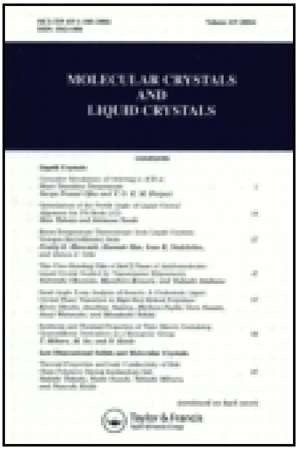

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Long-Period Fiber Gratings with Low-Birefringence Liquid Crystal

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Long-Period Fiber Gratings with Low-Birefringence Liquid Crystal

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The paper presents a long-period fiber grating (LPFG) with a unique liquid crystal (LC) cladding. We report the results of experiments on the LPFG's spectral properties that can be modified by temperature due to the presence of a low-birefringence nematic LC mixture. We also present our latest results concerning the influence of an external electric field on an LPFG with a medium-birefringence LC. The LPFGs are fabricated by using electric arc discharges in two types of fiber: single-mode (SM) fibers and photonic crystal fibers (PCFs). The experimental study is focused on achieving external tuning by adjusting thermal and electric field effects influencing the spectral properties of LPFGs using LCs.

Keywords: liquid crystals; long-period fiber grating; photonic crystal fiber

1. INTRODUCTION

The idea of integrating long-period gratings (LPGs) and photonic crystal fibers (PCFs) into one component opens up a wide range of new possibilities for developing novel devices capable of tuning light propagation properties [1,2]. PCFs have superb potential as sensors

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and as communication components due to their numerous unusual optical properties and to the fact that they offer much greater design flexibility than do conventional optical fibers. LPFGs have a number of unique advantages such as compact construction (the grating is an intrinsic fiber device), low-level back reflection and low insertion losses. LPFGs have found a variety of applications in optical communications and sensing, as gain-flattening filters for erbium-doped fiber amplifiers (EDFAs), wavelength-selective optical fiber polarizers or components in wavelength division multiplexing (WDM) systems [3–5].

It is well known that the optical properties of LPFGs can be tuned by controlling the properties of the material surrounding the LPFG. In this paper we propose liquid crystal (LC) as a surrounding material. LCs are especially interesting materials for this use, since their optical properties strongly depend on thermal, electric, magnetic and optic fields. We report here experimental results concerning thermal and electric field tuning of spectral properties of LPFGs by using LCs.

2. THEORY

The transmission characteristics of an LPFG, whether formed in a single-mode fiber or a waveguide, can be analyzed by the coupled-mode theory [6]. LPFGs couple the fundamental core mode to a series of forward-propagating cladding modes at discrete wavelengths. Consequently, the transmission spectra of LPFGs are characterized by rejection bands centered at resonance wavelengths λ_{res} that correspond to different cladding modes. The allowed resonant wavelengths λ_{res} of the mode coupling are given by the following phase matching condition:

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

where n_0^{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.

The inherent sensitivity of LPGs to the surrounding refractive index (SRI) acting on the fiber [7–9] is the most important property

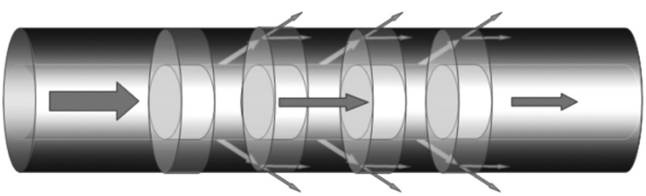


FIGURE 1 Propagation mechanism of the cladding modes of an LPFG in air.

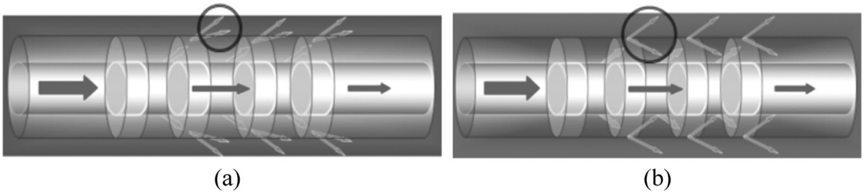


FIGURE 2 Propagation mechanism of the cladding modes of an LPFG when (a) $n_{cl} = n_{sur}$ or (b) $n_{cl} < n_{sur}$.

to be 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 (in the case of an LPG based on a standard fiber) or a modified TIR mechanism (in the case of a PCF-based LPG) at the interface between the cladding and the air (Fig. 1).

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 (Fig. 2a). As a result, we cannot observe any resonant wavelength effect. A whole new mechanism comes into play as soon as the index of refraction of the cladding is exceeded by that of the surrounding medium (Fig. 2b). Then the cladding cannot be considered infinite and the radiation mode description becomes invalid. The fiber cladding now becomes known as a 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 of importance here. Fresnel reflection coefficients dictate the proportion of light energy that is reflected (the remainder being refracted from the cladding into the surround, which explains the lossy nature of the leaky modes that are formed). The result is that the cladding modes can be leaky when the attenuated cladding modes are amplified along the direction of propagation.

3. MATERIALS AND EXPERIMENTAL SETUP

The LPFGs were fabricated by using the electric arc discharges presented elsewhere [1,9] in two types of fibers, one a conventional single-mode fiber, the other a PCF. The PCF used for the LPG fabrication was the endless single mode PCF (ESM-12-01, manufactured by *CrystalFiber)* which remains single mode at all the wavelengths transparent for the fused silica (Fig. 3a). In order to compare the transmission spectra of several different devices we also proceeded with the inscription of the LPGs in a conventional optical fiber (SMF-28). As an "active" element of the LPFGs we used two different classes of nematic LC mixtures with very low birefringence (0.04 ~ at 23°C) and medium birefringence (~0.16 at 23°C). The low-birefringence LC mixture No. 1550 [10] was used to investigate temperature influence. This LC mixture is especially interesting for silica glass fibers, as its ordinary refractive index in a specific temperature range is lower than the refractive index of the silica glass. The thermal characteristic of the refractive indices for the 1550 LC mixture is shown in Figure 3a and was measured at $\lambda = 589$ nm. It must be emphasized that the experiments were conducted in the range of wavelengths from 1480 to 1700 nm. Therefore the values of temperatures can be different for this part of the spectrum. However, all the special properties of the 1550 LC mixture, such as decay of its ordinary refractive index with increasing temperature and matching the ordinary refractive index for a certain temperature with the refractive index of silica, will still be valid. The prototype LC mixture No. 1702 was composed of fluorocyanophenyl esters of aromatic acid and cyanophenyl dioxanes. This LC mixture was especially chosen for the investigation of external electric field influence because it is characterized by a high (di)electric anisotropy (~48.4), enabling relatively easy molecular reorientation by using an external electric field.

The experimental setup for investigating the influence of the external electric field on an LPFG with LC is shown in (Fig. 4a). In

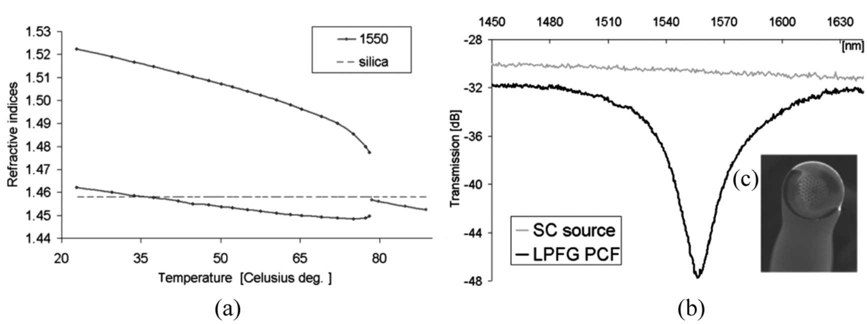
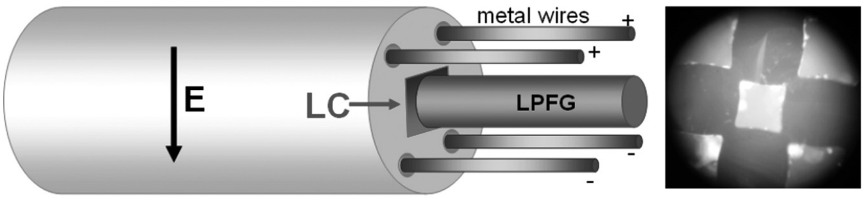


FIGURE 3 (a) Thermal characteristic of refractive indices for 1550 LC mixture (at. 589 nm). (b) Comparison of the transmission spectra of SC source and an LPG based on PCF. (c) SEM photograph of cross-section of an LPG based on the ESM-12-01; PCF contains a solid core with normalized hole diameters of 0.46 µm, outside diameter of 125 µm and core diameter of 12 µm. (prod. by *CrystalFiber*).



(a) (b)

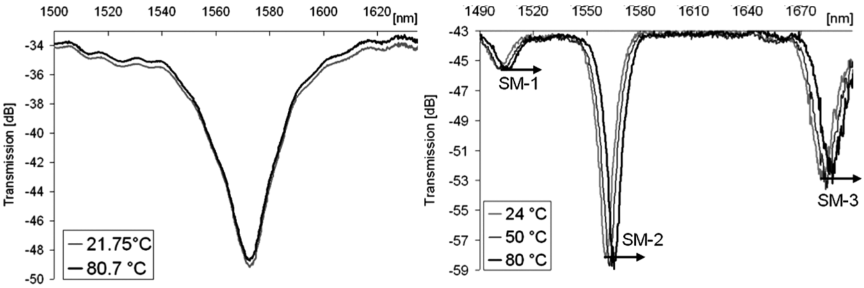
FIGURE 4 (a) Experimental setup for investigating the influence of an external electric field on an LPFG with LC. (b) Photograph of cross-section of a special glass capillary with 5 holes.

our experiments we used a special glass capillary with 5 holes (Fig. 4b). Metal wires were placed in four holes, serving as electrodes. The distance between the electrodes was 350 μm. The electrical field control was in the 0–1000 V range with frequency from 50 Hz to 2 kHz. In the central hole we placed the LPFG. The radius of the central hole was 220 μm. The LC was introduced into the space between the LPFG and the center hole surface by using capillary forces. Temperature sensitivity was investigated by placing the LPFG on an insulated Peltier heater. Temperature control and stabilization was in the range from 10°C to 100°C with ~0.1°C resolution. The transmission spectrum was investigated with the input light launched from a broadband supercontinuum (SC) light source (Fig. 3b) and the output signal was analyzed by an Optical Spectrum Analyzer (OSA) with a maximum resolution of 0.05 nm.

In our experiments we used a photocrosslinkable polyvinylcinnamate (PVCi) polymer to align the LCs in the capillary. The idea of using (PVCi) polymer for LCs aligning in microstructured fibers has been reported elsewhere [11]. The application of PVCi to the molecules of LC material alignment capillary had to be performed in three main steps. First, a thin film of PVCi was created on the surface of capillary. One end of the capillary was placed into the hermetically-sealed container with the PVCi solution. The container was supplied with high-pressure air and the capillary to be infiltrated. Then the capillary was irradiated with linearly polarized UV light. The polarization direction was parallel to the capillary axis. Finally, the capillary was infiltrated with a LC.

4. LONG-PERIOD FIBER GRATINGS WITHOUT LIQUID CRYSTAL

LPFGs are sensitive to a number of physical parameters. However, it is evident that these gratings are characterized by a non-conducting



(a) (b)

FIGURE 5 Transmission spectra of two LPFGs (a) based on PCF and (b) based on SM fiber at various temperatures.

(dielectric) structure and they are insensitive to external electric field. In the case of temperature, their sensitivity depends on the type of the fiber used to manufacture the grating. The transmission spectrum of PCF-based LPGs displayed a strong attenuation band located at 1562 nm. In our experiments the LPG based on PCF exhibited no temperature-induced changes in the resonant wavelength of the attenuation band (Fig. 5a). Generally, PCFs are characterized by a low temperature dependence because the core and the cladding effective indices are the same (close to that of pure silica).

For the LPG based on the SM fiber, temperature sensitivity was observed (Fig. 5b). The temperature sensitivity is apparently due to the fiber core being doped, which causes the difference between the core and the cladding index to be temperature-sensitive. The transmission spectrum of LPGs based on SM fiber displayed strong and narrow attenuation bands labelled as SM-1, SM-2, and SM-3 located at 1502 nm, 1562 nm and 1680 nm respectively at 23°C. As expected, each attenuation band of a LPFG based on SM fiber has a different temperature response and exhibits a linear trend of sensitivity to temperature (Fig. 6).

5. LONG-PERIOD FIBER GRATINGS WITH LOW-BIREFRINGENCE LIQUID CRYSTAL – TEMPERATURE EFFECTS

The spectral temperature sensitivities of the LPFGs based on the SM fiber and the PCF when surrounded by low-birefringence LC prototype mixture No. 1550 were investigated. The 1550 LC mixture was especially chosen for this experiment because its ordinary refractive

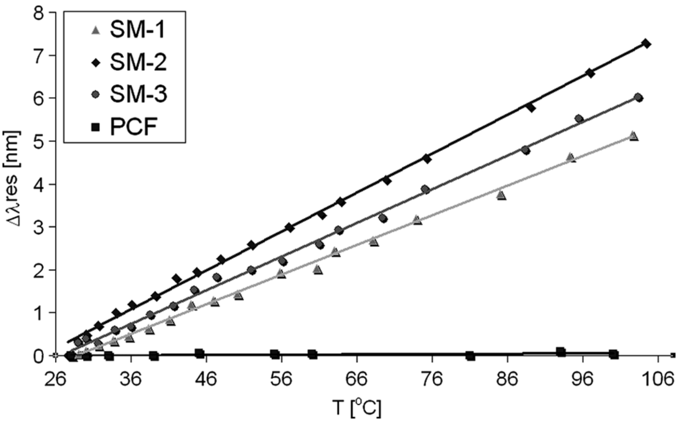


FIGURE 6 Temperature-induced resonant wavelength shifts measured for the three attenuation bands of an LPFG based on SM fiber and the one band of a PCF-based LPFG.

index in a specific temperature range is lower than the refractive index of the silica glass.

5.1. Long-Period Grating Based on SM-28 with 1550 LC Mixture

The temperature-induced change in the value of the refractive index of the 1550 LC mixture introduced significant changes in the depth of each attenuation band. When the ordinary refractive index of the 1550 LC mixture was equal to the refractive index of the silica

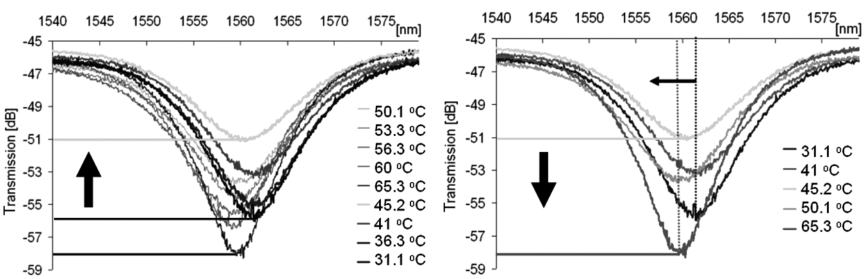
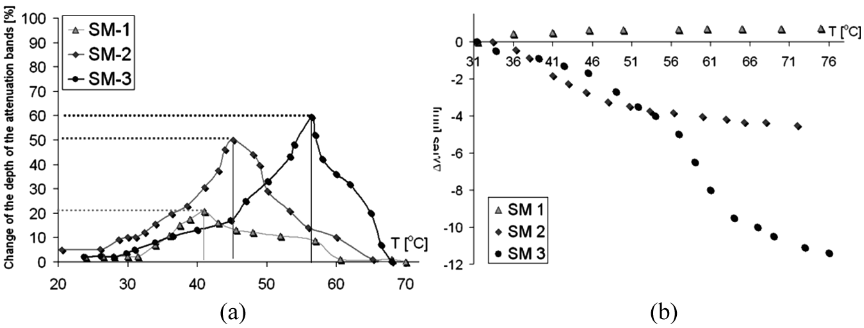


FIGURE 7 Transmission spectra for the SM-2 attenuation band of the LPFG based on SM fiber with 1550 LC mixture for (a) temperatures satisfying the condition $n_{o1550\,LC} \leq n_{cl,m}$; and (b) temperatures satisfying the condition $n_{o1550\,LC} \geq n_{cl,m}$.

glass, the maximum reduction of the depth of the bands was observed (Figs. 7a and 7b). The temperature corresponding with this effect was different for each attenuation band: 41°C, 45°C, and 56°C for SM-1, SM-2, and SM-3, respectively (Fig. 8a). The different values of these temperatures result from differences in the temperature and external index of refraction sensitivity of each attenuation band.

LPFG based on SM fiber exhibit shifts towards longer resonant wavelengths with increasing ambient temperature, while this LPFG surrounded with 1550 LC mixture exhibit negative temperature-induced spectral shifts for the SM-2 and SM-3 bands (the comparison Figs. 6 and 7c). For the LPFG based on the SM fiber surrounded by the LC mixture, temperature causes decrease of the effective refractive index of the *m*th cladding mode, which is dependent on the difference between the indices of refraction of the cladding and the LC medium external to the cladding. As a result, according to the temperature the attenuation bands SM-2 and SM-3 are shifted toward blue in the transmission spectrum (Fig. 7b).

This shift to larger resonant wavelengths with increasing temperature for the band SM-3 can by explained by the slightest temperature sensitivity in comparison with the others bands. Moreover, temperature response of LPFG based on SM fiber with LC exhibit a no-linear trend of sensitivity to temperature. The LPFG is most sensitive to external refractive index changes in this region where index-matching occurs between the cladding and the surrounding medium. Therefore, the higher changes in the attenuation bands, for SM-1, SM-2, SM-3 respectively, are visible close to the temperatures corresponding to the maximum decreases of the depth of the attenuation bands (Fig. 8a).



(a) (b)

FIGURE 8 Temperature-induced attenuation band decreases (a) and resonant wavelength shifts (b) measured for the three attenuation bands of the LPG based on SM fiber with the 1550 LC mixture.

5.2. Long-Period Grating Based on PCF with 1550 LC Mixture

As noted above, the PCF-based LPFG is characterized by extremely low temperature-sensitivity. In our experiment, for temperatures in the range from 20°C to 70°C, no changes in attenuation band position of the transmission spectrum were detected. However, it was observed that for temperatures close to 51°C the resonant effect was almost fully suppressed (Fig. 9a). This finding confirms the strong influence of the LC surrounding on the spectral properties of the PCF-based LPFG. Taking into account that the value of the ordinary refractive index of the 1550 LC mixture can match the refractive index of silica glass and that the PCF-based LPFG is temperature-insensitive, it becomes clear that such a combination can cause significant decreases in the depth of attenuation. Above a temperature of 51°C, the attenuation band reappears in this same place and becomes more pronounced with increasing temperature (Fig. 9b).

It must be mentioned that complete suppression of the resonant wavelength was not observed for either of the LPFGs studied here. A possible explanation is that orientation of the molecules of LC material was not uniform (planar) along the fiber axis. In our experiment we used a photocrosslinkable polyvinylcinnamate (PVCi) polymer for LCs aligning in a capillary. This distance appears to be 220 microns minus 125 microns divided by 2. It seems that the alignment occurred rather on the capillary surface but not on the fiber. This fact has to be taken into account in future work. One of the ways to improve the orientation of the molecules of LC material along the fiber axis would be to deposit a light-orientation layer directly on to the bare LPFG.

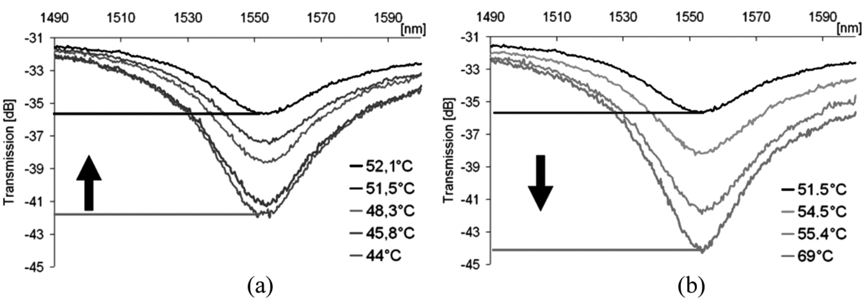


FIGURE 9 Transmission spectra for the PCF-based LPFG with the 1550 LC mixture for (a) temperatures satisfying the condition $n_{o1550\,LC} \leq n_{cl,m}$, and (b) temperatures satisfying the condition $n_{o1550\,LC} \leq n_{cl,m}$. Maximum decreases of the attenuation band are observed at ~51°C.

If this technique will prove effective then a complete suppression of the resonant wavelength should be obtained.

6. LONG-PERIOD FIBER GRATINGS WITH MEDIUM-BIREFRINGENCE LIQUID CRYSTAL – ELECTRIC FIELD EFFECTS

Influence of an external electric field on the spectral properties of the LPFG based on SM-28 fiber was investigated in our experiment. A key fact is that the optical properties of the LPFG with LC depend on the orientation of the molecules of LC material. As an "active" surrounding medium of the LPFGs we used the 1702 LC nematic mixture characterized by high (di)electric anisotropy, to enhance electric field-induced molecular reorientation.

Without an electric field, the position of the attenuation band of the LPFG surrounded by LC corresponds to the effective refractive index of the LC medium as a result of the orientation of the molecules of LC material (Fig. 10a). However, under the influence of the electric field, a threshold molecular reorientation occurs and at voltages higher than the threshold value, molecules of LC material tend to reorient themselves perpendicularly to the fiber axis (Fig. 10b).

In Figure 11 we can see that under varying voltages, changes are observed in the position (blue shift) and also in the depths of the attenuation bands. This indicates that the electric field can tune the spectral properties of the LPFG surrounded by LC. Moreover,

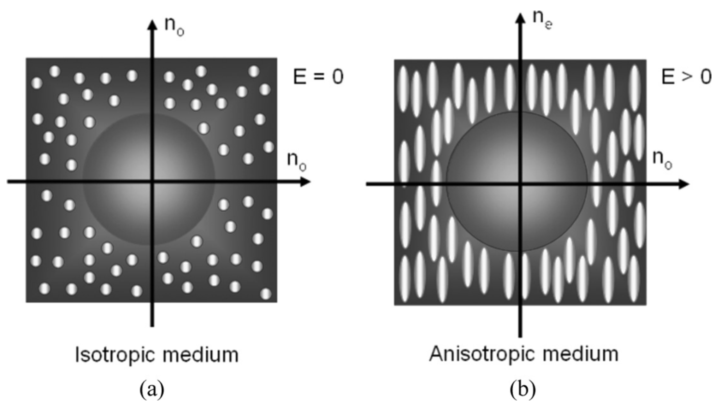


FIGURE 10 Orientation of molecules of LC material in the central hole of the capillary: (a) without electric field: LC acts as an isotropic medium and (b) with electric field: LC manifests its anisotropy.

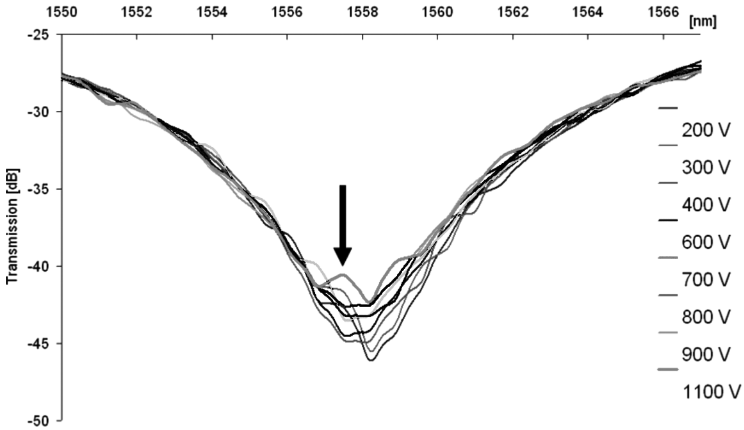


FIGURE 11 Progression of transmission spectra measured for the LPFG based on SM-28 fiber surrounded by the 1702 LC mixture exhibiting dual-peak separation as a result of external electric field.

the transmission spectrum of the LPFG with the 1702 LC mixture exhibits dual-peak separation under influence of the external electric field (voltages up to 1000 V). The results obtained suggest that the electric field induces birefringence in the medium surrounding the fiber: two different refractive indices, ordinary n_o and extraordinary n_e, and in consequence two different resonant wavelengths and two respective peaks appear.

7. CONCLUSIONS

In this work we have presented spectral effects in long-period gratings surrounded by LC mixtures that are induced by temperature and external electric field and have discussed their spectral properties.

The LPFG based on SM fiber exhibits linear temperature sensitivity, whereas the LPFG based on the PCF is temperature-insensitive. In LPFGs surrounded by low-birefringence LC, temperature was found to strongly influence the depth of the attenuation bands of the LPFGs whether based on SM fiber or PCF. In the case of PCF-based LPFGs, there were no changes in the spectral position of the attenuation band. The LPFG based on SM fiber with the 1550 LC mixture exhibited a non-linear temperature response that was particularly marked for temperatures corresponding with the ordinary LC refractive index close to the refractive index of the silica fiber clad. Moreover, this LPFG exhibited negative temperature-induced spectral shifts for two attenuation bands. This effect can be explained by the special properties of the 1550 LC mixture and may be used to propose a new method of temperature-compensation in LPFG-based sensors. Under the influence of electrical fields, the possibility of band splitting in the spectrum of the LPFG with LC was demonstrated. This effect can be explained in terms of electric field-induced birefringence in the surrounding LC medium in the cross-section of the LPFG responsible for two resonant wavelengths.

To summarize, liquid crystals are found to introduce a new level of tunability to LPFGs. Various combinations of LPFGs and LCs can be used to provide different types of filters, amplifiers, modulators and delay lines that could be easily incorporated into an optical fiber line.

REFERENCES

[1] Bock, W. J., Chen, J., Mikulic, P., Eftimov, T., & Korwin-Pawlowski, M. (2007). Pressure sensing using periodically tapered long-period gratings written in photonic crystal fibers. *Meas. Sci. Technol.*, *18*, 3098–3102.

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

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

[4] Kurkov, A. S., Vasil'ev, S. A., Korolev, I. G., & Medvedkov, O. I. (2001). Fibre laser with anintracavity polariser based on a long-period fibre grating. *Quantum Electronics*, *31*(5), 421–423.

[5] Kin Seng, Chiang & Qing, Liu. (2006). Long-period grating devices for application inoptical communication. *Proc. ICOCN 2006*, 128–133.

[6] Vengsarkar, A. M., Lemaire, P. J., Judkins, J. B., Bhatia, V., Erdogan, T., & Sipe, J. E. (1996). Long-period fiber gratings as band-rejection filters. *J. Lightwave Technol.*, *14*(1), 58–65.

[7] Patrick, H. J., Kersey, A. D., & Bucholtz, F. (1998). Analysis of the response of long-period fiber gratings to external index of refraction. *J. Lightwave Technol.*, *16*(9), 1606–1612.

[8] Cusano, A., Iadiciddo, A., Pilla, P., Contessa, L., Campopiano, S., & Cutolo, A. (2006). Mode transition in high refractive index coated long-period gratings. *Opt. Express*, *19*(14), 19–34.

[9] Pilla, P., Foglia Manzillo, P., Giordano, M., Korwin-Pawlowski, M. L., Bock, W. J., & Cusano, A. (2008). Spectral behavior of thin film coated cascaded tapered long-period gratings in multiple configurations. *Opt. Express*, *13*(16), 9765–9780.

[10] Wolinski, T. R., Ertman, S., Lesiak, P., Domanski, A. W., Czapla, A., Dabrowski, R., Nowinowski-Kruszelnicki, E., & Wojcik, J. (2006). Photonic liquid crystal fibers – a new challenge for fiber optics and liquid crystals photonics. *Opto-Electronics Review*, *14*(4), 329–334.

[11] Wolinski, T. R., Ertman, S., Czapla, A., Lesiak, P., Nowecka, K., Domanski, A. W., Nowinowski Kruszelnicki, E., Dabrowski, R., & Wojcik, J. (2007). Polarization effects in photonic liquid crystal fibers. *Meas. Sci. Technol.*, *18*, 3061–3069.