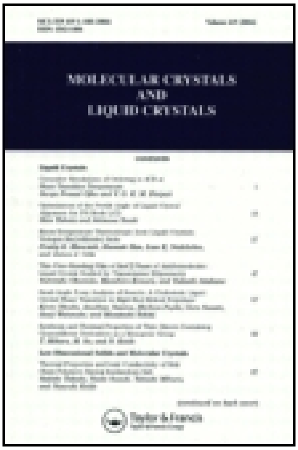

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We propose a cascaded structure of long period fiber gratings (LPFGs) with a liquid crystal (LC) as a surrounding medium. In this structure, the electro-optic tuning properties of each LPFG and the interferences between the spectra of LPFGs are studied. Since the electrically tunable cladding modes are radiation modes which are partially guided by Fresnel reflection, the modal interferences among the cascaded LPFGs are eliminated. The cascaded structure of LPFGs with LC claddings is suitable for arbitrary loss filters that compensate for nonuniform optical gain in an erbium doped fiber.

Keywords: cascaded long period fiber gratings; interference; liquid crystal cladding; radiation mode coupling; tunability

INTRODUCTION

An erbium doped fiber amplifier (EDFA) is useful for constructing a wavelength division multiplexing (WDM) network because it has a broadband optical gain spectrum and requires no conversion process from an optical domain to an electrical domain. However, since the gain spectrum is nonuniform, some gain-flattening filters such as a long period fiber grating (LPFG) should be used for obtaining uniform gain from EDFA. Since LPFG as a band rejection filter shows broadband loss spectra, it has potential to compensate for nonuniform gain from the optical amplifier [1]. However,

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most of conventional optical filters with LPFG are static elements and thus they are not suitable for dynamic control of optical networks.

In a case that a liquid crystal (LC) is used as a surrounding medium of the LPFG, the strength of a mode coupling can be controlled by varying the boundary condition of the cladding [2,3]. In this case, the cladding modes are different from those of most LPFGs which have air boundaries [4–6]. Because the refractive index of the surrounding medium (LC) is higher than that of the cladding (silica), the cladding modes can be leaky when guided by the Fresnel reflection.

In general, several LPFGs compensating for the gain spectra of the EDFA are required for constructing an ideal optical amplifier stage [7,8]. If several LPFGs are cascaded, the final transmissive spectrum has interference fringes between the individual LPFGs [9]. This is the main problem to design a gain-flattening filter.

In this paper, we demonstrate that cascaded LPFGs with LC claddings can control the loss spectra by an electric field across the LC layer and the interferences can be effectively suppressed by partially radiation modes. The cascading effects based on the radiation mode coupling are also described.

THEORY

The periodic core index modulation in each LPFG generates the co-directional mode coupling between the core mode and the cladding mode propagating forward. This produces loss spectra with tens of nanometer in the transmittance. The resonant wavelength, λ_{res}, of the mode coupling is given by the following phase matching condition.

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

where, n_{co}, n_{cl}^{m}, and Λ are the refractive index of the fiber core, the refractive index of the mth order cladding mode, and the periodicity of the index modulation, respectively. In the general case, the strength of the mode coupling, κ, can be described by

$$\kappa \sim \iint \mathbf{e}_{co}^{*}(x,y) \cdot \Delta\varepsilon(x,y)\mathbf{e}_{cl}(x,y)dx\,dy,$$

where $\Delta\varepsilon(x,y)$ is the perturbation in the core, and $\mathbf{e}_{co}(x,y)$ and $\mathbf{e}_{cl}(x,y)$ are the guided core and cladding mode fields, respectively.

The cladding modes are more sensitive to the change in the environment than the core mode. Depending on the boundary condition between the cladding and the surrounding medium, the cladding modes propagate in a different manner. If the refractive index of the surrounding is lower than that of the silica, the cladding modes propagate by total reflection and the resonant wavelengths of the LPFG are shifted by the variations of the refractive index of the surrounding. If the surrounding has the same refractive index of the silica, the cladding modes are totally leaky and the mode coupling can not exist. If the surrounding has a higher refractive index than the silica, the cladding modes are partially radiative and propagate by the Fresnel reflection only. In this case, the cladding mode field, $\mathbf{e}_{cl}(x, y, z)$, has the z component, and the leakage of $\mathbf{e}_{cl}(x, y, z)$ decreases since the difference in the refractive index between the surrounding and the cladding becomes larger. Then, the strength of the mode coupling becomes large and the loss at the resonant wavelength increases. It should be noted that the resonant wavelength remains nearly constant.

Figure 1 shows the director configuration of a nematic liquid crystal (NLC) around a LPFG. Since both the ordinary and extraordinary refractive indices of LC are higher than that of silica, the cladding modes become partially radiation modes. The coupling strength depends on the strength of an applied electric field through the dielectric interaction of LC. In the

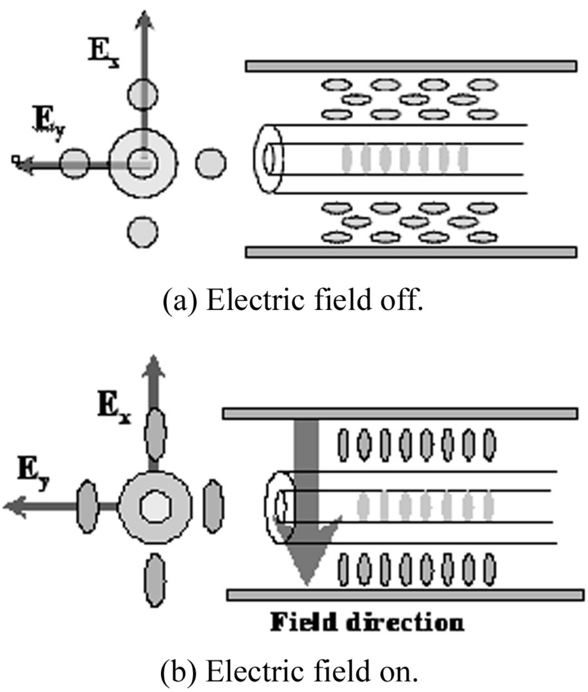

FIGURE 1 The reorientation of NLC around LPFG under an electric field and the corresponding polarization states.

absence of an electric field, the LC director for positive dielectric anisotropy is aligned along the fiber with surface treatment. Then, the propagating transverse cladding modes experience the ordinary refractive index of LC. As the field increases, the cladding modes parallel to the electric field becomes enhanced. In other words, the strength of the mode coupling increases. Note that the orthogonal component is still unchanged.

When ordinary LPFGs with the same order of the mode coupling are cascaded with air boundaries, the transmittance has narrow sinusoidal fringes by the Mach-Zehnder interference. The cladding modes generated in one of the cascaded LPFGs can be recoupled in another LPFG. This induces the interferences because the optical path between the core mode and the recoupled cladding modes are different. However, when the cladding modes are radiation modes, the cladding modes generated in each LPFG are not incorporated into another LPFG and the modal interferences between LPFGs are effectively suppressed. This means that the cascaded LPFGs with the LC cladding produce simple spectra without interference.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the schematic diagram of a LPFG structure with LC cladding. The cascaded LPFGs with LC claddings were fabricated by connecting a series of identical LPFGs. The diameter of the fiber was reduced from 125 μm to 40 μm by chemical etching with hydrofluoric acids. When the diameter of the cladding is reduced, the strength of the mode coupling in LPFGs increases and the spectra of the LPFG are more sensitive to the changes in environment [10]. The refractive index of the silica in the cladding of the fiber is 1.45. The reduced diameter enhances the stability of LC

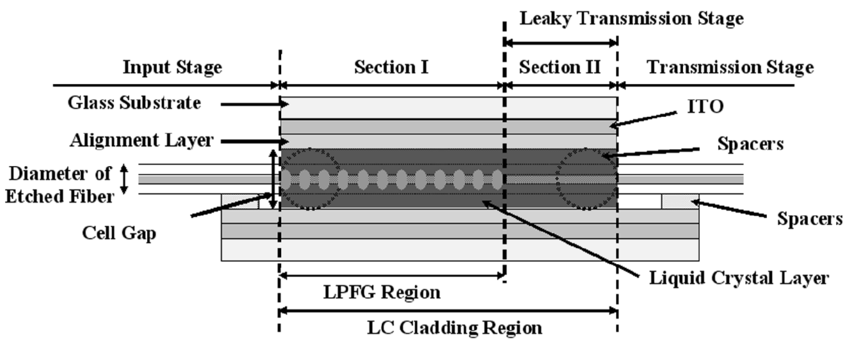

FIGURE 2 The configuration of an etched LPFG with LC cladding.

alignment and lowers the operating voltage. The periodic index modulation in an H_2-loaded fiber core was achieved by UV irradiation through an amplitude modulated photo-mask. The amount of index modulation in the core depends on the UV irradiation time.

The LC cladding was formed by injecting NLC (ZLI-1800-100, E. Merck) between two substrates maintained by 75 μm spacers. The ordinary and extraordinary refractive indices of NLC are 1.4661 and 1.5325 at the wavelength of 1550 nm, respectively. Indium tin oxide (ITO) is deposited on inner surfaces of the substrates to apply an electric field across the cell. On the top of each electrode, poly vinyl alcohol (PVA) was coated to align the LC director homogeneously. The PVA layers were unidirectionally rubbed along the fiber direction, and the resultant director was aligned as shown in Figure 1 (a).

Figure 3 shows the transmittance as a function of the wavelength which exhibits the interference effect in the cascaded LPFGs with LC claddings. The fiber was covered by LC claddings only in the grating region (Section I in Fig. 2). The period and the length of the LPFGs were 500 μm and 3 cm, respectively. Since two LPFGs possess identical resonant wavelengths and the separation between them is sufficiently long (15 cm), the interference between the two LPFGs is considerably large as shown in Figure 3(a). When one of the two LPFGs is covered by LC cladding, the interference becomes small. However, as shown in Figure 3(c), the interference still exists although the two LPFGs are covered by LC claddings. This means that the leakage itself in the grating region is not enough to eliminate the interference. For completely removing the interference, the LC cladding should be extended to the transmission stage (Section II in Fig. 2). Since the core of the fiber has no index modulation in the transmission stage, no more cladding mode is generated and only the leaky effect is present. When LC cladding is extended to the transmission stage, the transmission in cladding mode will be effectively eliminated.

For tailoring various loss spectra, consider a pair of LPFGs having slightly different transmittance spectra. The resonant wavelengths at each LPFG were 1575 nm and 1585 nm, respectively. Note that the LPFGs have the same period and the same length, given by 480 μm and 2.5 cm, respectively. The separation between the two LPFGs was 7 cm. The difference in the resonant wavelengths can be controlled by the UV irradiation time. In order to see the suppression effect of the cladding mode interference, LC cladding was extended to the transmission stage by 60% of the length of LPFG. Although the resonant wavelengths in the cascaded LPFGs were different with each other, the mode numbers of the two LPFGs were identical. For no LC cladding, the interferences between the LPFGs remain in the transmittance as shown by the dashed line in

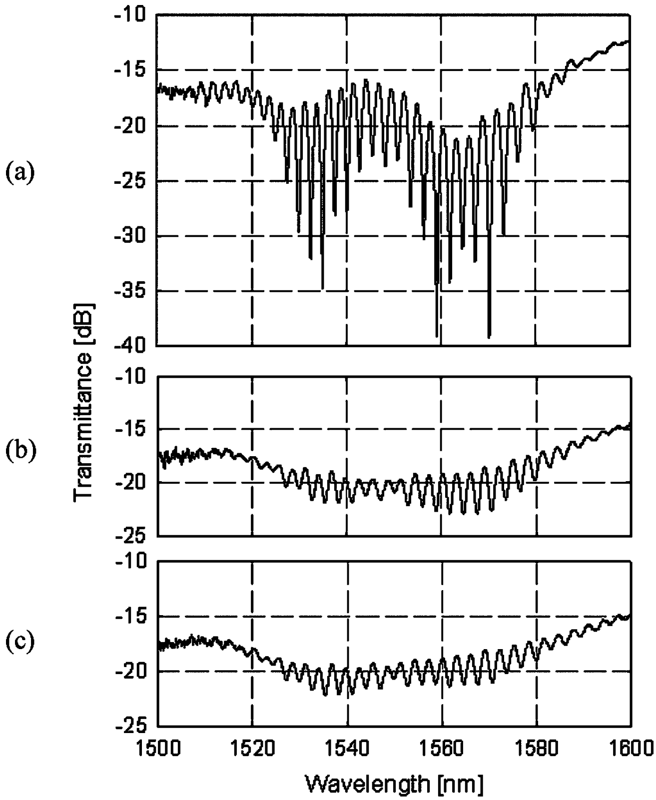

FIGURE 3 The transmittance as a function of the wavelength : (a) with no LC cladding, (b) with LC cladding on one side, and (c) with LC claddings on both sides.

Figure 4. However, for the extended LC claddings, the interferences were substantially suppressed by leakage transmission in Section II in Figure 2 and the solid line in Figure 4. Since each LPFG behaves independently, the output spectrum through the cascaded LPFGs with extended LC claddings can be obtained by multiplying the spectra associated with individual LPFGs.

Figure 5 shows the transmission spectra of the cascaded LPFGs with extended LC claddings at various applied voltages. The unpolarized light was used as an input beam to see the suppression effect only. With increasing the applied electric field, the strength of the mode coupling increases and thus the dip at the resonant wavelength become deep. The variation of the dip was found to be about 2 dB. Since the controlled radiation mode is involved in each LPFG, the resonant wavelength remains unchanged

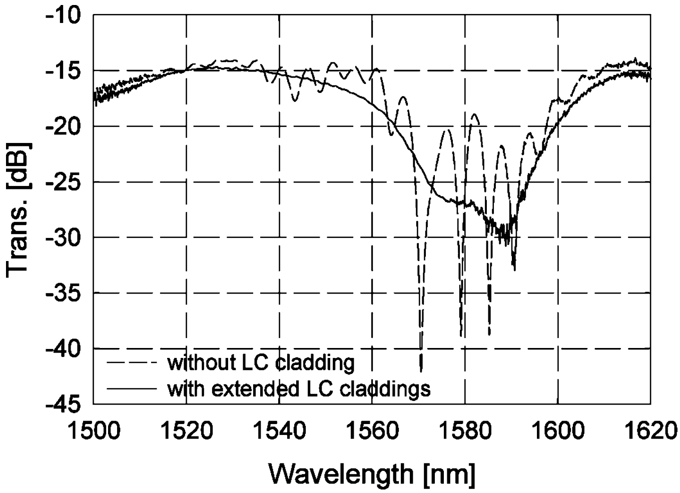

FIGURE 4 The transmittance of the cascaded LPFGs as a function of the wavelength at different surrounding condition.

even under the electric field. It is then concluded that the suppression of the interference can be achieved in the cascaded LPFGs structure with LC claddings. The degree of the suppression depends on the leakage of the cladding mode field.

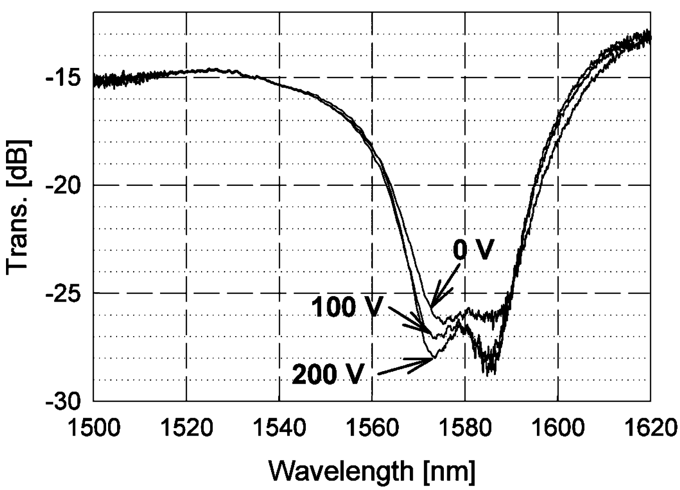

FIGURE 5 The transmittance of the cascaded LPFGs with the extended LC claddings as a function of the wavelength in the presence of various applied voltages.

CONCLUSION

We proposed a cascaded structure of LPFGs with LC claddings. Since the refractive index of LC is higher than that of silica, the cladding modes become the radiation modes which can be partially guided by the Fresnel reflection. The amount of the reflection can be controlled by an electric field across the LC cladding. The interference effects in the cascaded LPFGs can be suppressed using extended LC claddings. Moreover, the LPFG presented here would be very promising for use as a gain-flattening filter of EDFA in the future dynamic optical networks.

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