Optik 122 (2011) 2147–2150

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Optimal design of temperature-insensitive long period fiber gratings for athermal refractive-index sensor

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ARTICLE INFO

Article history:
Received 10 September 2010
Accepted 6 February 2011

Keywords:
Long-period fiber grating
Temperature-insensitive
Athermal refractive-index sensors

ABSTRACT

Based on coupled-mode theory of long-period fiber grating (LPFG), a theoretical analysis and simulations for the optimal design of a temperature-insensitive LPFG is presented in order to achieve an athermal condition for sensing the refractive index of the external medium. Effects of the variation of the cladding radius and grating period on the temperature sensitivity of the LPFG are discussed. Both of these parameters are found to be important to control the temperature sensitivity when the thermo-optic coefficients of core and cladding materials are of the same order. Other grating parameters are also optimized in order to achieve a good contrast of the grating period with resonance wavelength in the 1.5 μm region and to sense the external medium refractive index over a wide range. Variation of external medium refractive index from 1.0 to 1.45 results a red-shift in the LPFG resonance wavelength by 86 nm with its temperature sensitivity as low as 0.008 nm/°C over a temperature range of 0–80 °C for this optimally designed LPFG.

1. Introduction

Long-period fiber grating (LPFG) devices have attracted considerable interest in recent years in the fields of optical communication and sensors. Recently a number of such devices have been proposed and experimentally demonstrated in different fields, such as biochemical sensing, hydrogen detection, strain detection, concentration and temperature measurements [1–5], etc.

An LPFG couples light which propagates as a core mode into the cladding modes inducing transmission losses at resonance wavelengths. As the resonance wavelength of the grating depends on various physical and chemical parameters of the external surrounding medium such as strain, temperature, refractive-index, etc., such property of the LPFG can be used for sensing these quantities [6–8]. However, for a practical LPFG sensor, it is very important to separate the combined effect of these quantities. For example, for the measurement of refractive-index using LPFG, the resonance wavelength shift due to temperature variation, cladding modes materials and grating period, etc. must be optimized. To eliminate this effect and to avoid the use of a precise and sophisticated temperature controller unit, an optimization of grating parameters in which the core and cladding materials having different thermo-optic coefficients, has been reported [9].

In this paper, a detail numerical analysis has been made in order to design a temperature-insensitive and parameter optimized (core and cladding material, cladding radius and grating period, etc.) LPFG for realized an athermal refractive-index sensor. In order to achieve a good contrast for the wavelength region near 1.5 μm and to eliminate the effect of temperature dependence of the grating, the design is optimized by proper choice of the grating parameters. Analysis for the effect of the grating parameters on the temperature dependency of the LPFG resonance wavelength is also included. Optimization is focused on (i) eliminating the effect of ambient temperature changes on the grating resonance wavelength, (ii) period and cross-coupling coefficient of grating, (iii) cladding modes radius for increasing sensitivity of the surrounding refractive-index.

2. Theory

We first consider the transmission spectrum of a LPFG, relationship between the resonance wavelength and the temperature changes. An LPFG can be formed by introducing a periodic modulation of the refractive-index with a period of several hundred micrometers along the core of a silica fiber (Fig. 1). The transmission spectrum of a typical LPFG consists of a number of rejection bands that arise from light coupling form the guided mode (the LP_{01} mode) to the cladding modes (the LP_{0m} mode with $m = 2, 3, 4, \ldots$) of the fiber. The wavelength λ_m at which such resonance coupling takes place is given by [10]

$$\lambda_m = \Lambda \left(n_{co}^{eff} - n_{cl,m}^{eff} \right) \quad (m = 1, 2, 3, \ldots) \tag{1}$$

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0030-4026/$ – see front matter © 2011 Published by Elsevier GmbH.
doi:10.1016/j.ijleo.2011.02.002

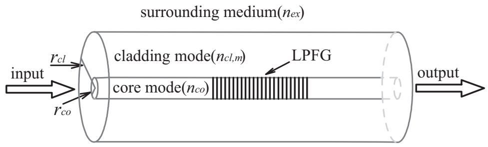

Fig. 1. Long-period fiber grating schematic diagram.

where n_{co}^{eff}, $n_{cl,m}^{eff}$ are the effective indices of the core mode and cladding mode, and Λ is the period of the grating, respectively. The temperature sensitivity of the LPFG can be expressed as

$$\frac{d\lambda_m}{dT} = \lambda_m \cdot \gamma_m \cdot (\alpha + \Gamma_m) \tag{2}$$

where α (∼0.5–10^{-6}/°C) is the thermal expansion coefficient of the silica fiber, on which the LPFG is written. γ_m are the waveguide dispersion factor of the LPFG and is given by

$$\gamma_m = \frac{d\lambda_m/d\Lambda}{\left(n_{co}^{eff} - n_{cl,m}^{eff}\right)} \tag{3}$$

and Γ_m shows the waveguide temperature sensitivity factor of the LPFG and is expressed as

$$\Gamma_m = \frac{C_{co}n_{co}^{eff} - C_{cl}n_{cl,m}^{eff}}{n_{co}^{eff} - n_{cl,m}^{eff}} \tag{4}$$

where C_{co} and C_{cl} are the thermo-optic coefficients of the core and the cladding respectively. Eq. (2) shows the temperature sensitivity of the LPFG, related to and the grating period, and gradient of the $d\lambda_m/d\Lambda$, and the thermo-optic coefficients and the effective indices, etc. factor, respectively.

Then we consider the refractive-index sensing, the transmission spectrum, the temperature sensitivity of the resonance wavelength loss peak amplitude value of the LPFG, which can be obtained from a standard coupled-mode theory. The result can be expressed as [11]

$$\frac{dP}{dT} = \frac{kL\sin(2kL)}{I}\left(\frac{dI}{dT} - \frac{I}{\lambda_m}\frac{d\lambda_m}{dT}\right) = \frac{kL\sin(2kL)}{I} \times \left[\left(\eta_{co}\frac{\partial I}{\partial n_{co}} + \eta_{cl}\frac{\partial I}{\partial n_{cl}}\right) + \left(\frac{\partial I}{\partial \lambda_m} - \frac{I}{\lambda_m}\right)\frac{d\lambda_m}{dT}\right] \tag{5}$$

where P and L are the loss peak amplitude value and the length of the LPFG, respectively, k is the cross-coupling coefficient, I is the mode field ψ_{01} of core mode LP_{01}, and the mode field ψ_{0m} of the cladding mode LP_{0m}, in the core region overlap integral. I and k can be expressed as

$$I = \frac{\int_0^{2\pi}\int_0^{r_{co}} \psi_{01}\psi_{0m} r dr d\varphi}{\left(\int_0^{2\pi}\int_0^{+\infty} \psi_{01}\psi_{01} r dr d\varphi\right)^{1/2}\left(\int_0^{2\pi}\int_0^{+\infty} \psi_{0m}\psi_{0m} r dr d\varphi\right)^{1/2}} \tag{6}$$

$$k = \frac{\pi \Delta n_{co}^{eff} I}{\lambda} \tag{7}$$

where Δn_{co}^{eff} is modulated of the refractive index.

According to Eq. (5), in general, $d\lambda_m/dT$ and dI/dT are of opposite signs. When λ_m decreases (increases), the overlap integral increases (decreases), because the LP_{01} mode confinement in the core increases (decreases) with the decrease (increase) in λ_m. However, whether the grating strength increases or decreases as the temperature changes also depends on the value of kL because of the periodic function sin(2kL). It is also important to note that from Eq. (5) the magnitude of the temperature sensitivity of the grating strength is amplified by the factor kL. While the same grating strength can be achieved with many possible values of kL, the smaller value of kL gives the smaller temperature sensitivity in the grating strength. When $kL = q\pi/2$ (q = 1, 2, 3, ...), the temperature sensitivity ability vanishes also when $kL = (2q-1)\pi/4$ (q = 1, 2, 3, ...), the temperature sensitivity tends to be maximum.

Thirdly, we consider the resonance wavelength shift values of an LPFG. In order to circumvent the difficulty of handling a three-medium case, we approximate the grating as a coreless waveguide in which the core radius goes to zero. This is good approximation because $r_{co} \ll r_{cl}$. In that case, the resonance wavelength shift [12] can be described as

$$\Delta\lambda = \frac{u_\infty^2 \lambda_m^3 \Lambda}{8\pi^3 n_{cl} r_{cl}^3}\left(\frac{1}{\sqrt{n_{cl}^2 - n_{co}^2}} - \frac{1}{\sqrt{n_{cl}^2 - n_{ex}^2}}\right) \tag{8}$$

where u_∞ are Bessel functions, Eq. (8) shows the resonance wavelength shift ($\Delta\lambda$) as a function of ambient refractive-index (n_{ex}), and in inverse proportional to cubic of the cladding mode radius (r_{cl}), and in direct proportional to biquadrate of the grating period (Λ). Therefore, ambient refractive index can be measured, when grating period and optical fiber material are known, the cladding mode radius (r_{cl}) decreases, resonance wavelength shift ($\Delta\lambda$) increases.

According to Eqs. (2), (5) and (8), temperature sensitivity of the LPFG, when the material (namely: optical fiber), and the grating period (Λ), the cladding mode radius (r_{cl}) and kL, etc. are properly chose, we can make the temperature sensitivity minimum.

3. Simulations results and discussions

A core with Ge-doping [13] (refractive index: 1.467 at 25 °C, λ: 1.55 μm, thermo-optic coefficient: 1.26×10^{-5} °C^{-1}), and with cladding parameters in the brackets (refractive index: 1.446 at 25 °C, λ: 1.55 μm, thermo-optic coefficient 1.22×10^{-5} °C^{-1}), have been considered for the simulations. The refractive index of the external medium varies from 1.00 to 1.45 under test, whereas the temperature is varied from 0 to 80 °C in the simulation. It is noteworthy to mention that the temperature sensitivity of the LPFG resonance wavelength [Eq. (2)] is applicable to both the LP_{01} and LP_{0m} modes, although there two polarization lead to a similar qualitative result with a quantitative difference. Therefore, in this study, the coupling between the fundamental guided-mode and the first higher-order cladding-mode is considered only for the LP_{0m} polarization.

3.1. Phase-matching curves

The phase-matching curves as Fig. 2 shows, is for various LP_{0m} modes of the LPFG considering r_{co} = 3.25 μm, r_{cl} = 62.5 μm, periodicity N = 50, and with the CO_2 pulsed laser writing the LPFG. A relationship among the resonance wavelength for various LP_{0m} (m = 1, 3, 5, ...) with the corresponding grating period been studied from this graph. It is observed that the slopes $d\lambda/d\Lambda$ of the curves are positive for all the modes, the grating resonance wavelength increases with the increases of the grating period. Further, the values of the slopes for the modes are different, whose magnitude is found to be increasing with the increase of the mode order. However, in this study, attention has been focused only on the interaction between fundamental core-mode and first order cladding-mode for the reason which is discussed previously, and the parameters are chosen accordingly.

3.2. Effect of cladding radius on LPFG temperature sensitivity

The temperature sensitivity and the resonance wavelength shift of the LPFG such as Fig. 3 shown, with the variation of the period and the cladding radius separately, keeping other parameters unchanged. It is observed that the temperature sensitivity of