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Optimal design of silica-based temperature-insensitive long-period waveguide gratings for realization of athermal refractive-index sensor

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Abstract

Based on silica-on-silicon planar technology, a theoretical analysis for the optimal design of a temperature-insensitive long-period waveguide grating (LPWG) is presented in order to achieve an athermal condition for sensing the refractive index of an external medium. Effects of the variation of the core and over-cladding thickness on the temperature sensitivity of the LPWG formed in the above material 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 same order. Other grating parameters are also optimized in order to achieve a good contrast of the notch filter having a resonance wavelength near 1.5 μm region and to sense the external medium refractive index over a wide range. Variation of external refractive-index value from 1.00 to 1.45 causes a blue-shift in the LPWG resonance wavelength by 99 nm with its temperature sensitivity as low as 0.004 nm/°C over a temperature range of 0–50 °C, for this optimally designed LPWG.

Keywords: Long-period waveguide grating (LPWG); Silica-on-silicon; Planar waveguide; Athermal refractive-index sensor; Temperature-insensitive

1. Introduction

Long-period waveguide grating (LPWG) based devices have attracted considerable interest in recent years in the field of optical communication and sensor application because of the flexibility in their structure and material as compared to the long-period fiber gratings. In addition, LPWGs have advantages in the field of optical integrated circuits and for mass production capability. Recently a number of such devices have been proposed [1–3] and experimentally demonstrated [4,5] using different materials and waveguide structures for the purpose of expanding the functionalities of long-period fiber gratings (LPFG).

An LPWG couples light that is propagating 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 like strain, temperature, refractive index, etc., the property of the LPWG can be used for sensing these quantities [6]. However, for a practical LPWG sensor, it is very important to separate out the combined effect of these quantities. For example, for the measurement of refractive index using LPWG, the resonance wavelength shift due to temperature variation must be eliminated. To eliminate this effect and to avoid the use of a precise and sophisticated temperature controller unit, an optimization of grating parameters comprising core and cladding materials having different thermo-optic coefficients, has been reported [7].

In this paper, a detail numerical analysis has been made in order to design a silica-on-silicon material (where core and cladding thermo-optic coefficients are of same order) based LPWG for realizing an athermal refractive-index sensor. In order to achieve a good contrast of the LPWG-based notch filter near the wavelength region of 1.5 μm and to eliminate the effect of temperature dependence of the grating resonance wavelength, the design is optimized by proper choice of the waveguide and

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grating parameters. Analysis and results are also included to describe the effect of the waveguide and grating parameters on the temperature dependency of the LPWG resonance wavelength. Attention is focused on silica-on-silicon material because of (i) its good compatibility to standard communication optical fibers exhibiting low insertion loss, (ii) coupling between the fundamental core-mode and only one or two higher order cladding-modes with an effective cross-sectional area of the structure that is comparable to a standard single-mode fiber, and (iii) relatively low waveguide birefringence property.

2. Theory

LPWG-based device consists of a higher-index partially corrugated guiding layer with a relatively lower-index over-cladding and under-cladding layers. Fig. 1 shows a schematic diagram along with the refractive-index profile of the LPWG with a grating period of Λ formed along the core of the channel waveguide with corrugation depth of h. $n_{\rm co}$, $n_{\rm ocl}$, $n_{\rm ucl}$, and $n_{\rm ex}$ are considered to be the refractive indices of the core, over-cladding, under-cladding and external medium, respectively, where $n_{\rm co} > n_{\rm ocl} \geq n_{\rm ucl} > n_{\rm ex}$. Thickness of the core, over-cladding and under-cladding are considered as $t_{\rm co}$, $t_{\rm ocl}$ and $t_{\rm ucl}$, respectively. By use of the coupled mode theory [8], for a grating period of Λ, the resonance wavelength of the LPWG can be obtained as

$$\lambda_{\rm m} = (N_{\rm o} - N_{\rm m})\Lambda \tag{1}$$

depending on the coupling between the forward propagating fundamental guided-mode and various co-propagating higher order cladding modes, where $N_{\rm o}$ and $N_{\rm m}$ ($m = 1, 2, 3, \ldots$) are the effective indices of the fundamental guided-mode and that of the higher order cladding modes, respectively.

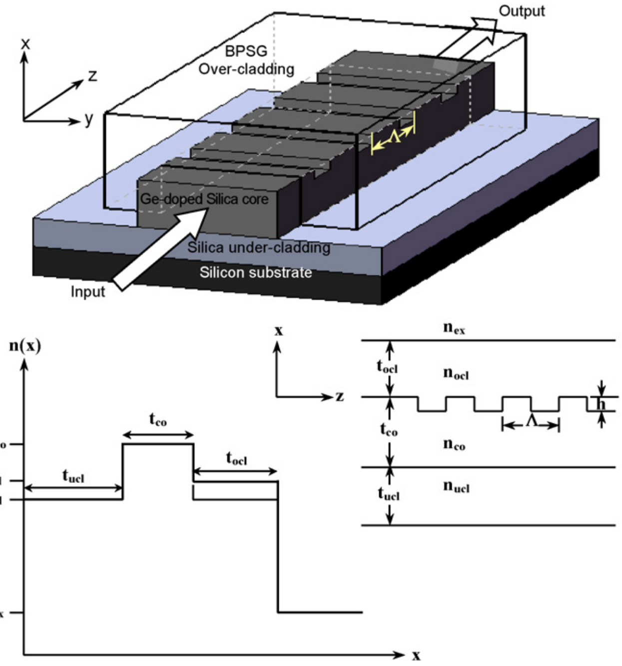

Fig. 1. A basic schematic of an LPWG structure and its refractive-index profile.

From the phase matching condition of the LPWG [governed by Eq. (1)], it is clear that the temperature sensitivity of its resonance wavelength depends on both the change in refractive index of the waveguide material with temperature, as well as the change in the grating period due to thermal expansion coefficient of waveguide. Therefore, the temperature sensitivity of the LPWG resonance wavelength can be explained as

$$\frac{{\rm d}\lambda_{\rm m}}{{\rm d}T} = \left(\frac{{\rm d}N_{\rm o}}{{\rm d}T} - \frac{{\rm d}N_{\rm m}}{{\rm d}T}\right)\Lambda + (N_{\rm o} - N_{\rm m})\frac{{\rm d}\Lambda}{{\rm d}T} \tag{2}$$

As the thermal expansion coefficient of Ge-doped silica (core material, in this study) is almost one order less compared to its thermo-optic coefficient [9], the second term of Eq. (2) can be neglected. Again, the refractive index of the core, over-cladding and under-cladding layers at any particular temperature, T, can be written as

$$\left.\begin{aligned} n_{\rm co}(T) &= n_{\rm co}(T_{\rm o}) + C_{\rm co}\Delta T \\ n_{\rm ocl}(T) &= n_{\rm ocl}(T_{\rm o}) + C_{\rm ocl}\Delta T \\ n_{\rm ucl}(T) &= n_{\rm ucl}(T_{\rm o}) + C_{\rm ucl}\Delta T \end{aligned}\right\} \tag{3}$$

where $T_{\rm o}$ is a reference temperature, $\Delta T = T - T_{\rm o}$ and $C_{\rm co}$, $C_{\rm ocl}$ and $C_{\rm ucl}$ are the thermo-optic coefficients of the core, over-cladding and under-cladding, respectively, i.e.,

$$\left.\begin{aligned} C_{\rm co} &= \frac{\partial n_{\rm co}}{\partial T} \\ C_{\rm ocl} &= \frac{\partial n_{\rm ocl}}{\partial T} \\ C_{\rm ucl} &= \frac{\partial n_{\rm ucl}}{\partial T} \end{aligned}\right\} \tag{4}$$

Assuming the values of $C_{\rm co}$, $C_{\rm ocl}$ and $C_{\rm ucl}$ are independent of temperature and taking into account the model dispersion factor [10], Eq. (2) can be rewritten as,

$$\begin{aligned} \frac{{\rm d}\lambda_{\rm m}}{{\rm d}T} \cong \Lambda \Bigg[\Bigg\{ &\left(\frac{\partial n_{\rm co}}{\partial T}\right)\left(\frac{\partial N_{\rm o}}{\partial n_{\rm co}}\right) + \left(\frac{\partial n_{\rm ocl}}{\partial T}\right)\left(\frac{\partial N_{\rm o}}{\partial n_{\rm ocl}}\right) \\ &+ \left(\frac{\partial n_{\rm ucl}}{\partial T}\right)\left(\frac{\partial N_{\rm o}}{\partial n_{\rm ucl}}\right) - \left(\frac{\partial n_{\rm co}}{\partial T}\right)\left(\frac{\partial N_{\rm m}}{\partial n_{\rm co}}\right) \\ &- \left(\frac{\partial n_{\rm ocl}}{\partial T}\right)\left(\frac{\partial N_{\rm m}}{\partial n_{\rm ocl}}\right) - \left(\frac{\partial n_{\rm ucl}}{\partial T}\right)\left(\frac{\partial N_{\rm m}}{\partial n_{\rm ucl}}\right)\Bigg\} \\ &+ \left(\frac{{\rm d}N_{\rm o}}{{\rm d}\lambda} - \frac{{\rm d}N_{\rm m}}{{\rm d}\lambda}\right)\frac{{\rm d}\lambda_{\rm m}}{{\rm d}T}\Bigg]. \end{aligned}$$

$$\begin{aligned} \frac{{\rm d}\lambda_{\rm m}}{{\rm d}T} = \Lambda \Bigg[&C_{\rm co}\left(\frac{\partial N_{\rm o}}{\partial n_{\rm co}}\right) + C_{\rm ocl}\left(\frac{\partial N_{\rm o}}{\partial n_{\rm ocl}}\right) + C_{\rm ucl}\left(\frac{\partial N_{\rm o}}{\partial n_{\rm ucl}}\right) \\ &- C_{\rm co}\left(\frac{\partial N_{\rm m}}{\partial n_{\rm co}}\right) - C_{\rm ocl}\left(\frac{\partial N_{\rm m}}{\partial n_{\rm ucl}}\right) - C_{\rm ucl}\left(\frac{\partial N_{\rm m}}{\partial n_{\rm ucl}}\right) \\ &+ \left(\frac{{\rm d}N_{\rm o}}{{\rm d}\lambda} - \frac{{\rm d}N_{\rm m}}{{\rm d}\lambda}\right)\frac{{\rm d}\lambda_{\rm m}}{{\rm d}T}\Bigg] \end{aligned} \tag{5}$$

Considering the grating-corrugation at the interface between the core and the over-cladding layer (as shown in the device structure), the coupling between the fundamental guided-mode and higher order over-cladding modes has been considered. However, the term developing a similar effect at the core and