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Control of resonant peak depths of tunable long-period fiber gratings using overcoupling

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We present a method to reduce changes in the resonant peak depth of a long-period fiber grating (LPFG) as the resonant band is tuned by varying the external refractive index. We theoretically analyze the effects of the initial coupling strength on the peak depth change as external refractive index is varied. By controlling the initial coupling strength, it is experimentally demonstrated that an optimum peak depth can be obtained over a range of operating wavelengths that will maximize the sensitivity and stability of LPFG based sensors and tunable filters.

1. Introduction

Adding tunable functionalities to optical devices has become a general trend to meet versatile needs in practical applications. The trend also has been applied to optical fiber gratings. In particular, long-period fiber grating (LPFG)-based sensors and tunable filters have received constant attention due to their excellent environmental sensitivity [1–4]. One of the most attractive tuning or sensing mechanisms for LPFG-based devices is to utilize an LPFG's intrinsic sensitivity to changes in the external refractive index (RI). The tuning efficiency of such devices can be amplified by varying the fabrication parameters, and true electro-optic tuning is feasible by using proper materials. Several methods for amplifying an LPFG's sensitivity to the external medium have been successfully demonstrated, including fiber cladding thinning [5,6] and the deposition of a second cladding or overlay [7]. With a reduced cladding thickness, the interaction between the cladding modes and the ambient medium becomes stronger, which leads to higher sensitivity to changes in the external refractive index [5,6]. The enhanced sensitivity to the ambient medium is a promising route to high speed electro-optic tunable LPFG filters. True electro-optic tuning, which had been prohibited for LPFG devices until recently due to electro-optically inactive silica cladding, was demonstrated with an electro-optic second cladding layer [8,9].

When the resonant wavelength peaks shift with the increasing ambient RI, they also experience a change in transmission depth. Such a phenomenon has been experimentally observed, and practical LPFG-based devices relying on external RI changes to invoke tuning are vulnerable to the peak depth changes. Although this peak reduction is undesirable in terms of maintaining a required level of isolation for filtering, signal processing, and reading of sensors, its importance has been generally overlooked as the focus has been given to monitoring the magnitude of the peak wavelength shift. The peak depth change problem needs to be addressed for the ambient RI range over which the LPFG is most sensitive since this is the range of RIs that will maximize device performance.

In this paper, the peak depth dependence on the external RI change is theoretically analyzed using coupled-mode theory (CMT) and a three-layer model [10]. A novel method for controlling the peak depth based on overcoupling is then proposed and experimentally demonstrated. Unlike another recently reported method for maintaining an LPFG's peak depth, the method considered in this paper does not rely on a thin, high RI indium tin oxide (ITO) overlay [11]. Instead, the LPFG is overcoupled during fabrication so that it will have a stable peak depth over its working range of external RIs. Without the addition of an overlay, the overcoupling method is simpler to implement and requires less fabrication steps than the aforementioned technique. In this paper, we only consider the single resonant peak present in the output sprectrum of a cladding-thinned three-layer LPFG. However, the validity of the method can be generally applied to other LPG-based devices.

2. Theory

The cladding modes involved in the mode coupling of LPFGs have oscillating fields in the cladding and evanescent tails in the

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external medium. Through the evanescent wave interaction, the effective refractive indices of the cladding modes are changed with the external RI change, which causes the resonant peak shift by the phase matching condition, $\lambda_{res}=(n_{co}^{eff}-n_{cl}^{eff})\Lambda$, where $\lambda_{res}$is the resonance wavelength, $n_{co}^{eff}$and n_{cl}^{eff} are effective refractive index of the core mode and the cladding mode, respectively, and Λ is grating period. Fig. 1 shows a simulation result of the change in the resonant spectrum of an LPFG in different ambient RIs. The corresponding grating parameters are core radius $a=4.15$ μm, cladding radius $b=20$ μm, core RI $n_1=1.4504$, cladding RI $n_2=1.4447$, grating period $\Lambda=450$ μm, grating length $L=20$ mm, and induced index perturbation normalized to n_1 $\sigma=1.7\times10^{-4}$. The single resonant peak in the spectra shown in Fig. 1 is a consequence of the wider spacing between available cladding modes in their dispersion curves due to the reduced cladding thickness. The resonant peak shifts to shorter wavelengths as the ambient RI increases. Note that the peak depth decreases with the blue shift of the resonant wavelength. As the ambient index is changed from 1.0 to 1.444, the peak depth is reduced from ~−20dB to ~−4dB. The peak depth reduction is more significant in the region of high sensitivity where the external RI is slightly smaller than that of the cladding. The guide line in Fig. 1(b) (vertical dotted line) is the lower bound of the high sensitivity region and the horizontal dotted line indicates the corresponding transmission dip. This peak reduction is a result of the change in the coupling strength due to the ambient RI change, as we will see.

The power cross-transmission (core to cladding) of an LPFG for two mode coupling is given by Eq. (1) [12].

$$t_{\times}=\frac{1}{1+\hat{\sigma}^2/\kappa^2}\sin^2\left(L\sqrt{\kappa^2+\hat{\sigma}^2}\right) \quad (1)$$

where $\hat{\sigma}$ is the general self coupling coefficient, L is the grating length, and κ is the cross-coupling coefficient given by Eq. (2).

$$2\kappa=\frac{\omega\varepsilon_0 n_1^2\sigma v}{2}\iint_{core} dxdy\ e_{co}(x,y)\cdot e_{cl}^{*}(x,y) \quad (2)$$

where v is the fringe visibility of the index change, and $e_{co}(x,y)$ and $e_{cl}(x,y)$ are core and cladding mode profiles, respectively.

As can be seen in Eq. (1), with $\hat{\sigma}=0$ at the resonant wavelengths, the power transfer reaches the maximum and becomes $\sin^2(\kappa L)$. With $\kappa L=\pi/2$, complete power transfer occurs. Note that the cross-coupling coefficient κ in Eq. (2) is dependent not only on the induced index perturbation σ, but also on the cladding mode field profile, $e_{cl}(x,y)$, which changes with the external RI. When the external RI approaches that of the cladding, cladding modes are less confined in the cladding and the evanescent tails spread out into the ambient medium due to weaker guiding effect. This leads to the reduction of κ and to the reduction of the peak depth according to Eq. (1) [13].

Fig. 2 shows 2κ divided by σ as a function of the ambient RI for the mode coupling between the core mode and the HE_{12} cladding mode at 1.5 μm and 1.6 μm. The cross-coupling coefficient rapidly decreases in the most sensitive range of the external RI, which explains the rapid decrease of the peak depth in Fig. 1. In rejection filter applications, any reduction that causes the peak depth to fall below a required minimum isolation level is unacceptable. For sensing applications, large fluctuations in output signal level require wide dynamic range of detector circuitry and make sensor reading and signal processing more complicated. Nevertheless, using the most sensitive range of the external RI is still necessary to maximize the tuning efficiency and sensitivity of the sensors.

The most common practice for fabricating LPFGs is to obtain grating strength with slight undercoupling or critical coupling in air ambient. However, it's not a good strategy in terms of maintaining the

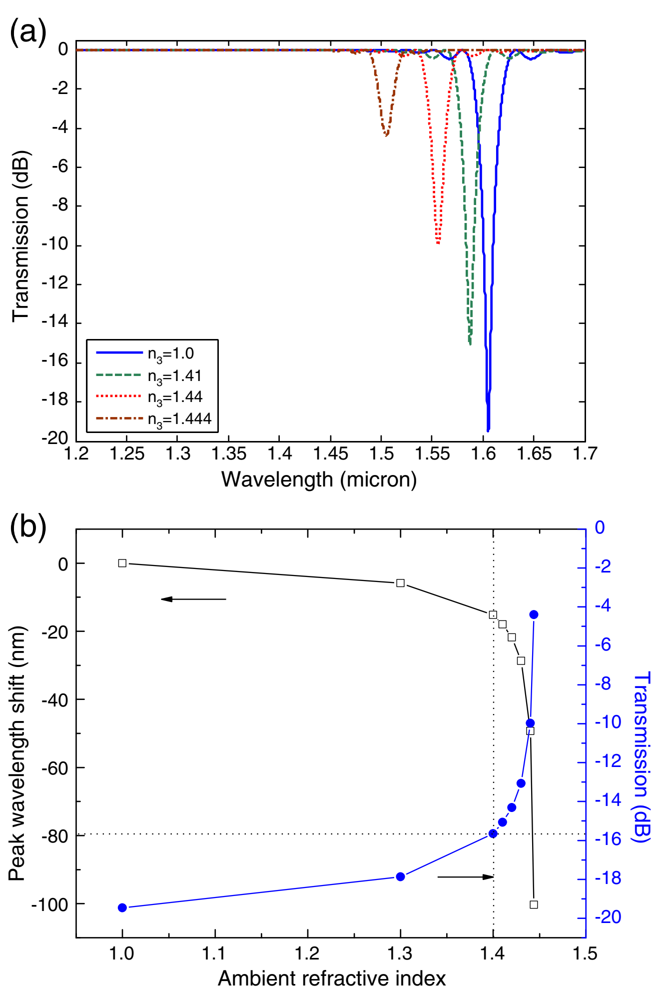

Fig. 1. (a) the calculated resonant spectrum change of a LPFG ($\sigma=1.7\times10^{-4}$) for several different ambient refractive indices, (b) the peak wavelength shift and the peak depth change versus ambient refractive index change for the LPFG in (a). the dotted lines in (b) are guide lines indicating the start of the most sensitive region and the corresponding transmission depth. As the external refractive index increases, the peak depth rapidly decreases with blue shift of the resonant wavelength.

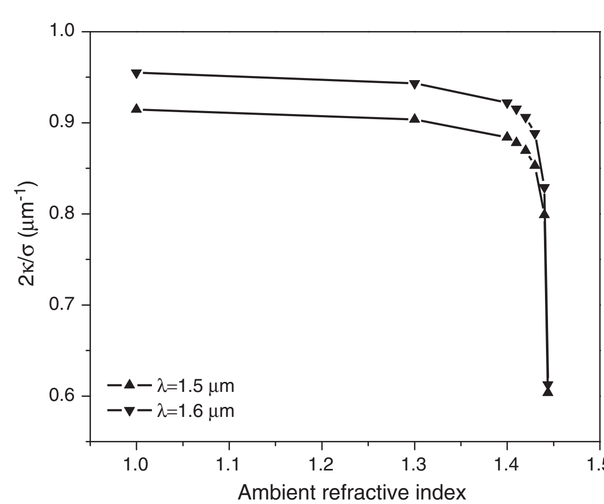

Fig. 2. The change of normalized cross-coupling coefficient versus ambient refractive index at two different wavelengths, 1.5 μm and 1.6 μm.