High-Efficiency Thermal Tuning of a Long-Period Fiber Grating Using a Liquid Crystal Layer

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Abstract— A high-efficiency thermal tuning filter based on a long-period fiber grating (LPFG) with a liquid crystal cladding layer is presented. The filter exhibits two different temperature sensitivities which depend on the temperature range of operation: for the temperatures from 23°C to 38°C, the thermal sensitivity is 0.279 nm/°C and for 41°C to 52°C, it is 0.929 nm/°C. These values are increased by more than one order of magnitude over the value for LPFGs without a liquid crystal layer whose thermal tuning efficiency is 0.056 nm/°C. The results show that the idea of integrating the LPFGs and the liquid crystals (LCs) 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.

Filters based on long-period fiber gratings (LPFGs) have generated a huge interest for applications in optical fiber systems. Such filters have a number of 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 as gain-flattening filters for erbium-doped fiber amplifiers (EDFAs), as wavelength-selective optical fiber polarizers or as components in wavelength division multiplexing (WDM) systems [1–3]. Tuning of the LPFGs is very attractive since it can offer a form of dynamic spectral control [4-6].

The transmission characteristics of an LPFG can be analyzed by the coupled-mode theory. There exists a specific wavelength, called resonance wavelength λ_{res}, at which the coupling between the guided mode and a specific cladding mode is strongest. The value of λ_{res} for *m*th cladding mode is given by the following phase matching condition:

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

where n_{o}^{eff} , $n_{cl,m}^{eff}$ and Λ stand for the effective refractive index of the core mode, the effective refractive index of the *m*th cladding mode and the period of the LPFG. The center wavelength (λ_{res}) of a rejection band is generally sensitive to a number of physical parameters, e.g. temperature, strain, surrounding refractive index (SRI). This property of the LPFG has been explored for the realization of tunable devices and sensors. However, regarding the temperature sensitivity, the resonance of an LPFG written in standard telecommunication fiber can only shift by 3 to 10 nm for a 100°C range [3]. This thermal sensitivity may be not sufficient enough for many applications.

In this paper we present an LPFG with a unique liquid crystal (LC) cladding. The inherent sensitivity of the LPFGs to the LC SRI acting on the fiber is the most important property 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 effect. A whole new mechanism comes into play as soon as the index of 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 researched LPFGs were fabricated by using the electric arc discharges presented elsewhere [5][7] in a conventional single-mode fiber (SM-28, manufactured by *Corning*). The LPFG had a period of 770 μm and a length of 4.5 cm. The experiments were conducted in the wavelength range from 1552 nm to 1564 nm. The transmission spectrum was investigated with the input light launched from an Erbium Ase Source (Agilent

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83439A) and the output signal was analyzed by an Optical Spectrum Analyzer (Agilent 86122B) with a maximum resolution of 0.06 nm. 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.

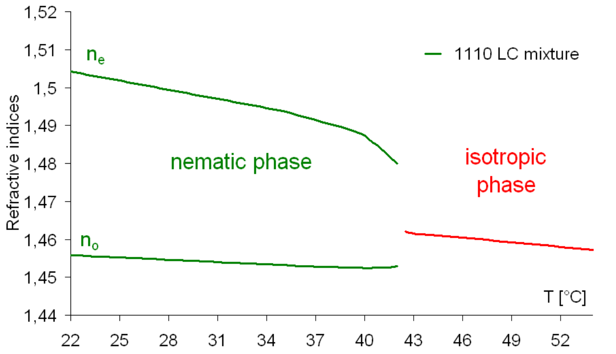

Fig. 1. Refractive indices as a function of temperature for 1110 LC mixture measured at 587 nm (synthesized at the Military University of Technology in Warsaw, Poland.)

As an ''active'' element of the LPFGs we used the LC mixture No.1110 [8] 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, dynamic control of the SRI value could be obtained. The thermal characteristic of the refractive indices for the 1110 LC mixture are shown in Figure 1. The thermal tuning experiment was implemented by placing the LPFGs on the top of an insulated Peltier module. Temperature control was conducted in the range from 22°C to 70°C with a 0.05°C resolution.

First, the LPFG in an empty capillary was heated. It was noted that the attenuation band shifted towards longer wavelengths as soon as the temperature increased. A maximum spectral shift of 2.5 nm, from 22°C to 60°C, was achieved. Changes in the attenuation band depth observed at the same time were negligible. When the bare LPFG was surrounded by the LC mixture, the red shift of 1.16 nm of the attenuation band was recorded. In addition, the attenuation band depth was reduced by 77% as indicated in Figure 2. Then, the LPFG with the LC surrounding was heated again. For the temperature range from 22.8°C to 34°C we observed a shift of 3 nm (from 1552.5 nm to 1556 nm) and a smooth reduction of the attenuation band. These effects can be explained by the fact that with increasing temperature, the value of the ordinary refractive index of the 1110 LC mixture approaches the value of the refractive index of the cladding of the fiber. Then, an interesting effect was observed at a temperature of 40°C: the attenuation band disappeared in the transmission spectrum. It seems that this value of temperature corresponds to the 1110 LC mixture phase-transition temperature. While we continued to heat the sample, the attenuation band reappeared in the transmission spectrum with its resonance wavelength at 1552.5 nm. An 8.32 nm tuning range was obtained over a? temperature cycle of only 8 °C.

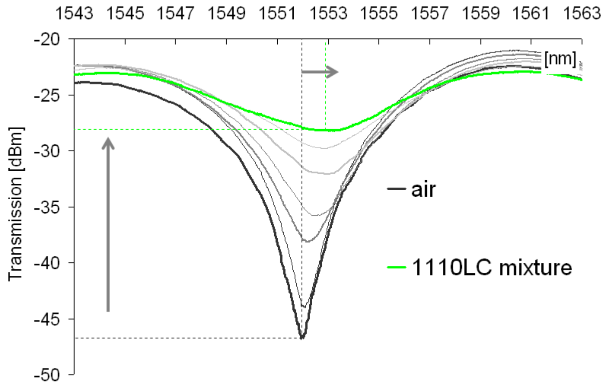

Fig. 2. The transmission spectra of the LPFG when the capillary is being filled by the 1110 LC mixture at room temperature (22.7°C)

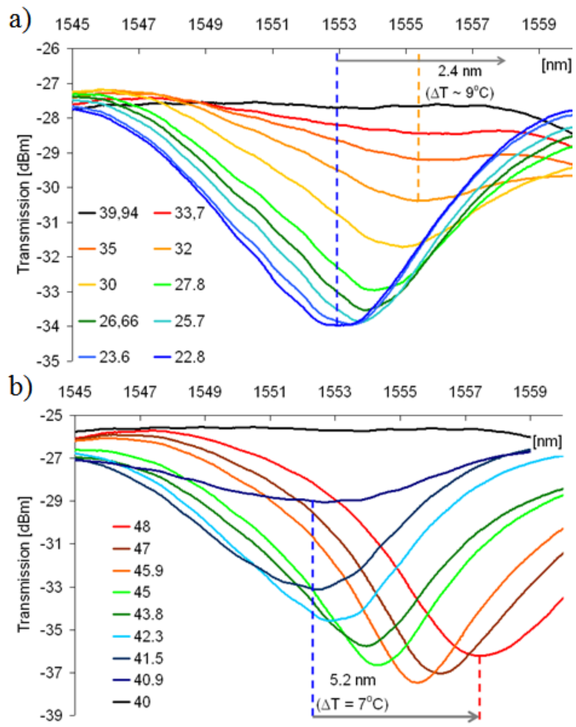

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Fig. 3. The transmission spectra of the LPFG with 1110 LC mixture for the temperature range from 22.8°C to 48 °C: nematic (a) and isotropic (b) phases of the 1110 LC mixture.

In conclusion, we have demonstrated a loss filter with a high-efficiency thermal tuning capability based on an LPFG surrounded by an LC mixture. The wavelength shifts for the LPFGs in air and in the 1110 LC mixture are plotted in Figure 4, showing a near-linear thermal response.

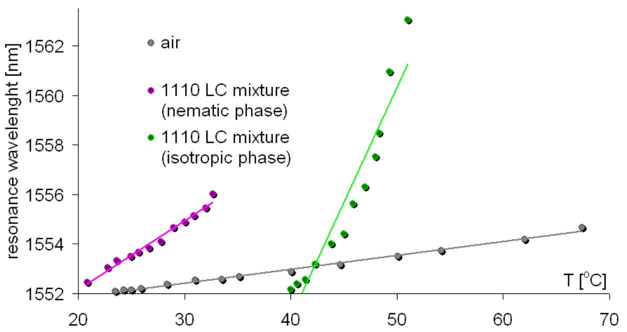

Fig. 4. Comparison of the thermal sensitivity of the resonant wavelength of the LPFG in air and in the 1110 LC mixture.

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

air	1110 Liquid Crystal mixture	
	Nematic phase	Isotropic phase
0.056 [nm/°C]	**0.279** [nm/°C]	**0.929** [nm/°C]

In Table 1 the measured values of the thermal sensitivity are presented. It seems clear that these values for LPFGs with an LC layer are increased by more than one order of magnitude over the values for LPFGs in air. 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 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.

These results show that the idea of integrating LPFGs and LCs into a single component opens up a wide range of new possibilities for developing novel devices capable of tuning light propagation properties. Furthermore, the high-efficiency thermal tuning loss filter demonstrated in this research would permit realization of thermal or electro-thermal tuning for high-speed fiber-optic systems.

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