

A microfluidic refractometric sensor based on gratings in optical fibre microwires

Fei Xu,¹ Gilberto Brambilla,² and Yanqing Lu¹

¹*Department of Materials Science and Engineering and National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, P. R. China*

²*Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom*

Abstract: In this paper we investigate a novel method to manufacture gratings in optical fiber microwires and discuss their application to sensing. Gratings can be manufactured by wrapping an optical fiber microwire on a microstructured rod. This method avoids post-processing the thin optical fiber microwire and it has great flexibility: chirping can be realized by designing the air hole size and position in the microstructured rod. By exploiting the large evanescent field in an inner channel, microfluidic refractometric sensors with sensitivity $> 10^3$ nm/RIU can be achieved.

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1. Introduction

Optical devices based on silica optical fiber microwires (OFM) have attracted increasing attention because of the recent developments in the fabrication technology [1–3]. OFM devices fabricated from sub-wavelength fibers offer several prospective benefits as compared to micro-photonic devices based on other principles; these include low insertion loss, complete fiber compatibility and flexibility. Being fabricated from a single-mode fiber, OFM devices do not experience any input/output coupling problem. Recently some devices have been realized with sub-wavelength OFMs, including OFM resonators which have been investigated intensively both theoretically and experimentally. Yet, there is much difficulty in manufacturing OFM gratings. The standard use of photosensitive fiber core and UV writing is inconvenient for a micrometer scale fiber taper due to the disappearance of the germanium core [4] and the decrease of the field overlap with the core. Alternative techniques, such as etching the standard fiber, focused ion beam milling or implantation [5], and femtosecond infrared irradiation [6] have been reported, although the last two methods managed to produce only third-order gratings.

In this Letter, we present a novel design to obtain gratings and chirped gratings in OFMs without post-processing: large chirps can be easily realized by designing a specific support rod. This device is very compact and can be coated and used as a sensor with large evanescent field in an inner fluidic channel. This effect can be exploited to design a microfluidic refractometric sensor with extremely high sensitivity.

2. Schematic of the grating structure

OFM gratings can be obtained by wrapping OFMs on microstructured rods, and then coating them with a low-loss polymer. The microstructured rod can be a thick microstructured fiber or it can be obtained by etching a cane used in the manufacture of microstructured fibres. Combining current enabling technologies on microstructured optical fibers [7, 8] and OFMs [9], it is possible to induce periodic or variable corrugations leading to the coupling between forward and backward propagating waves. The final OFM grating structure is shown in Fig. 1(a): it is a compact and robust micro-device with some air holes arranged in a circle. The mode propagating in the OFM experiences refractive index corrugations because its evanescent field overlaps with the support rod where there is alternation of glass and air holes. Here we only consider one ring of air holes; the inner large hole is also filled with air and the OFM is assumed perpendicular to the rod. When a coordinate increasing along the microfiber is used, the surface corrugations experienced by the mode propagating along the curvilinear coordinate are similar to those experienced by a mode propagating straight in proximity of a conventional planar grating. Unfolding the OFM, the OFM grating can be taken as a coated OFM on a planar substrate with air-hole corrugations: the equivalent structure is shown in Fig. 1 (b).

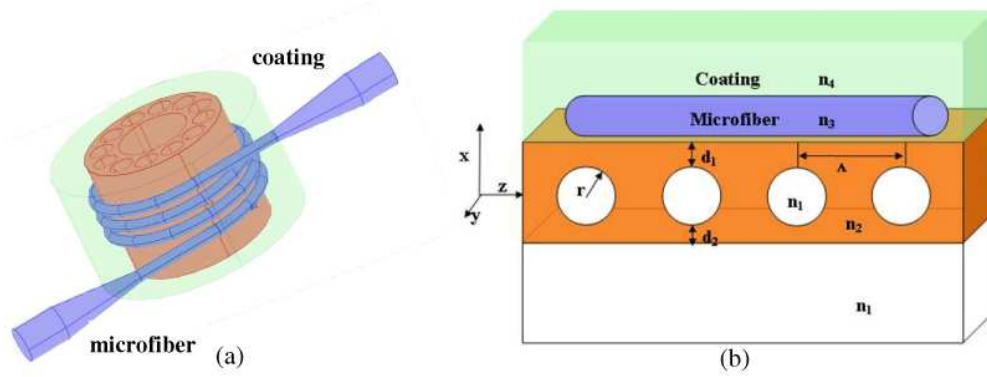


Fig. 1. (a) Schematic of the embedded OFM grating. (b) The equivalent planar structure; n_1, n_2, n_3, n_4 are the refractive indexes of the hole, the rod, the OFM, and the coating, respectively; Λ is the distance between two adjacent holes; d_1 and d_2 are the thickness of the outer and inner walls of the one-ring microstructured rod, r is the hole radius.

As in other planar Bragg gratings and DFB lasers, the Bragg wavelength of the OFM grating is expressed by $\lambda_B = 2n_{\text{eff}}\Lambda/m$ where n_{eff} is the mode effective index in the unperturbed (coiled) geometry, Λ is the period between two air-holes and m is the Bragg order.

The mode field in the unperturbed waveguide geometry is derived from the perturbed (straight) geometry using the method developed by W. Streifer [10, 11]: boundary between materials is shifted to compensate for the different geometry. If g_1 is the boundary between the materials with refractive indices n_1 (air) and n_2 (the rod material, generally silica) and g_2 is the boundary between the materials with refractive indices n_4 (coating) and n_2 , a new g_0 is chosen to match the volume of n_1 material extending into region A (above g_0) to the volume of n_2 material extending into region 1 (below g_0), as shown in Fig. 2(a). We introduce the effective distance d_{eff} between g_2 and g_0 as:

$$d_{\text{eff}} = g_1 + g_2 - g_0 = d_1 + d_2 + 2r - \pi r^2 / \Lambda \quad (1)$$

d_{eff} increases for increasing $d = d_1 + d_2$ and decreasing Λ .

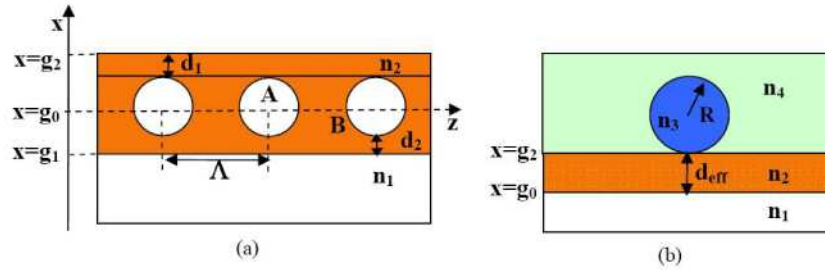


Fig. 2 (a) Illustration of the outer layer structure of the support rod in Streifer's theory. n_1 and n_2 represent the refractive indices of the hole and rod, Λ the distance between two adjacent holes, g_1 and g_2 the boundaries between different layers, g_0 the new equivalent boundary between n_2 and n_1 . (b) The cross-section of the OFM in the equivalent outer straight layer structure, n_3 and n_4 are the index of the OFM and coating, R is the radius of the OFM and d_{eff} is the effective wall thickness

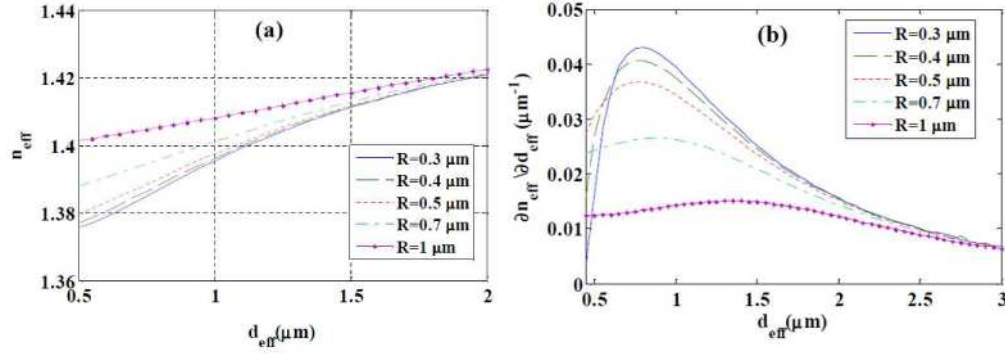


Fig. 3 (3) the effective index of OFM grating at different OFM radius depend on d_{eff} for $n_1=1$, $n_2=1.311$, $n_3=1.451$, $n_4=1.375$, and $\lambda=1550$ nm. (b) $\partial n_{eff}/\partial d_{eff}$ depends on d_{eff} at different OFM radius.

The OFM cross-section in the equivalent outer straight layer structure is shown in Fig. 2 (b) ; in our simulations, the effective index and related propagation constant were obtained using the finite element method (FEM). Fig. 3(a) shows the dependence of the effective index on d_{eff} for different OFM radii at $\lambda=1550$ nm. n_{eff} increases for increasing d_{eff} or R , as the OFM and rod have indices larger than that of the coating, and the mode is more confined in the microfiber when R increases or in the rod when d_{eff} increases.

This method to manufacture OFM gratings is extremely flexible: grating chirping can be achieved by tuning the hole radius and pitch, or by changing the distance between OFM and holes. Since $\lambda=2n_{eff}(d_{eff})\Lambda/m$, there are three simple ways to realize chirp: by tuning Λ , $d=d_1+d_2$, and r . Chirp rates are defined as:

$$\begin{cases} \frac{\partial \lambda}{\partial d} = \frac{2}{m} \frac{\partial n_{eff}}{\partial d_{eff}} \Lambda \\ \frac{\partial \lambda}{\partial \Lambda} = \frac{2}{m} \frac{\partial n_{eff}}{\partial d_{eff}} \frac{\pi r^2}{\Lambda} + \frac{2}{m} n_{eff} \\ \frac{\partial \lambda}{\partial r} = \frac{2}{m} \frac{\partial n_{eff}}{\partial d_{eff}} (2\Lambda - 2\pi r) \end{cases} \quad (2)$$

All the derivatives $\partial \lambda / \partial \Lambda$, $\partial \lambda / \partial d$ and $\partial \lambda / \partial r$ depend on $\partial n_{eff} / \partial d_{eff}$, which in turn is strongly dependent on d_{eff} and R . Fig. 3(b) shows that $\partial n_{eff} / \partial d_{eff}$ is of the order of $10^{-2} \mu\text{m}^{-1}$ and achieves the maximum at $d_{eff} \sim 1 \mu\text{m}$. For $m=2$, from Eq. (2) $\partial \lambda / \partial \Lambda \gg \partial \lambda / \partial d \sim \partial \lambda / \partial r$; since $\partial \lambda / \partial \Lambda > 1$, chirped grating can be easily realized by tuning the grating period: current photonic crystal fiber (PCF) fabrication techniques make the low-cost period-tuning possible. Moreover, $\partial \lambda / \partial d \sim \partial \lambda / \partial r \sim 10^{-5}$: this is enough to produce small precise chirps in a simpler and cheaper way than inducing a temperature, strain or refractive-index gradients. If chirping is to be achieved simply by wrapping the OFM around the support rod, hole periodicity repeats itself after each OFM turn, thus the rod circumference limits the chirp length. However, OFM and microstructured rods allow for another method to achieve chirped gratings. If the OFM is not perpendicular to the rod (they cross at an angle φ) the Bragg condition is expressed by [11] $\lambda=2n_{eff}\Lambda/\cos\varphi/m$; by changing φ gradually, the Bragg wavelength will change gradually, too. Thus by gradually changing φ it is possible to control the grating Bragg wavelength and get a chirped grating. When φ is very small, the chirp rate is given by

$$\frac{\partial \lambda}{\partial \varphi} = -2 \frac{n_{eff} \Lambda \sin \varphi}{m \cos^2 \varphi} \sim 2 \frac{n_{eff} \Lambda \varphi}{m} = \Lambda \varphi \quad (3)$$

The chirp range varies considerably: from 0.3 nm/o at $\varphi=0.1^\circ$ to 300 nm/o at $\varphi=10^\circ$.

These two chirping methods allow for a great deal of flexibility in the chirp design.

3. A refractometric sensor and its sensitivity

If the microstructured rod holes are used as microfluidic channels, the device shown in Fig. 1(a) can work as a refractometric sensor. The fluid can enter the microfluidic channels by capillarity. Because of the small hole size, extremely small fluid quantities are needed for the examination. Moreover, since only a very short piece of rod is needed for each device, the average device cost is very low. As a sensing device, the OFM is expected to have a considerable fraction of the power propagating in the evanescent field. Standard fiber gratings have thick claddings and this limits the extent of the evanescent field: they have to be post-processed (typically etching the cladding) to have a non-negligible fraction of power in the evanescent field. Moreover, a simple OFM has to be coated to avoid degradation [2] and this limits the extent of the evanescent field beyond the coating. On the contrary, OFM gratings can have a large evanescent field in an inner channel.

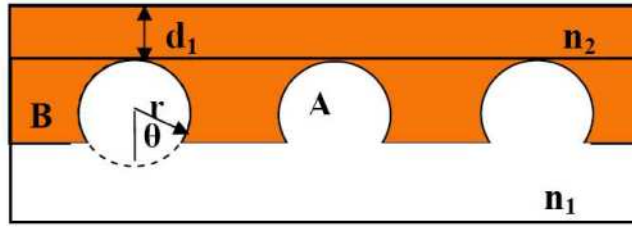


Fig. 4 Illustration of the outer layer structure of the support rod for $d_2 < 0$.

For sensing applications, large evanescent fields imply that d_1 and d_2 are expected to be as small as possible. Figure 4 shows that d_2 can be negative ($d_2 = -(r - r \cos \theta)$), thus:

$$d_{eff} = d_1 + r(1 + \cos \theta) - (r^2/\Lambda)(\pi - \theta + \sin \theta \cos \theta). \quad (4)$$

d_{eff} decreases when φ increases. A quantitative measurement of the sensor efficiency is given by the homogeneous sensitivity S , which can be obtained by monitoring the shift of the Bragg wavelength λ_B corresponding to a change in the analyte refractive index n_1 [12]:

$$S = \frac{\partial \lambda}{\partial n_1} = \frac{\partial \lambda}{\partial n_{eff}} \frac{\partial n_{eff}}{\partial n_1} = \frac{\lambda}{n_{eff}} \frac{\partial n_{eff}}{\partial n_1} \quad (5)$$

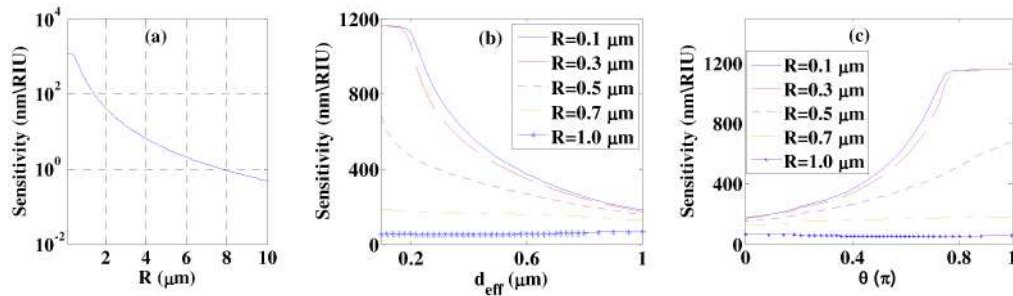


Fig. 5. (a) Dependence of the sensitivity S on OFM radius R for etched standard fiber gratings. $n_1=1.332$ and $\lambda=1550$ nm; (b) Dependence of S on d_{eff} for OFM gratings. $n_1=1.332$, $\lambda=1550$ nm and $n_2=1.311$ (Teflon). (c) Dependence of S on θ for OFM gratings, $d_1=100$ nm, $r=\Lambda/4$ and $m=2$.

Figure 5(a) shows the dependence of S on the OFM radius R for standard fiber Bragg gratings with etched cladding. Although S can achieve 1200 nm/RIU (where RIU is refractive

index unit) at $R \sim 200$ nm, it is very difficult to get such a thin OFM by etching; generally, OFM manufactured by etching are several micrometers thick and $S < 100$ nm/RIU in this range of diameters. Figure 5(b) shows the dependence of the sensitivity S on d_{eff} in OFM gratings: S increases for decreasing d_{eff} or R , because the fraction of the mode field inside the fluidic channel increases. S reaches 1200 nm/RIU at $R \sim 200$ nm. The dependence of the sensitivity S on θ is presented in Fig. 5(c): as before, because of the increased overlap between the mode propagating in the OFM and the microfluidic channel, S increases with θ . Table 1 compares the sensitivity of several typical evanescent field microfluidic refractometric sensors: the sensitivity of OFM grating is the highest. Sensor 7 is made by wrapping an OFM on a soluble rod and its S can be close to that of an OFM grating sensor for R close to 300 nm, but it drops quickly with R and it reaches 20 nm/RIU for $R \sim 1 \mu\text{m}$. Sensor 8 is a typical etched fiber grating sensor: $S \sim 100$ nm/RIU for $R \sim 1.5 \mu\text{m}$ (Fig. 5(a)); however, it has major drawbacks: it has neither a fluidic channel to delivery the analyte nor the coating to protect itself from degradation; moreover, OFM is difficult to be etched to such a small size.

OFMs with diameters of several hundreds nanometres can be used in OFM grating: S can reach hundreds of nm/RIU, considerably better than that calculated for etched standard gratings (Fig. 5(a)). To achieve high sensitivity OFM grating sensors, negative d_2 are required to easily achieve smaller d_{eff} . Although S increases for increasing θ , the coupling strength decreases because the teeth depth is small.

Table 1 . Sensitivity for evanescent field microfluidic refractometric sensors.

	Type of sensor	Sensitivity nm/RIU	Reference	Notes
1	Integrated optical hollow waveguides	~ 555	[13]	Wavelength 700nm
2	Liquid core optical ring resonator, Glass capillary and fiber taper	34	[14]	Wall thickness 2 μm
3	Optical liquid ring resonator, Coated glass capillary and fiber taper	~ 100	[15]	Wall thickness 0
4	On-chip Si/SiOx microtube	~ 62	[16]	
5	Thin capillaries	~ 100	[17]	Wall thickness 0.8 μm
6	Thin Cylindrical shell resonator, polymer	~ 31.5	[18]	
7	Optical fiber nanowire sensor	~ 1000 ~ 20	[19]	OFM radius 300 nm OFM radius 1000 nm wavelength 1550 nm
8	Etched standard grating	~ 100	[20]	Fiber radius: 1.5 μm
9	OFM grating	~ 1200	This work	

4. Conclusion

In conclusion, we have presented a novel method to manufacture gratings in OFM by wrapping an OFM on a microstructured rod. By designing microstructured rods with specific geometries or by changing the approach angle between microfiber and rod, grating chirping can be obtained. A refractometric sensor can be obtained exploiting the holes of the microstructured rod as microfluidic channels. The sensor sensitivity has been calculated and compared with other evanescent field refractometric sensors. OFM grating sensors can have extremely high sensitivity, in excess of 10^3 nm/RIU.

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