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Towards tuning of thermal sensitivity of the long period fiber gratings using a liquid crystal layer

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Abstract. A high-efficiency thermal tuning filter based on a long-period fiber grating (LPFG) combined with a low-birefringence liquid crystal (LB LC) cladding layer is presented. Two types of LPFGs were studied and compared: the LPFGs based on a standard telecommunication fiber produced by an electric arc technique, and the LPFGs based on a boron co-doped fiber written by a UV technique. Both types of LPFGs when enhanced with an external LB LC layer exhibit two different temperature sensitivities, which depend on the temperature range of operation. For the LPFGs based on standard telecommunication fiber we can conclude that the presence of the LB LC cladding increases the thermal tuning efficiency by more than one order of magnitude over the value for the LPFGs in air. In the case of the LPFGs based on the boron co-doped fiber we discovered it is possible to obtain either a temperature-independent attenuation band or the attenuation bands with high temperature sensitivities, just by careful choice of the order of the cladding mode and the operating wavelength.

Key words: long period fiber grating, liquid crystal, sensors.

1. Introduction

A grating formed in an optical fiber in order to achieve light coupling between two co-propagating modes usually requires a grating pitch of several hundred micrometers. This kind of grating is generally called a long-period fiber grating (LPFG). Compared to other optical devices, LPFGs have a number of unique advantages such as low-level back reflection, low insertion losses and compact construction (the grating is an intrinsic fiber device). LPFGs have found a variety of applications in optical communications as gain-flattening filters for erbium-doped fiber amplifiers (EDFAs), as wavelength division multiplexing (WDM) systems or as wavelength-selective optical fiber polarizer components [1–2]. Tuning of the LPFGs is very attractive since it can offer a form of dynamic spectral control [3]. For these reasons filters based on LPFGs have generated a huge interest for applications in optical fiber systems.

The main aim of presented work is an integration of an LPFG and a liquid crystal (LC) material into a hybrid structure, in order to develop innovative fiber optic devices. The LPFGs are based on the phase-matching condition between the guided and cladding modes in an optical fiber. A light launched in a guided core mode interacts with a long period grating and is partially converted into a number of cladding modes, which propagate over short distances in the cladding before being attenuated by jacket and bends in the fiber. The most significant property of these modes is their propagation characteristics, which are strong functions of the refractive index of the medium surrounding the cladding. The LCs are especially interesting materials for this use, since their optical properties strongly depend on thermal, electric, magnetic and optic fields [4–7]. It was demonstrated that the LPFGs are most sensitive to external refractive index changes in the region where index-matching occurs between the cladding and the surrounding medium [7]. This property is investigated here by using a low-birefringence (LB) 1110 LC nematic mixture [8] as an LC cladding of the LPFGs. This LB LC mixture has a very low value of ordinary refractive index, which is close to the refractive index of the fiber clad, and can be tuned by temperature (see Fig. 3). Two types of LPFGs were researched and compared: the LPFG based on a standard telecommunication fiber produced by an electric arc technique and the LPFG based on boron co-doped fiber written by a UV technique. The results showed that the idea of integrating the LPFGs and the LB LC into a single component opens up a wide range of new possibilities for developing novel high-efficiency thermal tuning devices with a fast response speed.

2. Theory

An LPFG is a periodic modulation of the optical characteristics of an optical fiber, obtained by either inducing a physical deformation in the fiber material (electric arc technique) or by modifying the refractive index of the fiber's core (UV technique).

The transmission characteristics of an LPFG formed in a single-mode fiber can be analyzed by the coupled-mode theory. The LPFGs allow the transfer of power between the modes of an optical fiber. This is achieved by perturbing the phase of one mode such that it matches the phase of another one: the so-called 'phase matching condition'. The phase matching condition between the fundamental mode and the forward propagating cladding mode for the LPFG is given by:

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$$\beta_{co} - \beta_{cl,m} = {}^{2\pi}/_{\Lambda}, \tag{1}$$

where β_{co} and $\beta_{cl,m}$ are the propagation constants of the forward fundamental mode and the forward cladding mode of order m, respectively. The resonant wavelength, $\lambda_{res,m}$, for a specific attenuation band is expressed as follows:

$$\lambda_{res,m} = \left(n_{co}^{eff} - n_{cl,m}^{eff}\right)\Lambda = \delta n_m^{eff}\Lambda \tag{2}$$

where n_{co}^{eff}, $n_{cl,m}^{eff}$ and Λ stand for the effective refractive index of the core mode, the effective refractive index of the mth cladding mode and the period of the LPFG. According to Eq. (2), variations in n_{co}^{eff}, $n_{cl,m}^{eff}$ or Λ will shift the position of the attenuation band. Thus from a sensing perspective, the LPFGs are of interest due to the fact that the positions of their attenuation bands are sensitive to a number of external factors.

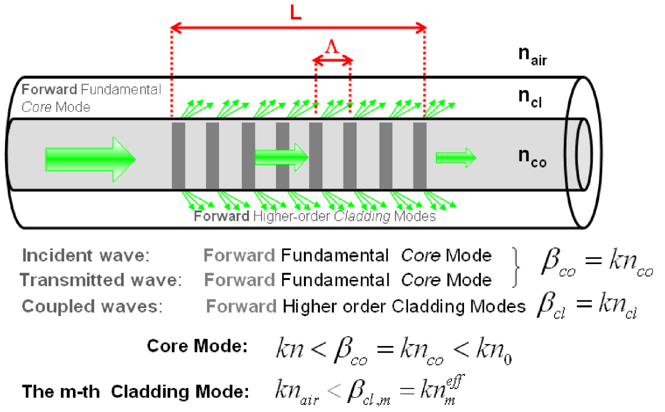

Fig. 1. Coupling of a fundamental guided mode to a number of cladding modes in a long-period grating

In this paper we present an LPFG with a unique liquid crystal (LC) cladding. The inherent sensitivity of the LPFGs to the surrounding refractive index of the LC material and to the temperature acting on the fiber are the most important properties considered in this research. Depending on the boundary condition between the cladding and the surrounding medium, the cladding modes propagate in a different manner [7, 8]. In air, the cladding modes experience a total internal reflection (TIR) mechanism at the interface between the cladding and the air. When the index of refraction of the cladding is equal to the refractive index of the surrounding medium, the cladding has an infinitely large radius, such that the cladding modes are converted into radiation modes as a result of the lack of TIR at the cladding boundary. Thus, we cannot observe any resonant wavelength effects. A whole new mechanism comes into play as soon as the refractive index of the cladding is exceeded by that of the surrounding medium. The fiber cladding now becomes leaky, due to the fact that no TIR exists. As with any interface between two dielectric media, a certain amount of reflection and refraction occurs and it is the phenomenon of external reflection that is important here. Then, Fresnel reflection coefficients dictate the proportion of light energy that is reflected.

The LPFGs with the LC layer were investigated with the gratings kept strictly straight. For this reason, the influence of bending, strain and torsion can be neglected and their sensitivities can be represented as follows [9]:

$$K_{LPFG}^{m} = \frac{\delta\lambda_{res,m}}{\lambda_{res,m}} = K_T\delta T + K_n\delta n_{LC}, \tag{3}$$

where T, n_{LC} stand respectively for temperature and LC surrounding refractive index. The sensitivities of the resonant wavelength $\lambda_{res,m}$ of the$m$th cladding mode to T and n_{LC} are given respectively by:

$$K_T^m = \frac{d\lambda_{res,m}}{dT}, \tag{4}$$

$$K_n^m = \frac{d\lambda_{res,m}}{dn_{LC}}. \tag{5}$$

By using (3) , the sensitivities from (4) and (5) can be written as:

$$K_T^m = \Lambda\frac{d\left(\delta n_m^{eff}\right)}{dT} + \frac{\lambda_{res,m}}{L}\frac{dL}{dT}, \tag{6}$$

$$K_n^m = \frac{d\lambda}{d\left(\delta n_m^{eff}\right)}\left[\frac{d\left(\delta n_m^{eff}\right)}{dn_{LC}}\right], \tag{7}$$

where $\delta n_{eff} = n_{eff,co} - n_{eff,cl}^{(m)}$ and L is the length of the LPFG.

3. Experimental setups and materials

For the needs of the present work, the LPFGs were manufactured using a standard telecommunication fiber (Corning SMF28) and using a boron co-doped photosensitive fiber (Fibercore PS1250/1500), designated by LPFG_SM and LPFG_PS, respectively. As far as the SM28 fiber is concerned, the LPFG were manufactured using a cost-effective electric arc method following a procedure similar to that presented in [10]. The LPFG_SMs had a period of 770 μm and a length of 4.5 cm. The LPFGs based on PS1250/1500 fiber were written by UV illumination. This fiber gives a possibility of writing the grating directly, without any hydrogenation procedure. Co-doping this fiber with boron enhances its photosensitivity, and consequently the UV exposure time required to achieve saturation of the index change is greatly decreased. The source of the UV light was provided by an Eximer laser (PulseMaster GSI Lumonics) emitting at 248 nm wavelength. A segment of PS1250/1500 fiber, with polymer coating removed, was spliced between two segments of SM28 fiber and placed in contact with the amplitude mask having a periodicity of 437 μm. Consequently, the fiber was irradiated by a UV light and the exposure was repeated until the index modulation has reached a sufficient level to provide the desired attenuation depth in the LPFG transmission spectrum, while the length of the LPFG was 4 cm.

To form an LC layer, a bare LPFG was introduced into a capillary with a radius of 136 μm. Then the capillary was filled with the LC mixture by using the capillary forces. Due to the flow- induced orientation during the capillary filling process and the small space between the inside surface of the capillary and the surface of the fiber (5.5 μm), a planar molecular alignment dominated. We assume that the propagating transverse cladding modes experienced an ordinary refractive index n_o of the LC mixture. The thermal tuning experiment was implemented by placing the LPFGs on the top of two insulated Peltier modules. Temperature control was conducted in the range from 22°C to 70°C with a 0.05°C resolution. The transmission spectrum was investigated with the input light launched from a broadband light source (Agilent 83437A) and the output signal was analyzed by an Optical Spectrum Analyzer (Agilent 86142B).

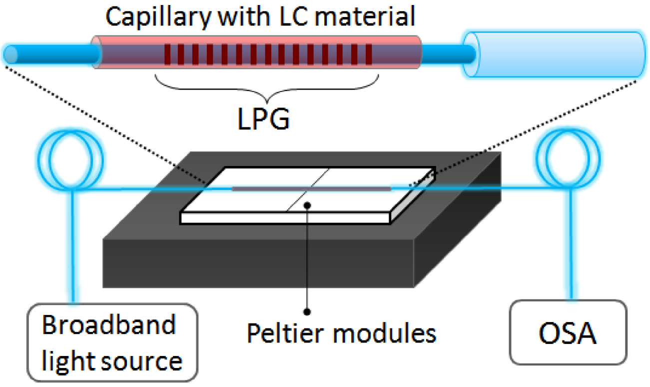

Fig. 2. Experimental setup for testing thermal sensitivity of LPFGs with LC layer

As an "active" element of the LPFGs we used the LC mixture No. 1110 [7] characterized by refractive indices higher than the refractive index of the cladding of the fiber. Due to the thermal dependence of the refractive indices of the LC mixture, a dynamic control of the SRI value could be obtained. The thermal characteristic of the refractive indices for the 1110 LC mixture are shown in Fig. 3.

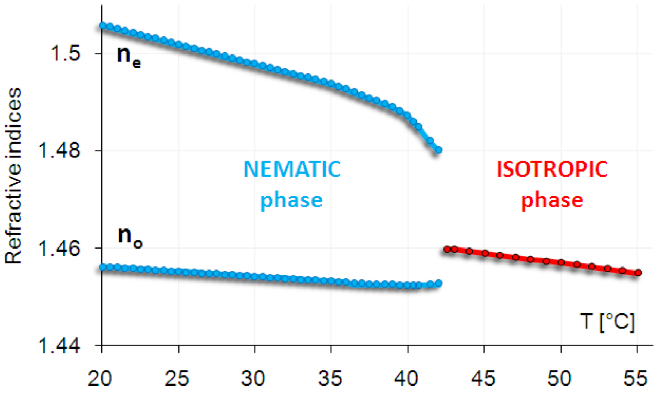

Fig. 3. Refractive indices as a function of temperature for 1110 LC mixture measured at 587 nm (synthesized at the Military University of Technology in Warsaw, Poland)

4. Results and discussion

First, the temperature sensitivity of the LPFGs was investigated in an empty capillary. It was noted that the attenuation bands shifted for the LPFG_SMs towards longer wavelengths as soon as the temperature was increased. A blue shift of the resonant wavelengths could be seen when the LPFG_PSs were heated.

The origin of the temperature sensitivity may be understood by differentiating Eq. (2) and this sensitivity is represented by Eq. (6). The first term on the right-hand side of Eq. (6) is the material contribution, and is related to the change in the differential refractive index of the core and the cladding arising from thermo-optic effect. This contribution is dependent upon the composition of the fiber and is strongly dependent upon the order of the cladding mode. For coupling to low order cladding modes (accessed using longer periods, >100 μm), the material effect dominates. The second term mainly denotes the change in grating periodicity (the so-called waveguide contribution). The investigated LPFGs have period higher than 100 μm, so the temperature-induced change of the grating periodicity could be neglected. Thus, the information about the polarity of the shift of the resonant wavelength versus temperature is given by thermo-optic coefficients of the core and cladding materials. According to Eq. (2), for LPFG_SM the effective refractive index of the core mode increases faster with temperature then the effective refractive indexes of the cladding modes causing a red shift of resonant wavelength. For LPFG_PS the temperature relation between the effective refractive index of the core mode and the effective refractive indexes of the cladding modes is negative. As a result, the blue shift of resonant wavelength is obtained for the LPFG_PSs. Thus, their sensitivity shows the opposite sign, such as indicated in Fig. 4. The sensitivity to temperature increases with the order of a claddings mode, reaching 0.059 C°/nm for the LPFG_SM and −0.504 C°/nm for the LPFG_PS.

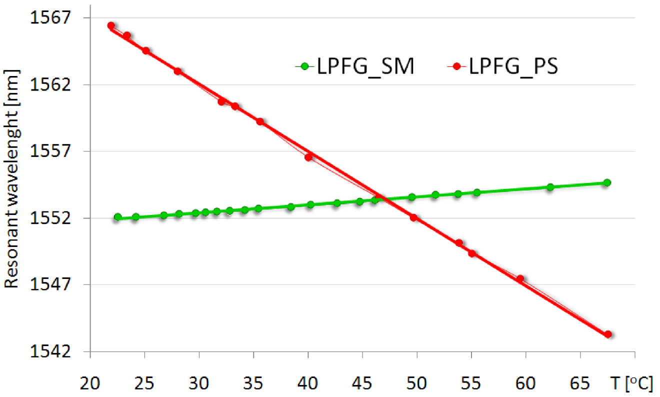

Fig. 4. Thermal sensitivity LPFGs for the attenuation band located around 1550 nm when the external medium is air

When the bare LPFGs were surrounded by the 1110 LC mixture, the red shift of the attenuation bands was recorded. This shift for the last attenuation band, located at 1557 nm for LPFG_SM and at 1567 nm for LPFG_PS, amounted to 1.16 nm and 11.3 nm, respectively. Significant difference between the response to the LB LC material may be due to different periods of the LPFGs studied here. In addition, the attenuation bands depths were reduced by 77% and 85% for LPFG_SM and LPFG_PS, respectively. This result indicates that the effective refractive index of the 1110 LC mixture is very close to the refractive index of the silica cladding, which is consistent with the specification of this LC material.

In the next part of our studies, the LPFGs with the LB LC surrounding were heated again.

For the temperature range from 22°C to 40°C (nematic phase of 1110 LC mixture) the value of the thermal sensitivity for the last attenuation band of the LPFG_SMs with a LC layer increases by more than one order of magnitude over the value for the LPFG_SMs in air. Thus, we can conclude that the presence of LC layer strongly increases the effect of temperature for the LPFG_SM, reaching sensitivity of 0.279 C°/nm.

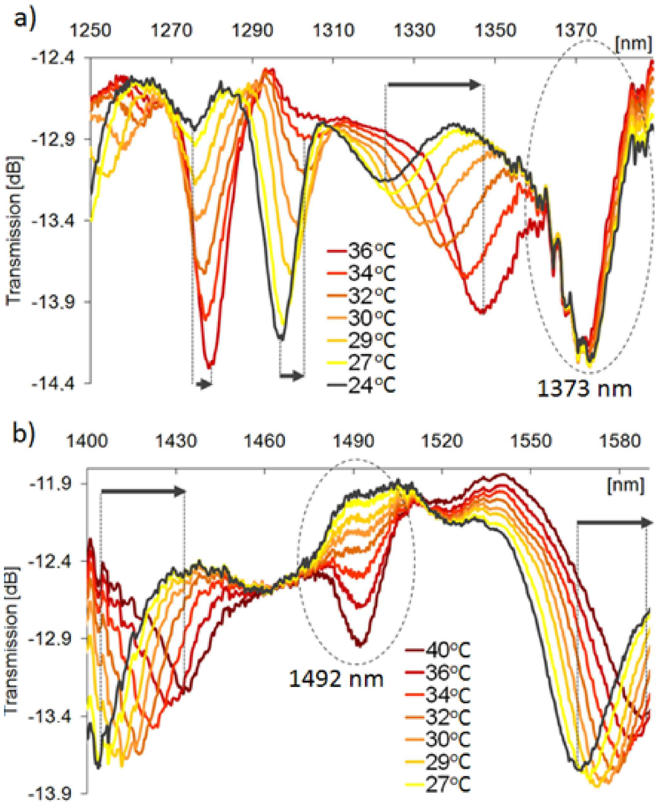

Fig. 5. Transmission spectra the LPFG_PS with LB LC layer versus temperature for the wavelength range 1250–1400 nm (a) 1400–1600 nm (b) – nematic phase of 1110 LC mixture

While the temperature of the LPFG_PS with LC layer increases, two effects take place. First, from the host fiber perspective, the LPFGs based on Be/Ge co-doped fiber exhibit shifts towards lower resonant wavelengths with increasing temperature. Second, from the LB LC material perspective, the value of the ordinary refractive index of 1110 LC mixture decreases with temperature. Thus, the presence of the LB LC medium around the LPFG should cause temperature shifts towards higher wavelengths. From Fig. 5 it can be seen that the attenuation bands located at room temperature at 1275 nm, 1297 nm, 1323 nm, 1403 nm and at 1566 nm in the transmission spectrum of LPFG_PS with LC layer move gradually as the temperature is being increased and their thermal sensitivity changes sign to positive. In addition, these bands are more sensitive to changes in ambient temperature. This result indicates that for those resonant wavelengths the influence of the LB LC surrounding is significantly stronger than the inherent temperature sensitivity of the LPFG_PS.

An interesting behavior was observed for the attenuation bands located at 1373 nm and at 1492 nm. The first one seems to be temperature insensitive in comparison with other bands, from the point of view of its depth and of resonant wavelength. The second one appeared only during heating, and the changes in the resonant wavelength of this band were negligible in comparison with changes measured for the other bands. It seems that the temperature compensation for this attenuation band was obtained. However, a detailed explanation of this result requires additional studies.

Next, an interesting phenomenon was observed at temperatures close to 40°C – corresponding to the phase-transition temperature of the 1110 LC mixture. For these temperatures, the attenuation bands in the transmission spectrum began to disappear for the tested LPFGs. While we continued to heat the samples, the attenuation bands reappeared, but this time with the other resonant wavelengths. For the last attenuation band in the transmission spectrum of the LPFG_SM and LPFG_PS, over a temperature cycle of only 5°C, a 5 nm and a 52 nm tuning range was obtained, respectively.

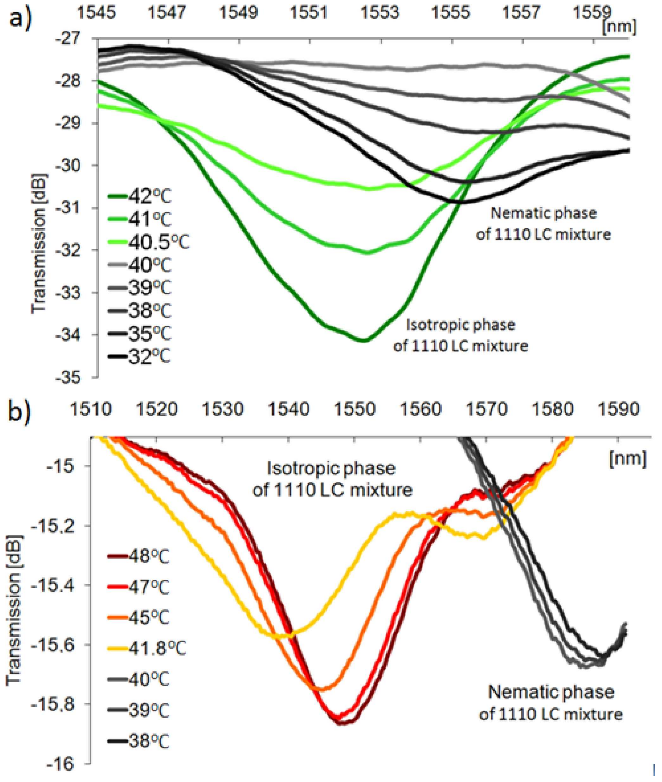

Fig. 6. Transmission spectra the LPFG_SM (a) and LPFG_PS (b) and for temperature range corresponds with transfer phase of 1110 LC mixture – a sudden change of the resonant wavelength is noticed

Consequently, for temperatures above 40°C (isotropic phase of the 1110 LC mixture), the attenuation band depth began to strengthen again and displayed the highest temperature sensitivity for both types of LPFGs. The thermal sensitivity of the last attenuation band reached 0.929 nm/°C for the LPFG_SMs and 2.380 nm/°C for the LPFG_PSs.

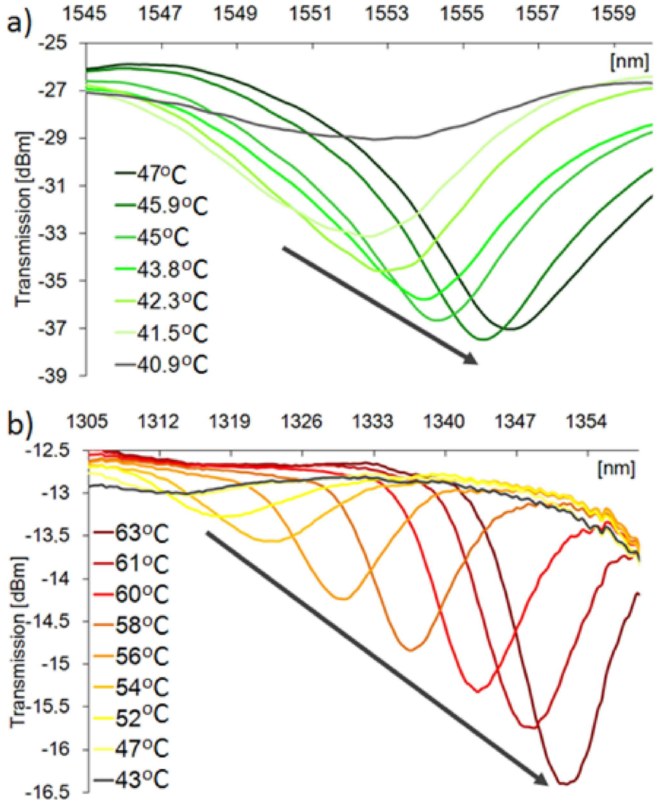

Fig. 7. Transmission spectra the LPFG_SM (a) and the LPFG_PS (b) with LB LC layer versus temperature – isotropic phase of 1110 LC mixture

5. Conclusions

In conclusion, we have demonstrated a loss filter with a high-efficiency thermal tuning capability, based on an LPFG surrounded by an LB LC mixture.

For such a device, the observed thermal sensitivity mainly results from the combination of several effects: the thermal changes of the refractive indices of both core and cladding modes, the changes in the LC refractive index due to the thermo-optic effect and the dependence of the grating sensitivity on the LC medium refractive index.

The wavelength shifts for the LPFGs in air and in the 1110 LC mixture are plotted in Fig. 8, showing a near-linear thermal response. To determine the average thermal sensitivities, a linear regression is used in two ranges of temperature corresponding to nematic and to isotropic phases of 1110 LC mixture. In Table 1 the measured values of the thermal sensitivity for the last band in the transmission spectrum of LPFGs are shown, where K^{m}_{LPFG} indicates the thermal sensitivities in air, in nematic and in isotropic phases of the LC mixture. Only the last band in the transmission spectrum is considered, because it corresponds to the coupling of the highest order cladding mode. Thus, this attenuation band is characterized by the highest sensitivity.

For both types of LPFGs, due to the presence of the 1110 LC mixture, two interesting effects were noticed. First, switching between two different thermal sensitivities in one LPFG device could be obtained. The "switch" value of the temperature is around 40°C and it corresponds to the temperature of the phase transition of the 1110 LC mixture. Second, with a change of temperature, a strong modulation of the attenuation band depth was observed. For temperatures lower than 40°C, a reduction of the attenuation band depth was recorded. Consequently, for temperatures above 40°C, the attenuation band depth began to strengthen again. As a reminder, as far the LPFG in air is concerned, the changes in the attenuation band depth were negligible.

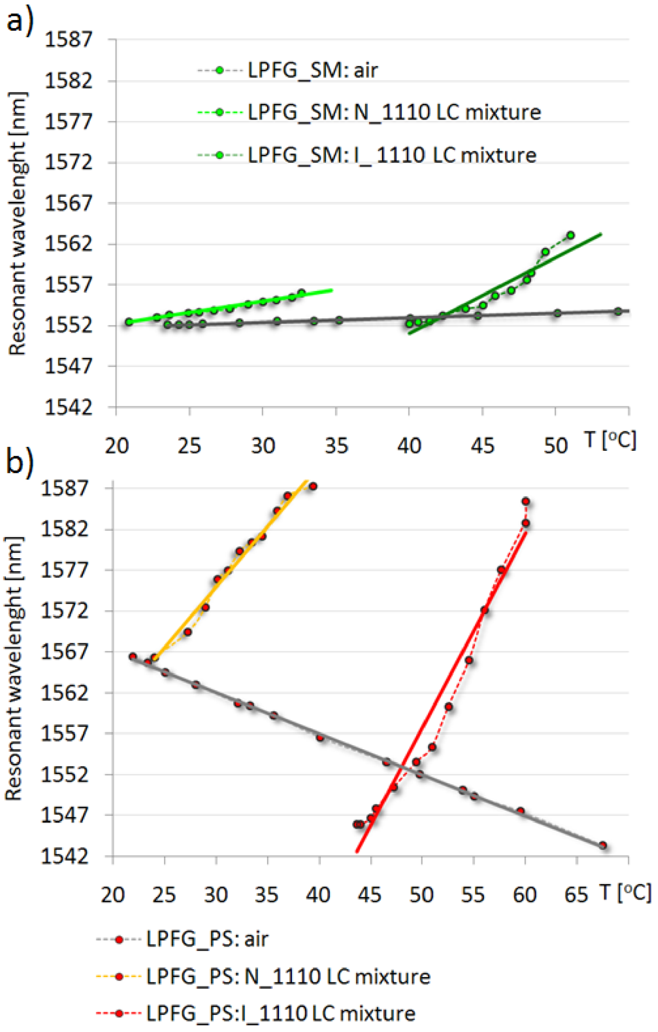

Fig. 8. Comparison of the thermal sensitivity LPFG_SM (a) and LPFG_PS (b) in air and in the 1110 LC mixture

Table 1
Measured thermal sensitivity shifts for the LPFG in air and in the 1110 LC mixture

Samples	K^{m}_{LPFG}		
	Air	1110 LC mixture	
		Nematic phase	Isotropic phase
LPFG_SM	0.056 nm/°C	0.279 nm/°C	0.929 nm/°C
LPFG_PS	−0.504 nm/°C	1.489 nm/°C	2.380 nm/°C

When the type of the LPFGs is considered, it seems clear that the values presented in Table 1 for LPFG_SM with a LC layer are increased by more than one order of magnitude over the values for LPFG_SM in air. Thus, we can conclude that the presence of the LC layer strongly amplifies the effect of temperature. The results shown in Table 1 for LPFG_PS indicate that the presence of surrounding LC changed the sign of the thermal sensitivity. In this spectral range, the LPFG_PS with LC layer is also more sensitive to changes in ambient temperature. It seems that for this resonant wavelength the impact of LC surrounding overrides the inherent thermal sensitivity of the LPFG_PS. However, tracking the attenuation band located at 1373 nm it was observed that it is temperature insensitive in comparison with other bands, from the point of view of its depth and of its resonant wavelength. Moreover, its thermal sensitivity for a corresponding attenuation band is almost 10 times lower than the sensitivity of the LPFG_PS in air (see Fig. 9). It seems that for the LPFG_PSs with LB layer, by careful choice of the order of the cladding mode and operating wavelength, it is possible to obtain a temperature-independent attenuation band, and simultaneously to produce the attenuation bands with high temperature sensitivities, as may be required for specific applications.

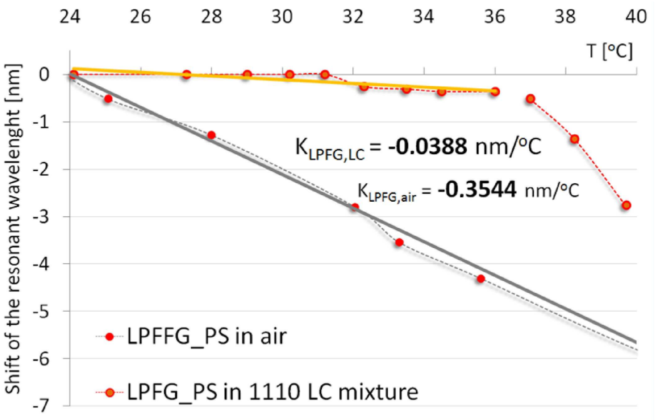

Fig. 9. Temperature-induced resonant wavelength shifts measured for LPFG_PS when external medium is air and 1110 LC mixture. At room temperature, the attenuation bands were located at 1381 nm and at 1373 nm when LPFG_PS is in air and in 1110 LC mixture, respectively

The obtained results show that the idea of integrating the LPFGs and the LCs into a single fiber-optic component opens up a wide range of new possibilities for developing novel devices capable of tuning light propagation properties. Such devices are expected to fulfill the need for a miniaturized, reliable and compact structures for future applications in communication and in sensing technology.

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REFERENCES

[1] O. Frazão, G. Rego, M. Lima, A. Teixeira, F.M. Araújo, P. André, J.F. Rocha, and H.M. Salgado, "EDFA gain flattening using long-period fibre gratings based on the electric arc technique", *Proc. London Communications Symposium* 1, 55–57 (2001).

[2] K. Seng Chiang and Q. Liu, "Long-period grating devices for application in optical communication", *Proc. ICOCN* 1, 128–133 (2006).

[3] D. Noordegraaf, L. Scolari, J. Legsgaard, L. Rindorf, and T.T. Alkeskjold, "Electrically and mechanically induced long-period gratings in liquid crystal photonic bandgap fibers", *Opt. Exp.* 13, 7901–7912 (2007).

[4] T.R. Woliński, P. Lesiak, and A.W. Domański, "Polarimetric optical fiber sensors of a new generation for industrial applications", *Bull. Pol. Ac.: Tech* 56 (2), 125–132 (2008).

[5] M.S. Chychłowski, S. Ertman, and T.R. Woliński, "Analysis of liquid crystals orientation in microcapillaries", *Photonics Letters of Poland* 2 (1), 31–33 (2010).

[6] M.M. Tefelska, M.S. Chychłowski, T.R. Woliński, R. Dąbrowsko, and J. Wójcik, "Tunable attenuation in photonic liquid crystal fibers", *Photonics Letters of Poland* 1 (2), 97–99 (2010).

[7] I. Del Villar, I.R. Matias, and F.J. Arregui, "Long-period fiber gratings with overlay of variable refractive index", *IEEE Photon. Technol. Lett.* 17, 1893–1895 (2005).

[8] T.R. Woliński, A. Czapla, S. Ertman, M. Tefelska, A. Domański, J. Wójcik, E. Nowinowski-Kruszelnicki, and R. Dąbrowski, "Photonic liquid crystal fibers for sensing applications", *IEEE Trans. Inst. Meas.* 57 (8), 1796–1802 (2008).

[9] S.W. James and R.P. Tatam, "Optical fibre long-period grating sensors: characteristics and applications", *Meas. Science and Technol.* 14 (5), R49–R61 (2003).

[10] M. Śmietana, W.J. Bock, and P. Mikulic, "Comparative study of long-period gratings written in a boron co-doped fiber by an electric arc an UV irradiation", *Meas. Sci. Technol.* 21 (2), 1422–1427 (2010).