Ultra-sensitive refractive index sensor based on extremely simple femtosecond-laser-induced structure

PENGCHENG CHEN1, XUEWEN SHU1,*, HANYUAN CAO1, KATE SUGDEN2

1 Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
2 Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK

* Corresponding author: xshu@hust.edu.cn

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We demonstrate here an extremely simple, compact and robust RI probe sensor based on a femtosecond-laser induced refractive-index-modified-dot (RIMD) fabricated near the end face of a single mode fiber. The RIMD and the fiber end face form a Fabry-Perot interferometer, which is highly sensitive to surrounding RI. The fabrication process of the RIMD involves only one step and takes ~0.1s, which is extremely short compared with other techniques. The proposed sensor exhibits an ultra-high sensitivity of ~2523.2 dB/RIU at an RI of 1.435, which is 1-2 orders of magnitude higher than that of the existing intensity-modulated RI sensors. Moreover, the proposed sensor has the distinct advantages of compact size (~50 µm), easy fabrication and no temperature cross-sensitivity. The advantages of the device make it a promising candidate for applications in designing highly sensitive sensors in biochemical and environmental measurement field.

© 2017 Optical Society of America

OCS codes: (060.2370) Fiber optics sensors; (230.4000) Microstructure fabrication; (120.3180) Interferometry; (120.2230) Fabry-Perot; (230.1150) All-optical devices.

http://dx.doi.org/10.1364/OL.99.099999

Optical fiber Fabry-Perot interferometers (FPFs) are attractive as RI sensors because they are compact, have high fringe visibility, high RI sensitivity and are simple to fabricate. Various fiber in-line FPI structures have been proposed. Currently, fiber in-line FPIs are mainly manufactured by fusion splicing different types of fibers together, such as photonic crystal fiber[1] and capillary tube[2]. However, these splicing methods have problems such as mode mismatch between the different parts, the splice being easily broken, and it being difficult to achieve good reproducibility due to the manual operation. Meanwhile, the use of expensive specialty fibers increases the cost of the sensors. Another method to fabricate fiber in-line FPI is to pretreat the end surface in advance, for example using chemical etching[3], multiple splicing arcs[4], or by coating a thin film or wafer[5, 6]. However, these approaches increase the number of manufacturing steps and the fabrication time. Moreover, the above methods have some inherent challenges. For example, it is difficult to predict or control the length of the cavity precisely and it requires a series of complicated fabrication processes such as assembling multiple components together, precise cleaving and correct arc conditions. In addition, many of those FPIs are rather fragile and have poor robustness. Recently, a direct femtosecond laser (fs-laser) or UV laser micromachining method has also been applied to fabricate air-gap cavities to produce a fiber in-line FPI [7-10]. For fs-laser micromachining, the length of the cavity can be controlled precisely but these devices have very poor mechanical properties and are susceptible to interference effects from things such as bending, or need an extra arc discharge to smooth the inner wall of the microchannel, which makes the fabrication process complicated and time-consuming. With UV laser micromachining, however, it is also hard to control the length of the cavity precisely and it requires additional fusion assembly [10].

In this paper, we propose and demonstrate an ultra-sensitive and extremely simple and robust RI probe sensor based on in-fiber refractive-index-modified-dot (RIMD) induced by femtosecond laser. The RIMD and the end-face of the cleaved single mode fiber (SMF) form a composite-cavity FPI. It can simultaneously measure temperature alongside exhibiting ultra-high RI sensitivity of ~25232 dB/RIU at the refractive index of 1.435, which is at least 10 times higher than previous reported results. The laser fabrication process takes only about 0.1s, which lends itself to efficient manufacture. Furthermore, compared with wavelength
modulated FPIs, our filling-free intensity modulated FPI is more reliable and attractive due to its insensitivity to bend, no temperature cross-sensitivity and no need for expensive wavelength demodulation equipment. Our further analysis and experiments also reveal two ultra-sensitive zones for such a structure, which may have great significance for sensing applications.

The light propagating in the fiber and reflected by the three mirrors will generate a three-wave FPI pattern in fiber. The interference pattern consists of both broad fringes and fine fringes that result from the interference of light inside the composite cavity formed by mirrors 1, 2 and 3. The strength of the interference fringes can be modeled using the following three-beam optical interference equation [10]

\[ I = R_i + A_i^2 R_s + B_i^2 R_e - 2 \sqrt{R_i R_s} \cos(2\phi_i) \cdot 2 \sqrt{R_i R_s} \cos(2\phi_e) + 2AB_i R_i R_s \cos(2\phi_i + \delta(\phi)) \]  

\[ \Delta n = \frac{n_{ex} - n_{co}}{n_{ex} + n_{co}} \]  

Where \( A_i = (1 - \alpha_i)(1 - \gamma_i)(1 - R_i) \), \( B_i = (1 - \alpha_i)(1 - \gamma_i)(1 - R_i)(1 - \alpha_i)(1 - \gamma_i)(1 - R_i) ; \phi_i = 4\pi n_i L_i / \lambda \) is the phase shift in the cavity \( j (j = 1, 2) ; n_i \) and \( L_i \) are the refractive index and length of the cavity \( j \), respectively; \( \alpha_i, \alpha_i \) are the intensity attenuation factors of the Mirror 1 and Mirror 2. \( \gamma_i, \gamma_i \) are defined as the transmission loss factors of the Cavity 1 and Cavity 2, respectively; \( R_i \) is the power reflection coefficients at mirror \( i(i = 1, 2, 3) \), which can be calculated by the Fresnel formula:

\[ R_i = \left( \frac{n_{ex} - n_{co}}{n_{ex} + n_{co}} \right)^2 = \left( \frac{\Delta n}{n_{ex} + n_{co}} \right)^2 \]  

Here \( n_{ex} \) is the refractive index of the RIMD, \( n_{co} \) is the RI of the measured liquid. Typically the value of \( \Delta n \) induced by fs lasers is \( \sim 0.01[11] \). When \( n_{ex} < n_{co} \), \( \delta(\phi) = 0 \). While when \( n_{ex} > n_{co} \), \( \delta(\phi) = \pi \), there is a \( \pi \) phase shift at reflection Mirror 3.

From Eq. (1), the fine fringe visibility \( V \) can be derived as:
From Eq. (2), one can see that only $R_1$ depends on the surrounding RI to be measured. When the surrounding medium is air, $\sqrt{R_i} + A\sqrt{R_i} \ll B\sqrt{R_i}$, thus $V \approx 0$, i.e. the visibility of the interference fringe pattern is very low. However, if the surrounding RI is increased, so that $B\sqrt{R_i}$ is approaching $\sqrt{R_i} + A\sqrt{R_i}$, $V$ will increase to $\approx 1$, which means maximum visibility can be obtained.

In order to illustrate this visually, we can simulate the evolution of the reflection spectra of the RI sensor at various RI based on equations (1) and (2) by calculating the normalized reflection of the reflection spectra of the RI sensor at various RI based on intensity measurement to date. Table 1 compares our RI sensor with the existing fiber-optic RI sensors based on intensity modulation.

### Table 1. Comparison of the existing optical fiber intensity-modulated RI sensors

<table>
<thead>
<tr>
<th>Sensor Structure</th>
<th>Fabrication</th>
<th>RI Sensitivity (dB/RIU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMF-MMI [13]</td>
<td>Special splice</td>
<td>Max. 87</td>
</tr>
<tr>
<td>FBG-FPI [14]</td>
<td>UV PMSBT.</td>
<td>$\approx 1$</td>
</tr>
<tr>
<td>PCF-FPI [1]</td>
<td>Special splice</td>
<td>$\approx 11.5$</td>
</tr>
<tr>
<td>HOF-FPI [2]</td>
<td>Special splice</td>
<td>16</td>
</tr>
<tr>
<td>Air hole [16]</td>
<td>Fs M.mac.</td>
<td>Max. 110</td>
</tr>
<tr>
<td>RMD-FPI [our sensor]</td>
<td>One Step Fs M.mac.</td>
<td>Max. 2523.3</td>
</tr>
</tbody>
</table>

**SEM**: Submarine equipment; **MMI**: Microwave interference; **MMF**: Multimode interference; **FBG**: Fiber Bragg grating; **PMSBT**: phase mask-scanning beam technique; **Max.**: Maximum Value

More interestingly, we find two extremely sensitive zones for RI sensing where $V \approx 1$. To explore this, Fig. 4 shows the relationship between the effective reflectance (i.e., $\sqrt{R_i} + A\sqrt{R_i}$ and $B\sqrt{R_i}$) versus surrounding RI. It can be seen that there are two intersection points between the red curve ($B\sqrt{R_i}$) and the straight blue line ($\sqrt{R_i} + A\sqrt{R_i}$). The RI values for the two intersection points are 1.438 and 1.482, respectively. We can define four different regions (i.e., RI $<1.438$, 1.438 $<$ RI $<1.46$, 1.46 $<=$ RI $<1.482$, and RI $>1.482$, marked as regions I-IV, respectively), which have different response trends for RI sensing. In order to verify the existence of these two extremely sensitive zones for RI sensing predicted by analysis, we experimentally tested the proposed sensor under higher surrounding RI. The close-up of the measured reflection spectra in regions I-IV for various RI values are shown in Figs. 5(a)-(c), respectively. It is clearly seen the spectral response trends agree well with the ones predicted. It is also experimentally verified the existence of the $\pi$-phase shift due to the half-wave loss. Fig. 5(d) shows the variation of the measured intensity of the interference fringe dip at wavelength $\sim$ 1578nm for RI $<1.46$ and 1570nm for RI $>1.46$ as a function of the surrounding RI. The measured intensity changes rapidly near the RI of 1.438 and 1.482, which means two ultra-sensitive zones are experimentally verified. The ultra-sensitive zones provide a highly-sensitive measurement for RI sensing and should find some important applications in practical environmental, chemical and biochemical sensing applications.
We further investigated the temperature response of the proposed RI sensor by mounting it on a hotplate. With increasing temperature, the reflection spectrum of the sensor hardly changed except for the whole spectrum slightly shifting to a longer wavelength. Fig. 6 shows the temperature response of the dip at ~1578nm, whose spectra was measured during the heating process is also illustrated in the inset. It is clearly seen that the wavelength of the sensor shifted toward a longer wavelength as temperature increased (with a sensitivity of 11.21 pm/°C), while the dip intensity of the interference fringe hardly changed (<0.02 dB), indicating that the dip intensity of the interference fringe is insensitive to temperature. Since the temperature information can be independently decoded from the wavelength shift of the fringe pattern, our proposed RI sensor can achieve simultaneous measurement of RI and temperature, and thus solve the cross-sensitivity problem between temperature and surrounding RI. Moreover, our theoretical analysis reveals the existence of two ultra-sensitive zones for RI sensing for each device, which is also verified experimentally. To the authors’ knowledge, it is the first time that this important phenomenon in FPI sensors is revealed. These excellent features of the device in addition to such merits as ultra-high sensitivity, low cost, a simple and compact structure, high reproducibility, good robust, time-saving in fabrication and the ability to overcome the temperature cross sensitivity make it a very promising candidate in practical environmental, chemical and biochemical sensing applications.

In conclusions, an in-line fiber intensity modulated RI sensor based on an FPI formed by inducing a refractive-index-modified-dot in a fiber using a fs laser has been demonstrated in this paper. The developed device has very favorable characteristics and numerous advantages. Experimental results show that such a FPI probe sensor exhibits an ultra-high resolution of \(4.0 \times 10^{-7}\, \text{RIU}\) and an ultra-high sensitivity of 2523.2 dB/RIU at the refractive index of 1.435, which is at least 10 times higher than the other intensity modulated RI sensors reported previously. Moreover, the probe can also be used to monitor temperature with a sensitivity of ~11.21 pm/°C, which allows a simultaneous measurement of the surrounding RI and temperature. Moreover, our theoretical analysis reveals the existence of two ultra-sensitive zones for RI sensing for each device, which is also verified experimentally. To the authors’ knowledge, it is the first time that this important phenomenon in FPI sensors is revealed. These excellent features of the device in addition to such merits as ultra-high sensitivity, low cost, a simple and compact structure, high reproducibility, good robust, time-saving in fabrication and the ability to overcome the temperature cross sensitivity make it a very promising candidate in practical environmental, chemical and biochemical sensing applications.

**Funding.** Director Fund of WNLO; National 1000 Young Talents Program, China; 111 Project (No.B07030)

**References**

full references


