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Electrically tunable long-period fiber gratings with low-birefringence liquid crystal near the turn-around point

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ABSTRACT

In this work, an electrically tunable long-period fiber grating (LPFG) coated with liquid crystal layer (LC) is presented. As a LC layer, a prototype low-birefringence 1550A LC mixture was chosen. As a LPFG host, two types of gratings were studied: the LPFGs based on a standard telecommunication fiber, produced by an electric arc technique with a period of 222 μm, and the LPFGs based on a boron co-doped fiber written by a UV technique with a period of 226.8 μm. The relatively short period of these gratings allowed exploiting unique sensing properties of the attenuation bands associated with modes close to the turn-around point. Experiments carried out showed that for the UV-induced LPFG with a LC layer, on the powered state the attenuation band could be offset from the attenuation band measured in the unpowered state by almost 130 nm. When the arc-induced LPFG was coated with the LC, the depth of the attenuation band could be efficiently controlled by applying an external E-field. Additionally, all experimental results obtained in this work were supported by the theoretical analysis based on a model developed with Optigrating v.4.2 software.

1. Introduction

The development of a long-period fiber grating (LPFG) has had a significant impact on research and optical communications network and fiber optic sensing system. Compared to other optical devices, LPFGs have several unique advantages such as low-level back-reflection, low insertion losses and a compact construction (the grating is an intrinsic fiber device) [1–5]. LPFGs can be found in a variety of applications in optical communications such as gain-flattening filters for erbium-doped fiber amplifiers (EDFAs) [1], wavelength division multiplexing (WDM) systems [2], and wavelength-selective optical fiber polarizer components [10,11]. LPFGs could also be successfully incorporated into a fiber-optic sensing system, since they provide a mechanism for producing a wavelength-dependent attenuation in the transmission spectrum which can be controlled by external effects [3,4].

The LPFG is a structure made by periodic (typically with period Λ of 100 to 700 μm) modulation of refractive index within the core of a single-mode optical fiber. The modulation induces coupling between the core mode (LP_{01}) and the co-propagating symmetric cladding modes (LP_{0m}, $m=2, 3, 4\ldots$), resulting in the emergence of a series of resonance attenuation peaks in a LPFG's transmission spectrum. These resonant wavelengths λ_{res}^{m} are defined by:

$$\lambda_{res}^{m} = (n_{eff,co} - n_{eff,cl}^{m})\Lambda, \quad (1)$$

where $n_{eff,co}$ and $n_{eff,cl}^{m}$ are the effective refractive indices of the fundamental core mode and mth cladding mode, respectively. The value of $n_{eff,cl}^{m}$ dependent upon the refractive index (RI) of the external medium n_{ext} [4] (increase of n_{ext} increases $n_{eff,cl}^{m}$). Thanks to this feature, changes in the n_{ext} can be simply detected by measuring the shift of the resonant wavelength in the LPFG transmission spectrum. This effect gets stronger when n_{ext} is closer to that of the cladding (typically made of fused silica), however, it does not occur when it is higher than RI of the fiber clad [3]. To overcome this limitation, the LPFGs coating with a high-refractive index (HRI) layer where presented [4]. They provide the shift of the highest RI sensitivity range towards its lower values. Such modification depends on layer thickness and its optical properties, mainly RI. Moreover, if the layer material selected is sensitive to a specific parameter, highly sensitive and specific devices can be obtained, including, e.g., a chemo-sensors and bio-sensors [6,7]. LPFG sensitivity can be also enhanced greatly if the grating period and layer RI are optimized in a way to operate at a point called turn around point (TAP)

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on phase matching curves of these gratings. Thus, a generation of dual resonant bands, which shows sensitivities of the opposite sign, can be observed in the LPFG transmission spectrum. TAP LPFGs are well known for their ultrahigh sensitivity to external parameters [8–10].

The sensing properties of LPFGs can be also improved by merging them with liquid crystals (LC). LCs are self-organized anisotropic materials that exhibit high electro- and thermo-optic effects associated with their birefringence, their dielectric anisotropy and thermal dependence of their RIs [11–15]. Consequently, LPFGs combined with LCs, known as LC-LPFGs, have been seen as promising structures for creating a new platform for tunable fiber devices; e.g., thanks to the electro-optical properties of the LC materials, the LC-LPFG will demonstrate electric sensitivity in addition to the sensitivities of the grating itself.

One of the first examples of LPFG tuning by using LC was demonstrated by Duhem et al. [16]. They proposed a modulation of the attenuation band intensity based on the electrical switching of a nematic liquid crystal (NLC) around a photoinduced LPFG. Yin et al. presented a device based on an ultrathin LPFG etched by hydrofluoric acid (HF) which was surrounded by a dye-doped NLC for tuning the resonant wavelength [17]. A cascade structure of LPFGs with LC as the surrounding medium was proposed furthermore by H-R Kim et al. [18] for arbitrary loss filters that could compensate a non-uniform optical gain in an EDFA. Also noteworthy are the results presented in Ref. [19] where LPFGs, based on the SMF-28 and photonic crystal fibers (PCF), surrounded by a low-birefringence (LB) 1550 LC mixture were thermally and electrically tuned. In this work, a special glass capillary with five holes was used, where metal wires were placed in four holes (serving as electrodes) while the LPFG was introduced in the central hole and, then, filled with the LC. Later, the idea of a coated LPFG with a thin LC layer (in the order of 1 μm) was brought forward by Luo et al. [20]. The host LPFG used in this research was fabricated by a CO2 laser irradiation, and a medium-birefringence (MB) LC was employed as a LC layer. The experimental results along with the theoretical analysis presented there showed that efficient thermal tuning can be achieved for such a LC-LPFG design (up to 80 nm). Later, in Ref. [21] the electric and thermal tuning of the UV-induced LPFG combined with low-birefringence (LB) LC mixtures was presented. In this work, two different methods were used in order to obtain a LC coating on the LPFG: placing the LPFG inside a capillary and filling it with LC, or directly coating the bare LPFG with a thin LC layer. It was shown that the LPFG, when enhanced with an external LB LC layer, exhibits two different temperature sensitivities which depend on the temperature range of operation (corresponding with a nematic and an isotropic LC phases). The "switching" functionality of this LC-LPFG around the LC clearing temperature *Tc* was also observed (useful, for example, in warning systems). For the grating coating with a LC layer the electric induced shift of the attenuation band (up to 11 nm) was achieved, as well. In Ref. [22] it was demonstrated that a temperature compensation effect could be obtained in the LPFG by a proper choice of the LC layer. In Ref. [23], the phenomenon of the dual-resonance was exploited for the first time to measure LC-LPFG structure thermal and electric field responses.

In this work the use of a hybrid LC-LPFG is aimed at taking advantage of the 1550A LB nematic LC serving as a thin layer on the LPFG bare. The LPFGs were fabricated on a boron co-doped photosensitive fiber (Fibercore PS1250/1500) by two methods: UV-irradiation method and arc-induced technique (detail description of this method can be find in Refs. [10,24]). To further explore the benefits of the host gratings we chose the relatively short periods of 226.8 μm (for the UV-induces LPFG) and 222 μm (for the arc-induced LPFG). This type of gratings offered the possibility of coupling the optical power to the higher-order cladding modes and for the UV-induced LPFG leads also to a phenomenon of dual resonance. These properties are exploited to measure LC-LPFGs electric field responses. Effective electric tuning for the UV-induced LPFG with 1550ALC layer was obtaind since the investigated attenuation band was close to TAP. For such a LC-LPFG design, in the powered state the attenuation band was offset from the one measured in the off-voltage state by almost 130 nm. Electrical tuning of the LC-LPFG close to TAP was also achieved for the arc-induced LPFG host. In this case a fast switching on/off of the attenuation band in the LC-LPFG transmission spectrum for the powered/unpowered states was obtained. Simultaneously, all experimental results obtained in this work were supported with a basis on a model developed with Optigrating v.4.2 software.

2. Materials and experimental procedure

In this experiment, we used a commercially available boron co-doped photosensitive fiber (Fibercore PS1250/1500) as a host fiber. The LPFGs were fabricated by two methods. We produced the grating with a period of 222 μm by electric arc discharge. The grating was fabricated with a period of 226.8 μm by using the UV Eximer laser irradiation (*PulseMaster GSI Lumonics* emitting at a wavelength of 248 nm). The details of the LPFGs fabrication procedure can be found in Refs. [10,24].

As an external layer for the LPFG, a prototype LC mixture 1550A was chosen (synthesized at Military University of Technology, Warsaw, Poland). The refractive indices' thermal characteristics (measured at 589 nm) for this LC are presented in Fig. 1a). Table 1 provides a summary of the electro-optical properties for 1550A LC.

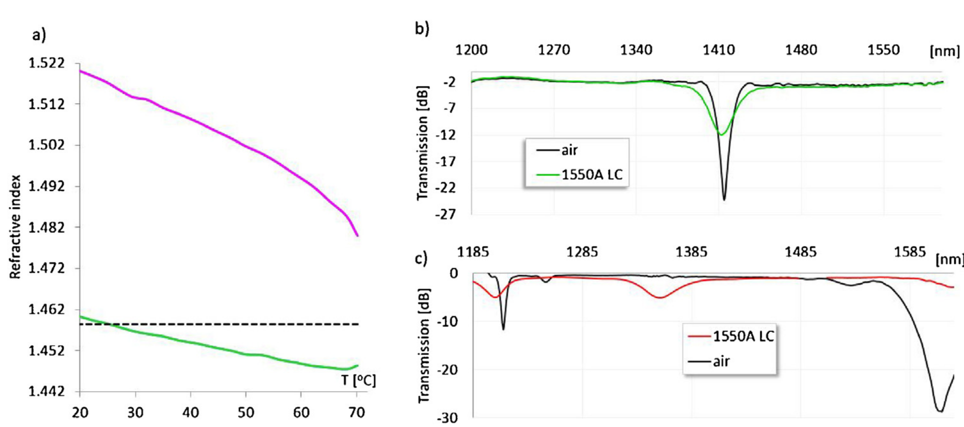

Fig. 1. a) The 1550A LC thermal dependencies of ordinary n_o (green line), extraordinary n_e (red line), as well silica glass n_{cl} (dashed line) refractive indices measured at wavelength of 589 nm. b) Transmission spectra of the arc-induced LPFG (b) and UV-induced LPFG (c) with and without LC layer.