0.5 m/min draw speed. The diameter of DRF is chosen to be 125 μm for easier splicing with the standard single-mode fiber (SMF). The scanning electron microscope (SEM) image of the fabricated DRF is shown in Fig. 3(a). The fabricated DRF is the same as the desired structure with measured parameters of \( d_{\text{core}} = 6.68 \) μm, \( d_1 = 35.1 \) μm, \( d_2 = 90.2 \) μm, and \( t_s = 2.51 \) μm. With the \( d_2 \) size as large as 90.2 μm, liquids and gases can be infiltrated into DRF more easily than the other reported micro-structured fibers [6,12-16,18,19].

In order to show the flexibility to fabricate DRF with different parameters and core sizes, a DRF cane is pulled with two steps of jacketing called single and double jackets. A single-jacketed canes is formed by inserting a 1 mm DRF cane into a capillary with a slightly larger inner diameter, while the double-jacketed canes is formed by inserting a DRF cane into two consecutive larger capillaries, as shown in Fig. 4.

The single- and double-jacketed DRF canes are then pulled into the standard fiber size of 125 μm, aiming the higher-order jacketed cane to produce a DRF fiber with a smaller core. For these fabrications, the head of 1 mm cane is fused for self-pressurization, while a vacuum pressure is applied from the top of the preform to collapse the jacket(s) with the DRF cane.
during the drawing process. The jacketed canes are pulled into the fiber size with a drawing speed of around 1.5 m/min and a temperature of around 1850°C. Figures 3(b) and 3(c) shows the SEM images of the fabricated single-jacketed DRF and double-jacketed DRF. Based on the SEM images, the waveguide parameters have been scaled down to $d_{\text{core}}$ of 4.96 μm, $d_1$ of 29.5 μm, $d_2$ of 62.8 μm, and $t_0$ of 1.45 μm in the single-jacketed DRF and further reduced to $d_{\text{core}}$ of 3.23 μm, $d_1$ of 21.36 μm, $d_2$ of 46 μm, and $t_0$ of 0.94 μm in the double-jacketed DRF. These measurements prove that fabrication of DRF with different parameters is possible. The smallest core size that we have successfully fabricated is 1.5 μm.

Figure 5 shows the experimental setup for a mode analysis of the fabricated DRFs. In this setup, a laser source (WSL-100, Santec) operating at 1550 nm wavelength is used to launch light into a 1 meter long DRF coupled via a SMF. Both DRF and SMF are aligned through butt coupling. The output from DRF is collimated by using an objective lens (M - 20 x, Newport) and directed to a beam splitter (FW1, Thorlabs) to split the output equally into a charge-coupled device (CCD) and directed to a beam splitter (FW1, Thorlabs) to split the output equally into a charge-coupled device (CCD) (7290A, Electrophysics) and a beam profiler (BP109-IR, Thorlabs). The experiment is then repeated by changing the fiber under test to single-jacketed DRF and double-jacketed DRF.

The simulation of the diamond ring fiber is done by using commercially available finite element method software, COMSOL MULTIPHYSICS, to solve the Maxwell’s equations. The SEM images of the DRFs are imported into the software to simulate the exact fabricated structures for comparison with the experimental results, as shown in Fig. 1 (b). In addition, a perfectly matched layer (PML) is added, surrounding the structure to attenuate and absorb the outward propagating electromagnetic wave from being reflected back into the simulation region.

The refractive index of silica, $n_{\text{silica}}$, is set according to the operating wavelength $\lambda$ using the Sellmeier equation [21].

DRF, single-jacketed DRF, and double-jacketed DRF are simulated at a wavelength of 1550 nm. In addition to the three different core sizes, DRFs with other different core sizes by scaling down the SEM image of DRF) are simulated to study their performance in terms of evanescent field exposure, $f$ [22], and confinement loss [23], as shown in Eqs. (2) and (3):\[ f = \frac{\int_{S_{\text{total}}} (E_x H_y - E_y H_x) dx dy}{\int_{S_{\text{total}}} (E_x H_y - E_y H_x) dx dy}, \tag{2} \]

where $E_x$, $E_y$ and $H_x$, $H_y$, respectively, are the transverse electric and magnetic fields of the mode:

\[
\text{confinement loss [dB/m]} = 8.66 \frac{2\pi}{\lambda} \text{Im}[n_{\text{eff}}], \tag{3}
\]

where $\text{Im}[n_{\text{eff}}]$ is the imaginary part of the effective refractive index of the guided mode.

The captured CCD images from the experiment show the power distribution of the guided mode in each fabricated DRFs, as depicted in Fig. 6. The intense spot shows the guided mode in the silica core. In DRF, a small fraction of the light penetrates into the ring. This is due to the thickness of the ring, which is relatively thick compared to the $\lambda$ of the light. The reduced ring thickness in single-jacketed DRF decreases the penetration of light into the ring. In double-jacketed DRF, the light is well guided inside the core. From Fig. 7, the simulated DRFs show the same changes in power distribution as the size of the structure reduces. The light power is getting more concentrated in the core as the ring thickness is being reduced. Hence, the experimental results are proven based on the simulation results. Less leakage of light into the ring allows higher exposure of evanescent field into the air surrounding the DRF core. Besides a thinner ring, DRF with a higher order of jacketing also has a smaller core, resulting in a higher evanescent field exposure compared to DRF with lower order of jacketing at a particular wavelength.

One-dimensional mode intensity profile is obtained for each DRF using a beam profiler and shown in Fig. 8. In a horizontal axis, DRFs show symmetrical mode profiles due to the symmetrical step-index profile. In a vertical axis, the step-index profile is air-silica-silica-air, which is asymmetrical due to the fact that silica contributed by the ring is relatively thin. However, double-jacketed DRF is able to show a symmetrical mode profile in horizontal axis since the ring thickness reaches the diffractive limit [24] of the silica.

While scaling down the structure of DRF, the core size gets smaller. When the core size is larger than the $\lambda$, only the guided mode protrudes into the surrounding medium, which is the
air. A smaller core size can expose more evanescent field to the air cavities. Figure 9 shows the relationship among \( f \), the confinement loss, and the core size of DRF. Reaching the condition where the core size is near to or smaller than the \( \lambda \), \( f \) starts to increase tremendously. In our simulation, we stop at the core size of 0.8 \( \mu \text{m} \) because significant increase in the confinement loss due to the diffraction limit of the silica is noticed. Using the DRF structure, the highest achievable evanescent field exposure is 39.56\% with the negligible confinement loss of <0.025 dB/m, at a 1550 nm wavelength and a 0.8 \( \mu \text{m} \) core size. Low confinement loss is important to further enhance the sensing performance by allowing a longer interaction path between the light and matter.

Figure 10 shows the dependence of \( f \) and the confinement loss to \( \lambda \), at the core size of 0.8 \( \mu \text{m} \). For \( \lambda \) smaller than 1550 nm, \( f \) increases at higher \( \lambda \) due to a higher penetration of the guided mode into the air cavities. When the \( \lambda \) becomes higher than 1550 nm, both the \( f \) and the confinement loss increase excessively, since the light is no longer well guided inside the relatively smaller core size. For any application that requires a smaller \( \lambda \), a high evanescent field exposure can still be obtained using DRF with a core size smaller than 0.8 \( \mu \text{m} \) without introducing significant confinement loss.

DRF that provides the aforementioned highest achievable \( f \) consists of a protected nanofiber measuring 0.8 \( \mu \text{m} \) in diameter and two cavities with the diameter of 4.2 and 10.8 \( \mu \text{m} \), respectively. In previous works, suspended-core holey fiber has been shown to be the best candidate for evanescent field enhancement. Suspended-core holey fiber can achieve \( f \) as high as 29\% with a core size of 0.8 \( \mu \text{m} \) at a wavelength of 1550 nm [18]. The average cavity size in this suspended-core holey fiber is around 3.6 \( \mu \text{m} \). DRF with the same core size is capable of delivering a much higher \( f \), while providing larger cavities for easing the infiltration of liquids and gases as shown above. We successfully infiltrated liquids and graphene in the DRF using a capillary effect, but the method of controlling the infiltration is under investigation. It is obvious that the proposed DRF is now a potential better evanescent field exposed structure than the reported suspended-core holey fiber.

In conclusion, DRF has been proposed as an advanced evanescent field exposed structure for the first time, to the best of our knowledge, which combines the advantages of a micro/nanofiber and a microstructured fiber. DRF delivers a high \( f \) with low confinement loss, while providing a large and enclosed light-matter interaction medium. Three DRFs with different parameters have been fabricated and tested on their light guiding ability. A numerical analysis shows that DRF with the core size of 0.8 \( \mu \text{m} \) can achieve an \( f \) as high as 39.56\% with a negligible confinement loss at a wavelength of 1550 nm. Due to a high evanescent field exposure with large air-hole channels proposed, a sensor will be suitable for sensing applications.

**Funding.** Ministry of Higher Education, Malaysia (MOHE) (UM.00000005/HIR.C1).

**REFERENCES**

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