5-2022

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Publication Information

Rana, Sohel; Kandadai, Nirmala; and Subbaraman, Harish. (2022). "Experimental Validation of a Reflective Long Period Grating Design Methodology". *Results in Optics, 7*, 100224. https://doi.org/10.1016/j.rio.2022.100224

Results in Optics 7 (2022) 100224

Contents lists available at ScienceDirect

Results in Optics

journal homepage: www.sciencedirect.com/journal/results-in-optics

Experimental validation of a reflective long period grating design methodology

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ARTICLE INFO

Keywords:
Long period grating
Temperature
Refractive index
Sensitivity

ABSTRACT

In this work, we present an experimental demonstration of our previously published modeling work on reflective long period grating (LPG). To provide the practical realization of the modeling work, we coat a long segment of fiber both in the tail length and the end facet beyond the gratings with silver to invert the transmission mode LPG to reflection mode LPG. We then measure the LPG characteristics in both the transmission and reflection mode and validate our findings from modeling work. We further build temperature and refractive index (RI) sensors and demonstrate temperature sensing from 21 °C to 191 °C with similar temperature sensitivity coefficients of 54.4 ± 2.9 pm/°C and 53.2 ± 2.6 pm/°C for transmission and reflection mode LPG, respectively whereas same RI sensitivity coefficient of 370 ± 2.2 nm/RIU.

1. Introduction

Long period gratings (LPG) are similar to fiber Bragg gratings (FBG) as in they have a periodic change in the refractive index (RI), but their grating period is much larger ranging between 100 and 1000 µm. LPGs works on the principle of light coupling from the core mode to a number of cladding modes and as a result, the transmission spectrum of an LPG shows a number of attenuation bands corresponding to coupling specific cladding modes (James and Tatam, 2003). The resonance wavelengths at which coupling occurs can be expressed by (James and Tatam, 2003)

$$\lambda_m = 2\left(n_{eff,co} - n^m_{eff,cl}\right)\Lambda \quad (1)$$

where λ_m is the resonance wavelength for m-th order cladding mode, m is the order of the cladding mode $n_{eff,co}$ is the effective refractive index of the guided core mode, $n^m_{eff,cl}$ s the effective refractive index of the m-th order cladding mode and Λ is the grating period. These attenuation bands are sensitive to any changes in external parameters such as temperature, strain, and refractive index (RI). While LPG based sensors compared to FBGs provide higher sensitivity to temperature and RI, their applications are limited in tight space or for remote sensing as they are transmissive mode sensors. To overcome these shortcomings associated with transmission mode LPG, several modifications of LPG designs have recently been reported that can convert the transmission mode sensor to a reflective mode (Qi et al., 2014;Jiang et al., 2009; Esposito et al., 2018) . Previous works showed that end metal coating a fiber by sputtering (Jiang et al., Sep. 2009), thermal evaporation (Qi et al., 2014), and Tollens' test (Esposito et al., 2018) converts the transmission mode LPG into a reflection one. However, none discussed the influence of coating length on the quality of the reflected spectrum. In our recent work, we modeled the effect of metal coating length on the LPG and showed that it has a significant effect on the reflected spectrum of the LPG (Rana et al., 2020). The modeling work reported that a coating length of 1450Λ (1450 × 390 µm = 56.55 cm) or greater for an LPG design centered around 1550 nm wavelength) is required to provide a reflection spectrum that exactly mimics the transmission spectrum. On the other hand, a coating length less than 56 cm either splits or makes the characteristics dips disappear, which has been utilized by other groups to develop sensors. While 56 cm or greater length is impractical for sensor deployment, an understanding of the effect of coverage and coating length on the spectrum quality is crucial for designers to understand, which we aim to provide here.

To support our modeling work in (Rana et al., 2020) and to enable a quick fabrication of the different coating lengths, we used a simple brush coating method to deposit silver as the coating material on two different LPG sensors but having different coating lengths (Rana et al., 2020). The experimental results show that while 60 cm of coating length provides a reflection spectrum that mimics the transmission spectrum, with a correlation factor exceeding 90%, the dips in the reflection spectrum either splits or shifts for a coating length of 1 cm (Rana et al., 2020), which

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https://doi.org/10.1016/j.rio.2022.100224
Received 2 February 2022; Received in revised form 21 February 2022; Accepted 24 February 2022
Available online 26 February 2022

advocates the findings of our modeling work in (Rana et al., 2020).

In this work, we coat an LPG with a grating period of 280 μm using a simple and cost-effective brush coating method in similar way described in our previous work (Rana et al., 2020) to realize a reflection mode LPG. The effect of coating length on the spectrum of reflective LPG is investigated by both in simulation and experiment. We also demonstrate that in order to achieve the same performance as a transmission LPG sensor, a reflection LPG with a coating length of at least 56 cm is necessary (Rana et al., 2021). We furthermore measure temperature and RI using the same LPG but both in transmission and reflection mode of operation and compared their sensitivity.

2. Experimental setup and results

We used commercially available LPG with a grating period of 280 μm and LPG length of 10 mm from TECHNICA. The reflected LPG was obtained by coating the tail end of the LPG using brush coating method detailed in (Rana et al., 2020). The coating length and the coating thickness of the reflective LPG were 60 cm and 6 ± 0.6 μm, respectively. Per our modeling, we first varied the coating length on the LPG. Fig. 1 shows a schematic of a reflective LPG showcasing three scenarios- 100% (full coating length), 50% coating length and end facet coating or tip coating (0% coating length) (represented by arrows). The experimental setup to record the reflection spectrum is shown in Fig. 2. The transmission spectrum from uncoated LPG was measured using a superluminescent diode (SLD) source (SM Benchtop SLD source, Thorlabs) and an optical spectrum analyzer (OSA, MS9740A, Anritsu). Please note that transmission spectrum was always measured before applying metal coating the LPG. In order to measure the reflected spectrum from coated devices, an optical circulator was added to this setup. We connected port 1 of the optical circulator (6015-3-FC - Fiber Optic Circulator, Thorlabs) to the SLD light source, port 2 to the coated LPG device, and port 3 to the OSA. The effect of coating length on the reflection spectrum is shown in Fig. 3 (a) numerically and Fig. 3(b) experimentally. For our modeling work (Rana et al., 2020), we used commercially available FIMMWAVE software, a fully vectorial mode solver. We considered a grating period of 280 μm and SMF-28 fiber's parameters. It was found from the simulation results that the core mode couples to the $LP_{0,7}$ cladding mode within the wavelength range 1460–1580 nm. It can be seen from both simulation and experimental results in Fig. 3 that when the coating was applied only at the tip of the 60 cm length fiber beyond the grating, the reflection spectrum (red color) looks like an interferometric fringe. However, when the coating length was increased to 50% (30 cm), the depth of the dip around 1500 nm in the reflection spectrum (yellow color) started to increase. However, one can see from the experimental result that the spectrum for 50% coating length also demonstrate interferometric fringes similar to tip coating although a small dip can be seen around 1500 nm. The possible reason might be the insufficient absorption of cladding mode within the coated metal providing additional interferometric fringes at other wavelengths. The reflection spectrum (purple color) followed the transmitted spectrum (blue color) only when the coating was applied to the full 60 cm length of the fiber. Since the core

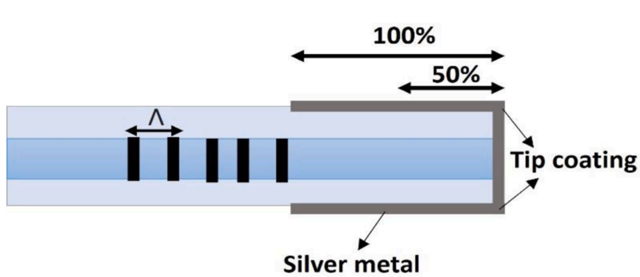

Fig. 1. Schematic of different coating length on LPG contained fiber.

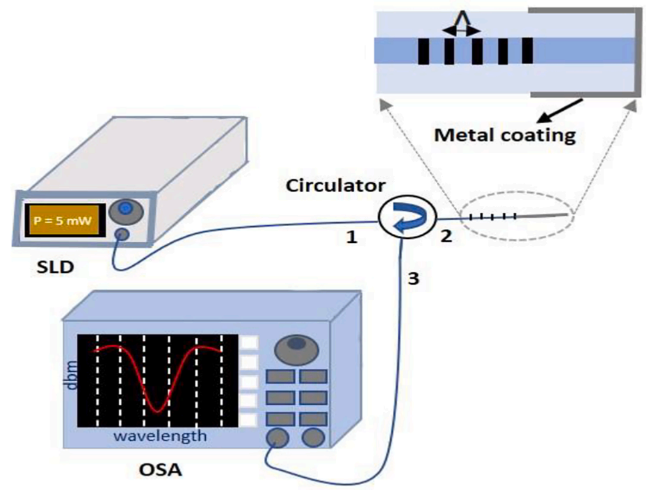

Fig. 2. Experimental setup to record the reflected spectrum from the coated reflective LPG (1,2 and 3 indicate the circulator port number).

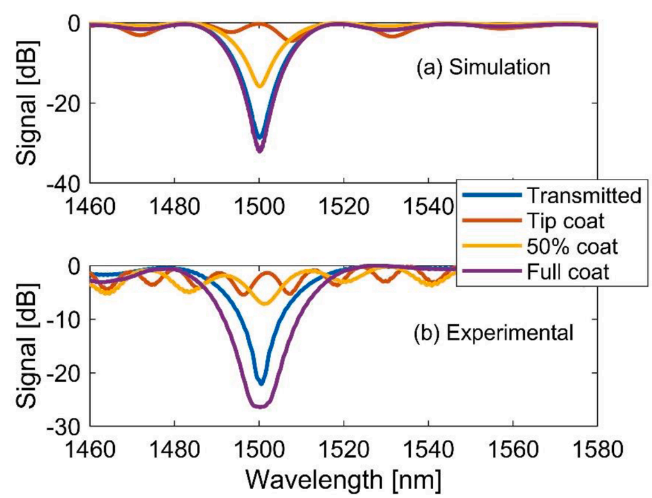

Fig. 3. Effect of coating length on the reflection spectrum of the LPG: (a) simulation results and (b) experimental results.

mode travels twice into the grating and the metal coating itself absorbs light, the reflection light for 100% coating length shows reduced intensity compared to the transmission light. Based on these results, it can be said that the coating effect on the reflection spectrum follow the same trend observed through simulations. This effect of coating length on the reflection spectra supports our modeling work in (Rana et al., 2020). To demonstrate how good a fully reflective LPG compares to its transmissive LPG counterpart, we also used our coated LPG as a sensor to measure temperature between 21 and 191 °C and for RI sensing of a water/glycerol solution. We compared the results from our reflected LPG against uncoated transmitted LPG.

2.1. Temperature sensing

The effect of temperature on LPG can be found by partially differentiating the Eq. (1) with respect to temperature and can be expressed as (Bhatia, 1999)

$$\frac{d\lambda_m}{dT} = \frac{d\lambda_m}{d(\partial n_{eff})}\frac{d(\partial n_{eff})}{dT} + \frac{d\lambda_m}{d\wedge}\frac{d\wedge}{dT} \quad (2)$$

where T is the temperature and $\partial n_{eff} = n_{eff,co} - n^m_{eff,cl}$ is the differential effective refractive index. Equation (2) consists of two parts: the first term on the right-hand side denotes the material contribution and the second term indicates the waveguide contribution to the thermally induced shift. To realize the temperature sensitivity of the transmission mode and reflection mode LPG sensors, we used a controllable hot plate to heat the LPG section from 21° to 191 °C with a step of 2 °C/min. We also placed a k-type thermocouple at the interface of gratings and hot-plate for measurement accuracy. We saved the data at every 20 °C interval. Fig. 4 shows the relative shift in the resonance wavelength of the LPG. The red circles in Fig. 4 represent the experimental data and blue line is a first order polynomial fitting to these data points. It can be seen that the resonance wavelength shows a redshift with increasing temperature since the effective refractive indices of the core and the cladding increase with temperature. However, the core RI changes more compared to the cladding one due to the presence of germanium dopants in the core. We found that for the transmission mode LPG results shown in Fig. 4(a), the resonance wavelength shift was 9.25 nm, leading to a temperature sensitivity coefficient (S_T) of 54.4 ± 2.9 pm/°C. The obtained sensitivity coefficient for the reflection mode LPG data in Fig. 4 (b) is 53.2 ± 2.6 pm/°C which is very close to the transmission mode LPG case. For both cases, the sensitivities are larger than short period gratings (Bhatia, 1999; Bhatia, 1996; Khaliq et al., 2002; Bhatia and Vengsarkar, 1996). Since we used the coating on a commercially available LPG from TECHNICA, there was no room for modifying structural parameters except coating the fiber and measuring the parameters. As a results, the sensitivity of the our LPG is smaller compared to reported works in (Bhatia, 1999; Bhatia and Vengsarkar, 1996; Zhang, 2020). However, the temperature sensitivity can be increased in several ways reported in (Biswas et al., 2015; Bhatia, 1996; Khaliq et al., 2002; Bhatia and Vengsarkar, 1996). It can also be seen in Fig. 4 that the resonance wavelength change with temperature is not linear, and this non-linearity can be attributed to temperature dependent thermo-optic coefficient of the core and the cladding (Handbook of Glass Properties, 1986). This non-linearity is insignificant for several practical applications since the wavelength shift versus temperature curve can follow a second or a higher order polynomial relationship. However, this non-linear behavior may limit the performance of LPG sensor when simultaneous strain and temperature measurements are performed.

2.2. Refractive index sensing

Next, we used the metal coated LPG to sense the RI of water/glycerol solution. The solution was prepared by mixing glycerol with de-ionized water with various concentration ratios and their corresponding RIs taken from (Jiang et al., 2009). We carried out the RI measurement at a constant room temperature. Eq. (1) suggests that the increment of cladding RI reduces the RI difference between the core and the cladding which in turns provides a blueshift of resonance wavelength. When the LPG was placed in a water/glycerol solution, the RI of the surrounding medium around the cladding increases, which ultimately increases the RI of the cladding modes. It is expected that the resonance wavelength would give a blueshift when the LPG is immersed into the solution. We increased the concentration of glycerol from 0% to 70% and recorded the spectrum. The relative wavelength shift as a function of RI is shown in Fig. 5. The red circles indicate experimental data and blue line shows the second order polynomial fitting for these data points. It can be seen that the resonance wavelength provides blueshift with increasing RI. In both transmission mode and reflection mode LPG, the resonance wavelength provides a blueshift of 3.7 nm when the RI changed from 1.33333 (10% solution concentration) to 1.42789 (70% solution concentration), leading to a sensitivity of 370 ± 2.2 nm/RIU, which is large compared to FBG based RI sensor (Osório et al., 2017). It is known that when the RI of the surrounding medium becomes comparable to the cladding RI, the resonance wavelength shows a significant shift (Tsuda and Urabe, 2009) which is seen for the 70% glycerol concertation in the solution. The reason is that at 70% concentration of glycerol, the RI of the solution (1.42789) becomes comparable to the RI of the cladding (1.444). Since we carried out the RI experiment on a commercial LPG sensor, with no room for modifying any structural parameters, the reported RI sensitivity of our sensor is smaller

compared to (Qi et al., 2014; Jiang et al., 2009; Zhang, 2020). However, like temperature sensitivity, several methods can be employed to enhance the RI sensitivity which includes introducing sensitive doping material (Jiang et al., 2009), coupling to higher order or TAP modes (Biswas et al., 2015; Li, et al., 2016) and thinning the cladding diameter (Li, et al., 2016; Yang et al., Aug. 2006). Please note that this work is the extended version of our previous work reported in (Rana et al., 2021).

As the spectral dependence of each coupled mode to the external parameters is different, multi-parameters can be sensed using a single LPG. Although the temperature sensitivity coefficient of the LPG sensor is one order magnitude higher than the FBG sensor (Bhatia, 1999; Khaliq et al., 2002; Bhatia and Vengsarkar, 1996), it has several limitations. As LPG contains a broad dip compared to the Bragg peak of FBG, it makes it difficult to detect the dip. Moreover, LPGs are very sensitive to bends

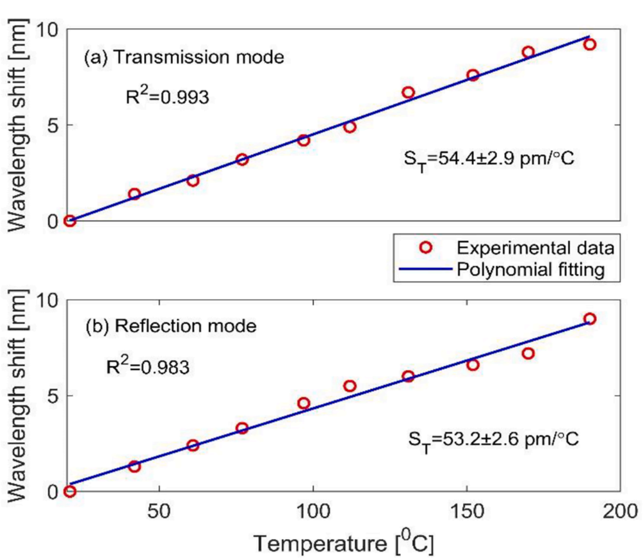

Fig. 4. The measured relative wavelength shifts of LPG as a function of temperature: (a) transmission mode LPG and (b) reflection mode LPG.

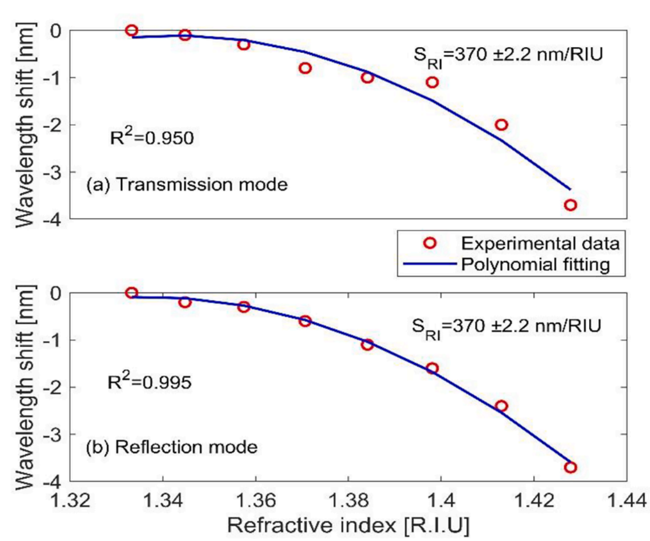

Fig. 5. The measured relative wavelength shift of LPG as a function of RI: (a) transmission mode LPG and (b) reflection mode LPG.

and refractive index changes that may induce an error in temperature measurement. Additionally, multiple resonance dips along with a wide spectrum can limit their multiplexing capabilities.

3. Conclusions

In conclusion, we have shown experimentally the effect of coating length on the reflection spectrum of LPG to validate our previously published modeling work. While short coating length is more practical and expected, we tried to show the coating effect to validate our modeling work which can aid designers in choosing appropriate coating lengths for their structures. In addition, we measured the temperature and RI using the same LPG but in both transmission mode and reflection mode and compared their corresponding sensitivity coefficients. We found similar sensitivity coefficients both in the transmission mode and the reflection mode LPG. This is the first demonstration of an experimental comparison between the transmission and the reflection mode LPG.

Funding

This work was performed using faculty start-up funds of Prof. Subbaraman and Prof. Kandadai. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We thank Prof. Kurtis Cantley for allowing us to use his programmable hot plate for temperature sensing experiments.

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