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Numerical analysis of refractive index sensitivity of long-period gratings in photonic crystal fiber

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Abstract

The modal coupling properties and resonance spectral response of long-period gratings (LPGs) in index-guiding photonic crystal fiber (PCF) are numerically investigated with respect to its sensitivity to changes in the index of refraction of the measurand in the PCF air channels using a full-vectorial mode solver combined with frequency-domain method. We show that the shift of wavelength resonance of a PCF-LPG structure can be extremely sensitive by appropriately designing the cladding air-channel dimension and geometry as well as the periodicity of the LPG inscribed in an endlessly single mode PCF (ESM-PCF-LPG). Specifically, a sensitivity of 4.3×10^{-8} refractive index unit (RIU) can be obtained in a refractive index range of 1.33 and 1.4 using an ESM-PCF-LPG with hexagonally arrayed 4-ring air channels at the grating periodicity of 1300 μm. A sensitivity of 4.1×10^{-7} RIU can be achieved in the range of 1.0–1.25 employing an ESM-PCF-LPG with similarly arrayed but 5-ring air channels at the grating periodicity of 350 μm. The predicted index sensitivity, coupled with other schemes for selectivity and specificity, opens the ESM-PCF-LPG structure for a variety of sensing and detection applications.

Keywords: Photonic crystal fiber; Long-period grating; Fiber Bragg grating; Fiber-optic refractive index sensor; Refractometer

1. Introduction

Abbe refractometers, typically with a sensitivity of about 10^{-5} refractive index unit (RIU), are perhaps the most commonly used refractometers nowadays. They are based on the measurement of the refractive index of a liquid or solid by determination of changes in the angle of total internal reflection in conjunction with the use of a high-index prism with which the material of interest is in direct contact. Fiber-optic-based refractometers have been increasingly explored for the interrogation of index of refraction changes of gas or liquid medium due to many advantages such as high sensitivity, immunity to electromagnetic interference, accessibility to harsh and hostile environment, small size, and cost-effectiveness. Listed in Table 1 are performance parameters of a variety of fiber-optic refractometers documented in the open literature [1–15]. Typical schemes include surface plasmon resonance (SPR) with a multimode fiber (MMF) [1], fiber Fabry-Perot interferometer (FFPI) formed by a fiber Bragg grating (FBG) [2], tapered optical fiber [3], thinned FBG [7], whispering-gallery mode (WGM)-based microcavity (MC) [10], D-shape optical fiber Bragg grating [12], FBG [8], and long-period gratings (LPG) in photonic crystal fiber (PCF) [15], among others. These schemes reply principally on the evanescent field effect, which requires close proximity of the measurand to the lightguiding core with (in the case of SPR) or without metallic nanostructures. While fiber-optic refractometry presents an attractive platform for index measurements, the use of conventional all-solid fiber for refractive index sensing needs the removal, physically or chemically, of the cladding in order to reveal the fiber core for exposure to the measurand, compromising device reliability. In addition, both sensitivity and resolution are limited due to inherently small power overlap of evanescent mode with the measurand. Although the FBGs and LPGs in conventional optical fibers represent a significant advance for fiber-optic index measurements by monitoring the shifts of resonance wave-

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Table 1
Performance parameter of current fiber-optic refractometers

Sensor type	Detecting range of refractive index	Sensitivity (RIU/pm)	Reference
SPR-D-MMF	1.40–1.44	1.9×10^{-6}	[1]
	Above 1.44	5.7×10^{-7}	
FBG-FFPI	1.33324–1.33476	1.4×10^{-5}	[2]
Cladded and tapered-MMF	1.36–1.46	$<10^{-4}$	[3]
FBG	1.455 at 839 nm	1.4×10^{-5}	[4]
	1.445 at 980 nm	4×10^{-6}	
Tapered-SMF	1.37–1.40	5×10^{-4}	[5]
MMI-fiber	1.33–1.45	5.4×10^{-5}	[6]
	1.38–1.45	3.3×10^{-5}	
Thinned-FBG	Close to 1.333	$\sim10^{-4}$	[7]
	Close to 1.45	$\sim10^{-5}$	
PCF-FBG	2-Ring of air channel at 1550 nm: 1.33	7×10^{-4}	[8]
	2-Ring of air channel at 1550 nm: 1.44	2×10^{-5}	
	Six air channels at 1550 nm: 1.33	4×10^{-3}	
	Six air channels at 1550 nm: 1.44	6.8×10^{-6}	
SPR-fiber	Close to 1.333	3.35×10^{-4}	[9]
	Close to 1.398	4.99×10^{-5}	
WGM-MC	1.3330–1.3614	1×10^{-4}	[10]
MMF-SMF-MMF	Close to 1.45	7×10^{-5}	[11]
D-FBG	1.33–1.44	5×10^{-4}	[12]
Tapered-PCF	>1.440	$\sim10^{-5}$	[13]
LPG	1.330–1.426	2.1×10^{-5}	[14]
LMA-PCF-LPG	1–1.44	1.4×10^{-5}	[15]
ESM-PCF-LPG	1–1.44	1.3×10^{-4}	[15]

length of the gratings, their susceptibility to cross-sensitivity of temperature requires the addition of temperature compensation schemes for measurement accuracy. As shown in Table 1, the sensitivity of most fiber-optic refractometers to date ranges from 10^{-4} to 10^{-6} RIU, depending on the refractive index range.

PCF, also termed microstructured fiber or holy fiber, is a pure silica fiber containing an array of axially aligned air channels in the cladding region along the entire fiber length. Light guide in the core of PCF is either via total internal reflectance (index-guiding) in the case of a solid core [16] or through bandgap confinement in the case of a hollow core [17,18]. The open air channels allow liquid or gas measurand to be transported and brought to intimate contact with the waveguiding core of a solid-core PCF without any material removal as in the case of the conventional optical fiber, making PCF a potentially robust platform for evanescent field sensing over the entire fiber length. A drawback for index-guiding PCFs in practice is the small overlap between the fundamental core mode and the first ring of air channels surrounding the solid core. Typically less than 1% of the core mode's power is localized in the air channels [19] due to the limit in achievable air fill ratio (also related to the silica web thickness between adjacent air channels) using existing fiber fabrication technique.

LPGs consist of periodical refractive index modulation that satisfies the phase-matching condition between the fundamental core mode and the forward propagating cladding modes of a single mode fiber. The coupled co-propagating cladding modes in an LPG are rapidly attenuated, giving rise to a series of loss bands rather than a counter-propagating core mode like FBGs. LPGs have a competitive advantage over FBGs in that they are relatively easy to fabricate. They can generate well-isolated resonance that can be made highly sensitive to various measurands by proper selection of the cladding mode for coupling. An LPG written in an ESM-PCF used as a refractometer eliminates the cross-sensitivity to temperature perturbation because of dopant-free PCF (based solely on pure silica) [15].

In this paper, we report a numerical analysis of modal coupling properties and resonance wavelength of LPGs in endlessly single mode PCF (ESM-PCF) in response to changes in refractive indices of the medium contained in the cladding air channels. A full-vectorial mode solver combined with frequency-domain method is used for the analysis. The ESM-PCF-LPGs refractive index sensitivities are determined. We predict extremely high sensitivity (∼ppb) of select ESM-PCF-LPG structures by design optimization of the cladding air-channel geometry and arrangement of PCF as well as the periodicity of the LPGs.

2. Numerical model

The ESM-PCF-LPG refractometry scheme with high-index sensitivity is based on the noticeable dispersion of the fundamental core mode $\partial n^{\mathrm{eff}}_{\text{co-m}}(n_{\mathrm{co}}, n_{\mathrm{cl}}, \lambda)/\partial\lambda$ and the ith cladding mode $\partial n^{\mathrm{eff}(i)}_{\text{cl-m}}(n_{\mathrm{cl}}, n_{\mathrm{sur}}, \lambda)/\partial\lambda$ in the grating when measurand is present in the air channels, where $n^{\mathrm{eff}}_{\text{co-m}}(n_{\mathrm{co}}, n_{\mathrm{cl}}, \lambda)$ and $n^{\mathrm{eff}(i)}_{\text{cl-m}}(n_{\mathrm{cl}}, n_{\mathrm{sur}}, \lambda)$ are the effective refractive indices of the fundamental core mode and a given cladding mode; n_{co} and n_{cl} are the refractive indices of the core and cladding; λ is wavelength in free space; and n_{sur} is the refractive index of surrounding medium. In the case of conventional optical fiber, the change in the effective refractive index of the cladding mode with wavelength is almost constant while only a small change in