Temperature insensitive high-precision refractive-index sensor using two concatenated dual-resonance long-period gratings

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In this Letter we report on fabricating and analyzing a temperature insensitive refractometer based on two concatenated dual-resonance long-period gratings (LPGs) with an appropriate inter-grating space (IGS) in between. The IGS provides a temperature-dependent extra phase difference between the core and cladding modes, making the refractometer similar to a Mach–Zehnder interferometer with its arms phase shifted. We demonstrate that an appropriate IGS can produce temperature-insensitive resonance wavelengths. The interferometer is highly stable over a wide range of temperature (20°C–100°C). The measured refractive index sensitivity for aqueous solutions (1.333–1.343) is ~2583 nm/RIU, which is the highest reported so far for biological samples. The interferometer can be used for various other temperature-immune sensing applications also.

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Being a fundamental material property, an accurate and simple measurement of refractive index (RI) is of prime importance in both the scientific and industrial sectors. Recently, photonic biosensors capable of measuring extremely small changes in the RI of biological samples have received considerable attention, and a number of optical platforms based on long-period gratings (LPGs), surface-plasmon polariton (SPP), and microstructured fibers have been investigated [1–3]. Although these sensors are highly sensitive (1000–2000 nm/RIU), often a precise determination of RI needs temperature isolation/calibration, since the RI of biological/chemical samples and the waveguide regions changes with temperature.

Over the past few years, a number of innovative ways to facilitate temperature compensation, like combining FBGs with LPGs in optical waveguides [4], cascaded LPGs in double cladding fiber [5], $\pi/2$ phase shifted dual-resonance LPG (DRLPG) [6], etc., have been suggested. All of these schemes, however, rely on measuring the response for two parameters and retrieving the desired response using a 2×2 matrix that increases the complexity of detection system. Other methods involve suitably chosen cladding and core materials with opposite thermo-optic coefficients [7] and an overall coating of sensor with a suitable composite material [8] to compensate for the temperature-induced wavelength shifts. The requirement of custom-made fibers in the former increases the cost of the sensor while the extra coating in the latter reduces the RI sensitivity. Further, often an attempt to increase RI sensitivity also ends up in increased temperature sensitivity. A simple, accurate, and cost-effective temperature-insensitive RI sensor would definitely be preferred over the above mentioned sensor schemes.

Recently, we analyzed various concatenated LPGs with suitable inter-grating space (IGS) to obtain a tunable WDM channel isolation filter [9] and an extremely high RI sensor [6]. Cascaded LPGs have also been used in realizing low threshold optical switching [10] and filter action [11] etc. In this Letter, we present a simple, cost effective, temperature-insensitive, ultrasensitive RI sensor based on two concatenated DRLPGs with a suitable IGS between them (Fig. 1). The IGS provides an extra phase difference between the core and cladding modes, making the sensor similar to a Mach–Zehnder interferometer with both of its arms phase shifted. We show that by adjusting the length of the IGS, temperature-induced phase changes in the grating regions can be compensated with that in the IGS. As a result, the device can be made temperature insensitive at a certain wavelength, without affecting the RI sensitivity of the structure.

In our experiments, we first fabricated several photosensitive LPGs in hydrogen loaded SMF-28 (Corning, New York, 14831, USA), using a chromium amplitude mask ($\Lambda = 226.8$ μm) and KrF excimer laser (Lumonics

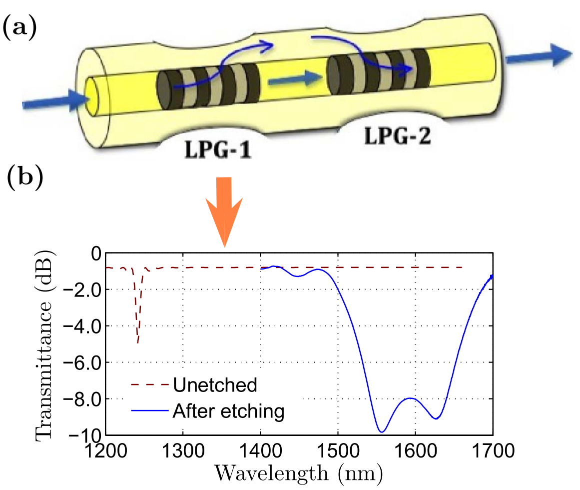

Fig. 1. (a) Schematic diagram of the sensor structure. (b) Transmission spectrum of single LPG.

Lasers: Pulse Master-840) emitting at 248 nm at a pulse repetition rate of 100 Hz, pulse duration of 12 ns, and peak pulse energy of 10 mJ. The grating length is 5 cm. The LPGs were then annealed at 150°C for~4 h to release the excess hydrogen, stabilizing their optical properties. The LPGs so fabricated had a single resonance wavelength (λ_R) near 1245 nm. To obtain the dual resonance, we slowly etched the cladding of the fiber in 4% HF acid for ~3 h. This shifted the λ_R close to its turning point (λ_D) ~1.595 μm [Fig. 1(b)]. The typical RI and temperature sensitivities, recorded for the lower λ_R (= 1557 nm), are 1837 nm/RIU and 0.95 nm/°C and for the upper λ_R (= 1627 nm) are 2464 nm/RIU and 1.03 nm/°C, respectively. A pair of LPGs with identical transmission spectrum were then selected and spliced axially with varying IGS inbetween them. The sensor was finally passed through a heating tube filled with water to measure its temperature response.

Bends across the sensing region were avoided by maintaining a constant tension throughout the experiments by fixing the fiber near one end of the LPG to a stationary stage and applying a fixed force near the other end of it. Light was launched into the fiber using an Agilent-83437A broadband source and transmission spectrum was recorded using an Agilent-86142B optical spectrum analyzer and Agilent-N1031A BenchLink Lightwave application software having a spectral resolution of 10 pm.

In Fig. 2, we have plotted the transmission spectrum for three different temperatures ($T = 40$°C, 50°C, and 60°C) recorded for (a) an IGS (ℓ) = 18 cm and (b) IGS (ℓ) = 21 cm, with a wavelength resolution of 0.05 nm. In order to ensure temperature stabilization, the sensor was kept at fixed temperatures for ~20 min before taking observations. Compared to the sensitivity of a single DRLPG (1.03 nm/°C), Fig. 2(a) shows a reduced temperature sensitivity of 0.17 nm/°C at $\lambda = 1627$ nm for IGS (ℓ) = 18 cm. Increasing ℓ further to 21 cm, we observe in Fig. 2(b) nearly temperature insensitive minima (maxima) above 1627 nm (initial resonance minima of single DRLPG), most prominently for transmission minima at 1650 nm. In Fig. 2(c), we have plotted the variation of reference minima near 1650 nm for $\ell =$ 21 cm as a function of temperature using a wavelength resolution of 0.02 nm, which shows a temperature sensitivity of −0.45 pm/°C, a reduction by a factor of 4×10^4 compared to 1.03 nm/°C obtained for a single DRLPG (Fig. 1). Increasing ℓ even further resulted in a unilateral red shift with increasing temperature. This behavior has been shown in the inset of Fig. 2(c) where we have plotted the measured resonance wavelength shift ($\Delta\lambda$) corresponding to the maxima/minima near 1650 nm for different ℓ, for a temperature increase of 20°C, which shows that a complete temperature insensitivity is possible near $\ell \sim 20.7$ cm. Next, we varied the ambient RI of the sensor and traced the 1650 nm reference minima over the biologically relevant ambient RI range of 1.333–1.343, which has been plotted in Fig. 2(d), the slope being 2583.3 nm/RIU. An increase in the RI sensitivity for sensors incorporating IGS can be attributed to the fact that for the current measurements, the resonance (reference) wavelength (1650 nm) is slightly higher than that of the single DRLPG (1627 nm), leading to an increased cladding mode evanescent field in the ambient region. The RI sensitivity can be further improved by (i) reducing the grating period to couple the power to even higher order cladding modes and (ii) operating the gratings near λ_D to enhance the spectral shift.

To understand the origin of temperature insensitivity theoretically, we consider an optical fiber with core and cladding regions made of 4.1 mol. % GeO_2 doped SiO_2 and fuzzed SiO_2, respectively, their radii (r_c and r_{cl}) as 4.1 and 62.5 μm, respectively, and ambient RI as 1.333. The overall transmission of the sensor basically depends upon two factors: (i) the phase matching within the

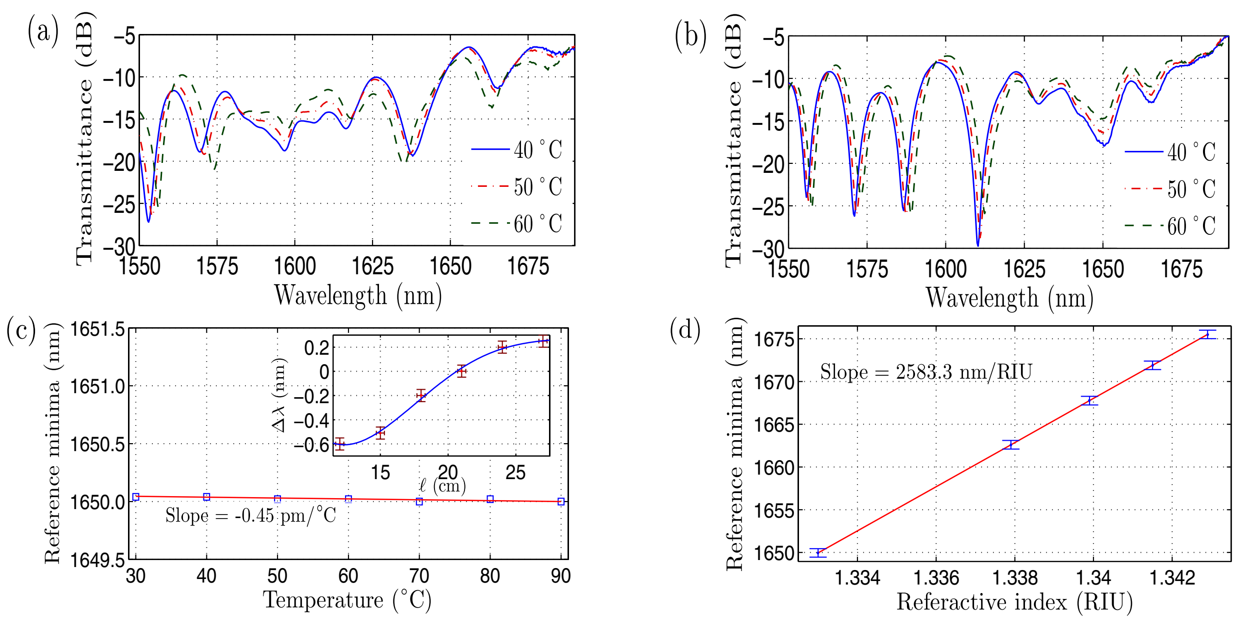

Fig. 2. Experimental transmission spectrum for (a) $\ell = 18$ cm and (b) $\ell = 21$ cm. Variation of reference minima near 1650 nm, for $\ell = 21$ cm, as a function of (c) temperature and (d) ambient RI. The spectral shift, corresponding to maxima/minima near 1650 nm, for different ℓ is shown in the inset of (c) for a temperature increase of 20°C.

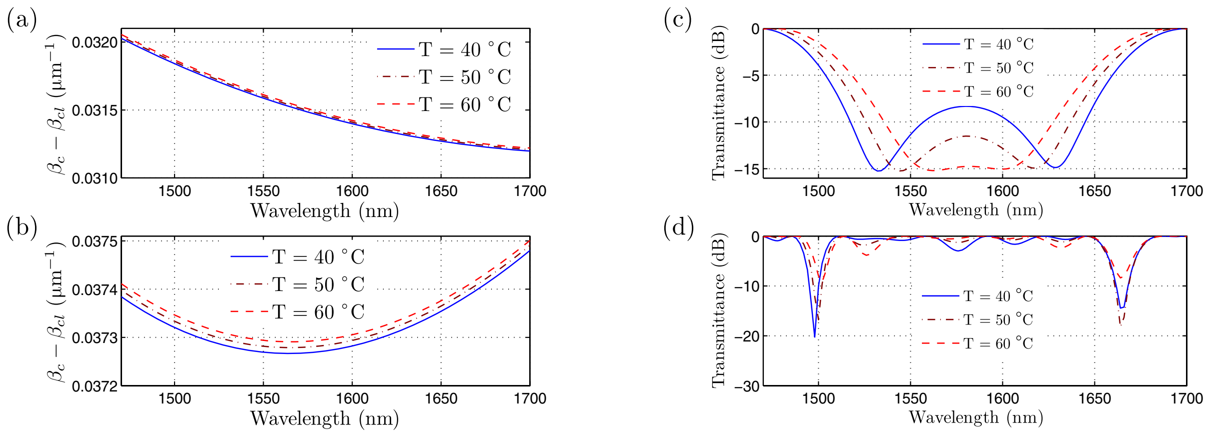

Fig. 3. Spectral variation of the propagation constant difference between the core mode and the cladding mode ($\beta_c - \beta_{cl}$) in the (a) unetched region ($r_{cl} = 62.5$ μm) and (b) etched region ($r_{cl} = 55$ μm) of optical fiber. Theoretical transmission spectrum employing (c) single LPG in etched fiber and (d) concatenated LPGs in etched fiber separated by an unetched IGS ($\ell = 5$ cm). The ambient region is taken as water (r.i. = 1.333) throughout the calculations.

grating regions (which are used to excite and recouple cladding mode back to the core mode) and (ii) modal interference within the IGS region. Both of these factors are governed by the propagation constant difference between the core and cladding modes ($\Delta\beta = \beta_c - \beta_{cl}$). The transmitted field amplitudes of core and cladding modes (A_c and A_{cl}) are obtained using

$$\begin{bmatrix} A_c \\ A_{cl} \end{bmatrix} = T_{\mathrm{LPG}} \times \begin{bmatrix} e^{i\beta_c \ell} & 0 \\ 0 & e^{i\beta_{cl} \ell} \end{bmatrix} \times T_{\mathrm{LPG}} \times \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad (1)$$

where T_{LPG} is the transfer matrix of LPG [6, 12]. In Fig. 3 we have plotted the spectral variation of $\Delta\beta$, considering LP_{010} cladding mode for an (a) unetched cladding ($r_{cl} = 62.5$ μm) and (b) etched cladding ($r_{cl} = 55$ μm). Figure 3(b) shows the λ_D near 1570 nm, with a negative slope of $\Delta\beta$ versus λ curve for $\lambda < \lambda_D$ and a positive slope for $\lambda > \lambda_D$. The opposite slopes of $\Delta\beta$ versus λ curve give rise to opposite spectral shifts for the resonance minimum of LPG written in etched fiber, supporting the dual resonance [6, 12]. Figure 3(a) on the other hand shows a unilateral negative slope over the entire wavelength range. For $\lambda > \lambda_D$ the spectral shifts introduced by an unetched IGS region, therefore, counteract the spectral shifts induced by the LPGs. At an appropriate ℓ, the two spectral shifts completely nullify each other, producing temperature insensitive maxima/minima [similar to Fig. 2(b)]. To show this behavior theoretically, we first plot, in Fig. 3(c), the transmission spectrum of a single LPG (etched). The grating strength, period, and length have been taken as 4.4×10^{-5}, 166.8 μm, and 4 cm, respectively. Finally, in Fig. 3(d) we plot the transmission spectrum of concatenated DRLPGs in etched fibers ($r_{cl} = 55$ μm) separated by an IGS of 5.2 cm in unetched fiber. Temperature insensitive minima (for $\lambda > \lambda_D$) induced by the IGS are obtained at 1663 nm. Using known LPG parameters, therefore, an appropriate ℓ can be calculated using Eq. (1). For unknown LPG parameters, on the other hand, ℓ can be interpolated from the values of IGSs of sensors showing opposite sensitivities for $\lambda > \lambda_D$.

In conclusion, in this Letter we have proposed and demonstrated a simple, accurate, cost effective, temperature-insensitive, highly sensitive RI sensor based on two concatenated DRLPGs with an appropriate IGS in between. Over a certain wavelength, the thermally induced phase changes in the grating regions are compensated by that of the IGS, enabling an overall temperature insensitivity. Based on this, we have shown a considerable reduction in the temperature sensitivity of DRLPG based sensors.

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