Highly sensitive refractometer with photonic crystal fiber long-period grating

Lars Rindorf and Ole Bang
COM•DTU, Department of Communications, Optics and Materials,
Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

We present highly sensitive refractometers based on a long-period grating in a large mode area PCF. The maximum sensitivity is 1500 nm/RIU at a refractive index of 1.33, the highest reported for any fiber grating. The minimal detectable index change is $2 \times 10^{-5}$. The high sensitivity is obtained by infiltrating the sample into the holes of the photonic crystal fiber to give a strong interaction between the sample and the probing field.

PACS numbers: 050.2770, 060.0060, 060.2370, 060.3735, 060.5295, 230.3990.

Optical fiber sensors are attracting increasing interest. Fiber grating sensors are being used for a variety of purposes including temperature, strain, and refractive index sensing. The sensors possess high sensitivity as well as low susceptibility to interferences. In long-period fiber gratings (LPGs) a core mode is coupled resonantly to a cladding mode. In standard optical fibers the cladding mode probes the surroundings of the fiber and in this way the resonance wavelength may be shifted. The shift in resonance wavelength is used as the indicator of the refractometry [1]. At a refractive index of 1.33, typical for aqueous environments, the typical sensitivity of an LPG in a standard telecom fiber is typically 50 nm/RIU [2].

Long-period gratings can also be realized in photonic crystal fibers (PCFs) [3]. PCFs have an array of air holes running along the fiber axis, which confine the light to the core. The propagating wave inside the PCF has a particular strong evanescent wave compared with a standard optical fiber due to a much closer proximity of the electromagnetic wave and the holes than the outside of the cladding. PCFs are characterized by their hole diameter, $d$, and the pitch of the structure, $\Lambda$. Fini [4] has shown that the probing of the holes is strong when the structure has a large air filling fraction, and the feature size is comparable to the wavelength, i.e. for small pitch and for large air holes. The probing also increases when the contrast between the refractive index of silica and the refractive index of the holes is small. Phan Huy et al. [11] has recently studied the sensitivity of a PCF with a Bragg grating to refractive index. By fabricating a PCF with a very small core, and thus large evanescent field, $f_n$, the sensitivity was increased by two orders of magnitude with respect to a large core design.

In this Letter we show that the refractive index sensitivity for a photonic crystal fiber long-period grating is almost two orders of magnitude larger than the sensitivity for long-period grating for a standard optical fibers. The sensitivity is enhanced by a factor of three by choosing longer wavelengths. Finally, guidelines to PCF-LPGs with even surpassing sensitivity are discussed.

In an LPG the incident core mode can be coupled resonantly to a cladding mode by a period perturbation that equals the beat length between the two modes. According to coupled mode theory [5] the resonance condition is $\lambda_r = (n_{co}(\lambda) - n_{cl}(\lambda))\Lambda_G$. The effective indices also depend on wavelength, and this must be taken into considerations. The PCF used was a large mode area PCF with a mode diameter of 10 $\mu$m. The structure parameters were $\Lambda = 7.12 \mu$m and $d/\Lambda \approx 0.478$ making the PCF almost single-mode. The long-period gratings were inscribed with the CO$_2$ laser method. We used a Synrad Fenix CO$_2$ laser with a maximum output power of 75 W which is set to 3 %. There was no collapsing of the holes, which has also been observed by others [6]. In our experimental setup the PCF is mounted in a stage on top of two linear stages. The stages move the fiber in and out of the CO$_2$ laser beam, which is kept fixed. The stages are controlled by a Labview program, and the inscription is fully automated. The inscription progress is monitored in situ. The setup gives a high degree of freedom by the choice of the number of grating periods and the grating period, $\Lambda_G$. Four PCF-LPGs are fabricated with grating periods 820, 740, 620, 580 $\mu$m. The number of periods is 60, the

![FIG. 1: The spectra of the PCF-LPG filled with air and methanol. Each pair is offset by 5 dBm for clarity. Inset: the refractive index of silica glass, water and methanol.](image)

---

*PACS numbers: 050.2770, 060.0060, 060.2370, 060.3735, 060.5295, 230.3990.*
Methanol has a refractive index close to that of water. Their refractive indices are displayed in Fig. 1 along with the refractive index of silica calculated from a Sellmeier expression. The refractive indices of water and methanol are found from empirical Cauchy expressions \cite{7}, \( n = A + B/\lambda^2 \), with the fitted parameters (400-800 nm): methanol \( A = 1.29461 \pm 1 \times 10^{-5}, B = 12706.1 \pm 0.1 \text{mm}^2 \), water \( A = 1.3242 \pm 1 \times 10^{-5}, B = 3063.799 \pm 0.031 \text{mm}^2 \). The thermo-optic coefficient of methanol is dependent on the wavelength but can be found using the equation of Murphy and Alpert \cite{7}.

The methanol is infiltrated into the PCFs by immersing one end inside a pressure chamber with the other end outside. A 200 kPa overhead was applied for an hour, after which no bubbles were observed at the exit facet. The methanol is degassed 30 min in vacuum prior to infiltration to avoid the formation of air bubbles inside the PCF. The resulting spectra are seen in Fig. 1. The magnitude of the shifts clearly increases with the resonance wavelength. The resonance wavelengths are obtained by interpolating the transmission (on a linear scale) around the resonance dip with a second order polynomial. Large red shifts of 48, 72, 97, and 127 nm in the resonance wavelength are seen. With such large wavelength shift linearity can not be expected. The sensitivity itself increases with increasing refractive index. To obtain the correct sensitivities at a refractive index of the liquid we tune the refractive index by temperature through the thermo-optic coefficient of the liquid. The temperature response of the PCF-LPG with air in the holes is negligible, a mere \( \sim 6 \text{ pm/}^\circ\text{C} \) was measured.

The PCF-LPGs were mounted onto a heater stage with temperature control (MC60 & TH60, Linkam Scientific Instruments). The temperature was increased in steps up to \( 60^\circ\text{C} \). The refractive index of the methanol decreases with temperature, since the thermo-optic coefficient is negative (Table 1) thereby blueshifting the resonance wavelengths (Fig. 2). In each experiment the temperature was decreased to \( 30^\circ\text{C} \) to estimate the hysteresis. The hysteresis was 1.4, 0.4, 0.05, -1.0 nm, for \( \Lambda_G = 580, 620, 740, 820 \mu\text{m} \), respectively.

The sensitivity increases more than three times from the resonance wavelength 650 nm to 1050 nm, as seen in the inset of Fig. 2. We will allude to this dramatic increase in the following. It may also seem surprising that the resonance wavelength is redshifted rather than blueshifted when the methanol is infiltrated into the PCF-LPG. One would suspect that the cladding index was increased more than the core index, and that the resonance wavelength should be blue shifted according to the resonance condition. The supposed anomaly originates in the wavelength dependence of the effective indices. The wavelength dependence causes the resonance wavelength to decrease with increasing grating period as seen in Table 1. A consistent treatment of the resonance condition with the chain rule yields the surprising result for the resonant wavelength shift

\[
\Delta \lambda = \frac{\lambda_r}{n_{g,cl}} \frac{d (n_{g,cl} - n_{g,co})}{dn_r},
\]

where \( n_r \) is the refractive index of methanol and \( n_{g,cl} = n_i - \alpha \partial \phi n_i \) is the group index of mode \( i \). The group index mismatch, \( n_{g,co} - n_{g,cl} \), can be calculated from the resonance wavelengths and the grating period by

\[
\frac{d (n_{g,co} - n_{g,cl})}{dn_r} = \frac{\lambda_r}{\Lambda_G - \lambda_r \partial \phi (\lambda_r/\Lambda_G)},
\]

to obtain the curves in Fig. 3. Clearly, the group index mismatch is negative, and this accounts for the redshifting of the resonance wavelength for increasing refractive index, since \( \frac{d (n_{g,co} - n_{g,cl})}{dn_r} \) is negative giving an overall pos-

|  | Air | Methanol |
|---|---|---|
| \( \Lambda_G \) | \( \lambda_r \) | \( n_r \) | \( \frac{d \lambda_r}{dn_r} \) |
| 820 \( \mu\text{m} \) | 623 nm | 671 nm | 415 nm | 1.3228 | -4.067 \times 10^{-4} |
| 740 \( \mu\text{m} \) | 704 nm | 776 nm | 651 nm | 1.3157 | -3.977 \times 10^{-4} |
| 620 \( \mu\text{m} \) | 832 nm | 929 nm | 1140 nm | 1.3093 | -3.896 \times 10^{-4} |
| 580 \( \mu\text{m} \) | 923 nm | 1050 nm | 1460 nm | 1.3061 | -3.856 \times 10^{-4} |

TABLE I: Resonant wavelengths, \( \lambda_r \), and grating periods, \( \Lambda_G \). The resonant wavelengths for methanol filled PCF-LPGs and the corresponding material parameters \( n_r \) and \( \frac{d \lambda_r}{dn_r} \) for methanol at the resonance wavelengths.
itive sign. Using perturbation theory it is possible to derive an analytical expression for the sensitivity
\begin{equation}
\frac{d\lambda_r}{dn_r} \propto \frac{d(n_{co} - n_{cl})}{dn_r} \simeq \frac{2n_{co}}{n_r}(f_{u,co} - f_{u,cl}),
\end{equation}
where $f_{u,i}$ is the fraction of field inside the holes of the PCF of mode $i$. The fraction for the core and cladding mode has been calculated using a commercial implementation of the finite element method [10]. The fraction increases, as expected, with wavelength. The cladding fraction is much larger than the core fraction, Fig. 3. Thus the contribution to the wavelength shift exclusively determined by the perturbation the cladding mode.

It is enticing to design a LPG-PCF with as high sensitivity by adjusting the PCF structure. One such opportunity is obtaining group index matching, $n_{g,co} - n_{g,cl} \sim 0$, since the resonance wavelength shift is inversely proportional to this as mentioned earlier. Such a sensor could thus have extremely high sensitivity. Unfortunately, the full-width half maximum of the resonance dip also depends on the group index mismatch, and such a PCF-LPG will have very wide resonance dips [3]. Taking this fact into account it is still possible to enhance the sensitivity by designing the PCF structure.

The optimized PCF used by Phan Huy et al. [11] achieved an increase in sensitivity by two orders of magnitude with respect to a large core design. We anticipate that a similar increase could be realized for a PCF-LPG. Indeed, theoretical considerations predict a minimal detectable refractive index change of $10^{-7}$ RIU [9], comparable to the best surface plasmon resonance biosensors. This could lead to competitive PCF-LPG biosensors [12].

![Figure 3: The group index mismatch calculated from the resonance wavelengths and grating periods for air and methanol filled PCF-LPG. The field fraction as function of wavelength for the core and cladding mode.](image)

In conclusion, we have demonstrated highly sensitive refractometers in photonic crystal fiber with a long-period grating by infiltrating the fluid into the fiber. The sensitivity is increased by a factor of three from the resonance wavelengths 671 to 1050 nm.

We acknowledge Crystal-Fibre A/S [?] for providing the PCF.

[1] V. Bhatia and A. M. Vengsarkar, Opt. Lett. 21, 692 (1996).
[2] J. H. Chong, P. Shum, H. Haryono, A. Yohana, M. K. Rao, C. Lu, and Y. Zhu, Opt. Com. 229, 65 (2004).
[3] B. J. Eggleton, P. S. Westbrook, R. S. Windeler, S. Späler, and T. A. Strasser, Opt. Lett. 24, 1460 (1999).
[4] J. M. Fini, Meas. Sci. & Technol. 15, 1120 (2004).
[5] A. Yariv, IEEE J. Quant. Electron. QE-9, 919 (1973).
[6] Y. Zhu, P. Shum, J.-H. Chong, M. K. Rao, and C. Lu, Opt. Lett. 28, 2467 (2003).
[7] H. El-Kashef, Physica B 279, 295 (2000).
[8] X. W. Shu, L. Zhang, and I. Bennion, J. Lightwave Technol. 20, 255 (2002).
[9] L. Rindorf and O. Bang, Submitted (????).
[10] Http://www.comsol.com.
[11] M. C. P. Huy, G. Laffont, V. Dewynter-Marty, P. Ferdinandy, P. Roy, J.-L. Auguste, D. Pagnoux, W. Blanc, and B. Dussardier, Opt. Lett. 32, 2390 (2007).
[12] L. Rindorf, J. B. Jensen, M. Dufva, L. H. Pedersen, P. E. Hoiby, and O. Bang, Opt. Express 14, 8824 (2006).