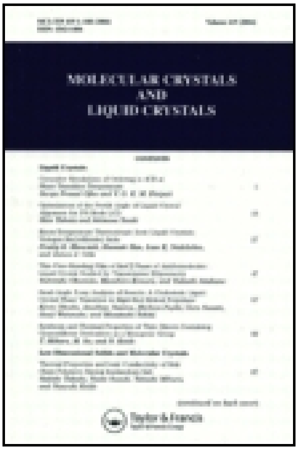

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A Tuneable Waveguided Optical Filter Made of Polymer and Liquid Crystal Slices Operating in C-band: Analysis of Transmission and Reflection Properties

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We present the modelisation and simulation at wavelengths about 1550 nm of a waveguide grating made up of polymer and liquid crystal slices as the core layer and glass as cladding layers. The model combines a matrix-transfer method with a Modal Analysis. The pre-polymerised mixture considered in our calculations is made of NOA61 and 5CB. We derive that the device can behave as either an electrically tuneable narrow notch filter, or a switchable bandpass filter. A tuning range of 7 nm can be obtained for the notch filter with an optical bandwidth at –20 dB less than 1 nm.

Keywords: composite materials; holographic gratings; integrated optics; nematic liquid crystal; optical filters; polymers

INTRODUCTION

In recent years POLICRYPS (POlymer and LIquid CRYstal Slices) have driven much attention to make permanent switchable diffraction gratings [1] that can be used for optical communications, optical data storage and processing. POLICRYPS is the name given to the holographically obtained morphology assumed by a polymeric-nematic liquid crystal (LC) composite material structured in stacks of LC slice/polymer slice [2]. It has been used to fabricate permanent and electrically switchable diffraction gratings which exhibit high diffraction

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efficiency and low switching voltages with respect to PDLC (Polymer Dispersed Liquid Crystlas) [3,4]. Therefore we want to benefit from the robustness and homogeneity of this technique in order to fabricate waveguided Bragg gratings.

In this paper, we model the POLICRYPS grating and adapt the model to integrated optics. Then we assess this device to operate as an optical filter in reflection and in transmission.

STRUCTURE OF THE DEVICE

The structure of the device is sketched in Figure 1. The core of the waveguide consists in the POLICRYPS grating, cladded above and below by an optical buffer (Spin-On Glass) of refractive index 1.4. The boundary conditions imposed by the confining walls of the polymers in the POLICRYPS ensures that the LC alignment is along the z-axis. The electrodes are put below and above the claddings, which are assumed thick enough so that we could neglect their effects.

The polymer used for the POLICRYPS is NOA 61, whose refractive index at $\lambda_0 = 1550$ nm is $n_P = 1.5419$, and the nematic LC is 5CB, whose ordinary and extraordinary refractive indices are respectively 1.5108 and 1.6807 at 20°C.

The thickness of the core is taken 1.1 μm so that the waveguide is monomode at $\lambda = 1550$ nm for refractive indices in vicinity of the one of the polymer.

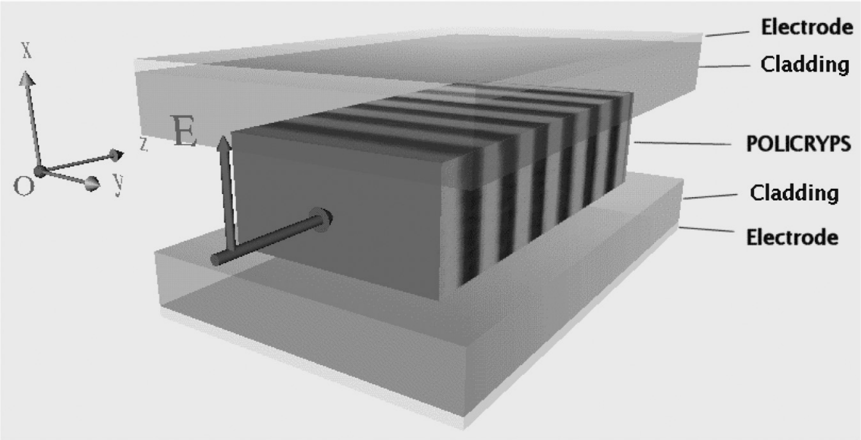

FIGURE 1 Structure of the waveguided grating. (See COLOR PLATE XXXV)

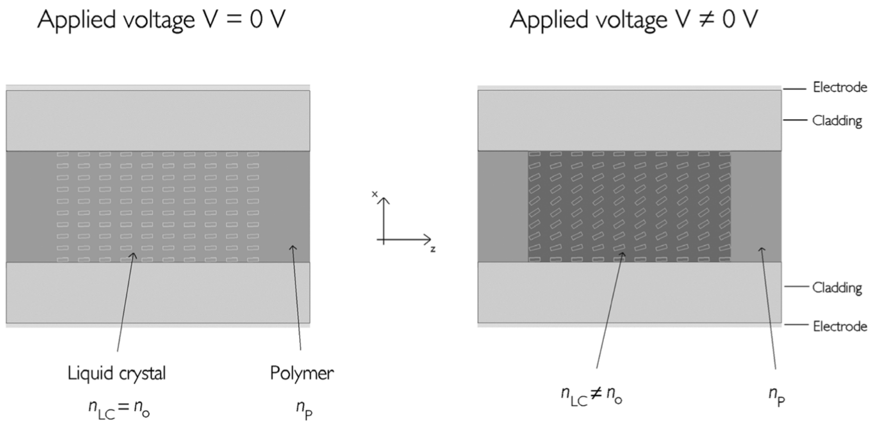

FIGURE 2 Orientation of the molecules and refractive index change when the applied voltage is 0 V (left) and non-0 V (right). (See COLOR PLATE XXXVI)

In the absence of external electrical field, the director of the LC molecules is aligned normally to the Polymer/LC interface (homeotropic alignment), as observed experimentally in a standard POLICRYPS cell [3]. A TM optical field propagating along (Oz) will see the ordinary index n_o of the LC. Applying an external electrical field (see Fig. 2), the molecules rotate in the plane (xz) and the TM optical field will see a refractive index $n \in [n_o; n_e]$.

To explain the operation of the device, let us consider (Fig. 3) that the starting point is the perfect matching between LC and polymer refractive indices. Varying the external electrical field, one can vary the index mismatch, letting the Bragg grating appear and opening a photonic band gap in the transmission curve. The index mismatch influences the optical path length therefore the position of the gap given by the Bragg relation, $l\lambda = 2n\Lambda$ (l being the order, n being an average refractive index and Λ being the length of the grating period), the gap width and the transmission minimum. In the case of small index relative mismatch $\Delta = |n_{LC}\text{-}n_P|/n_P$, the relative bandwith is [5]:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta}{2}$$

The behaviour of the grating should be described by the Floquet theorem and Bloch equations [5]. However the coupled-mode theory or a perturbation method have also been used [6] in cases where the grating is not periodic or where the waveguide is weakly coupled with the grating. In our case, the grating occupies the entire core of the

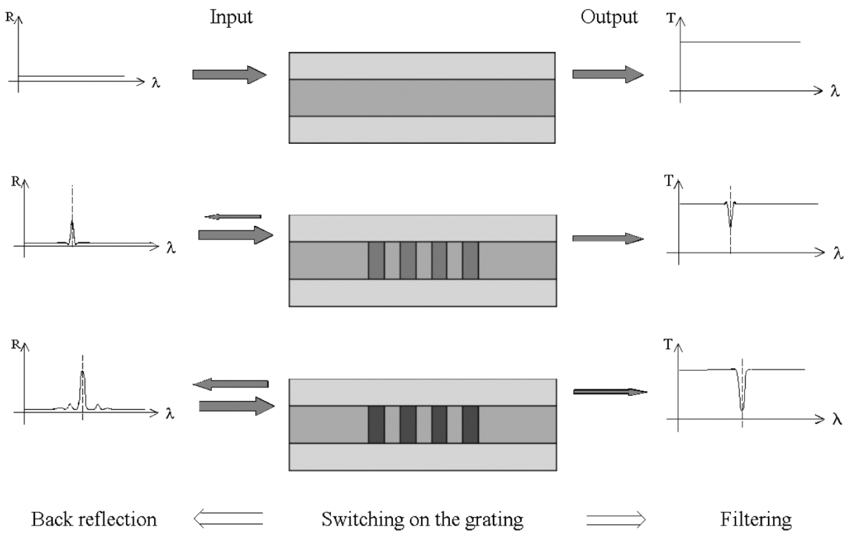

FIGURE 3 Switching operation of the grating. (See COLOR PLATE XXXVII)

waveguide and the grating period is rather long. Our approach is to use a transfer-matrix method for the amplitudes of the guided modes.

NUMERICAL MODEL

We write the electric field transverse component of the guided light along the x direction for the forward (F) and backward (B) propagation:

$$\begin{cases} \vec{E}^F = A.E_0(x)e^{i(wt-\beta z)}.\vec{u}_x \\ \vec{E}^B = B.E_0(x)e^{i(wt+\beta z)}.\vec{u}_x \end{cases}$$

where E_0 is the normalized mode in the considered region (polymer or LC), β is its propagation constant and A and B are constant in one slice. The condition for crossing an interface between the slice m and the slice $m+1$ can then be written:

$$\begin{cases} E_m^F + E_m^B + E_{ug,m} = E_{m+1}^F + E_{m+1}^B + E_{ug,m+1} \\ \frac{n_m^2}{N_m}E_m^F - \frac{n_m^2}{N_m}E_m^B + E'_{ug,m} = \frac{n_{m+1}^2}{N_{m+1}}E_{m+1}^F - \frac{n_{m+1}^2}{N_{m+1}}E_{m+1}^B + E'_{ug,m+1} \end{cases}$$

where N_m is the effective index for TM-polarization calculated in the slice m of refractive index n_m (see [5] for a complementary discussion on the calculation of N for TM polarization in corrugated media), and E_{ug} is the unguided (radiative) field due to the fact that the overlap integral between the modes $E_{0,m}$ to $E_{0,m+1}$ is not unitary. However the radiative power in slice m coming from the mode mismatch with slice m-1 will be able to couple back in slice $m+1$ if the radiative mode does not diverge too much. That is the reason why we choose the hypothesis:

$$\int E_{0,m} E^*_{ug,m} \mathrm{d}x = 0$$

$$\int E_{0,m} E^*_{ug,m+1} \mathrm{d}x \leftarrow 0$$

The consequences of this assumption are:

we take into account the decrease of efficiency due to the fact that at each interface a small part of the power will not participate;
we tend to over-evaluate the transmit power (no scattering loss);
we do not take into account the noise due to unguided light.

Using the following notations for the overlap integrals:

$$I = \int E_{0,m} E^*_{0,m+1} \mathrm{d}x, \quad J_m = \int n^2 |E_{0,m} E_{0,m}|^2 \mathrm{d}x,$$
$$K_m = \int n^2 E_{0,m+1} . E^*_{0,m} \mathrm{d}x$$

we project the condition of interface crossing upon E_m and express it respect to A and B. For one period it leads to:

$$\begin{pmatrix} A_{m-1} \\ B_{m-1} \end{pmatrix} = \begin{pmatrix} I & I \\ \frac{K_{m-1}}{N_{m-1}} & -\frac{K_{m-1}}{N_{m-1}} \end{pmatrix}^{-1} \begin{pmatrix} 1 & 1 \\ \frac{J_m}{N_m} & -\frac{J_m}{N_m} \end{pmatrix}$$
$$\times \begin{pmatrix} e^{j\frac{2\pi N_m}{\lambda}d} & 0 \\ 0 & e^{-j\frac{2\pi N_m}{\lambda}d} \end{pmatrix} \begin{pmatrix} I & I \\ \frac{J_m}{N_m} & -\frac{J_m}{N_m} \end{pmatrix}^{-1}$$
$$\times \begin{pmatrix} I & I \\ \frac{K_{m+1}}{N_{m+1}} & -\frac{K_{m+1}}{N_{m+1}} \end{pmatrix} \begin{pmatrix} e^{j\frac{2\pi N_{m+1}}{\lambda}d} & 0 \\ 0 & e^{-j\frac{2\pi N_{m+1}}{\lambda}d} \end{pmatrix} \begin{pmatrix} A_{m+1} \\ B_{m+1} \end{pmatrix}$$

The overall transfer matrix of the grating is then:

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = \left(\prod_{m=1}^{M} M_p M_{LC} \right) \begin{pmatrix} A_{2M} \\ B_{2M} \end{pmatrix} = \begin{pmatrix} C & D \\ E & F \end{pmatrix} \begin{pmatrix} A_{2M} \\ B_{2M} \end{pmatrix}$$

A 1D modal analysis permits to calculate the effective indexes, the mode profiles therefore the overlap integrals I, J and K. Then we compute the matrices multiplication to calculate the overall transfer matrix and deduce the reflection and transmission coefficients which are given by:

$$R = \left| \left(\frac{B_0}{A_0} \right)_{B_{2M+1}=0} \right|^2 = \left| \frac{E}{C} \right|^2$$

$$T = \left| \left(\frac{A_{2M} + 1}{A_0} \right)_{B_{2M+1}=0} \right|^2 = \left| \frac{1}{C} \right|^2$$

SIMULATION DATA

By hypothesis we choose equal phase shifts in LC and polymer slices, and higher-order ($l > 1$) grating operation (hence grating periods in the range of photolithography capacity, and narrower optical bandwidth). For a filter centred at $\lambda_0 = 1550\,\text{nm}$, the liquid crystal slice width is 1.31 μm and the polymer slice width is 1.31 μm, the grating period is 2.62 μm.

The thickness of the POLICRYPS being 1.1 μm, the polymer effective index is 1.4822.

We have noted that the effective index should be calculated at each wavelength, whereas the refractive index dispersion can be neglected.

RESULTS OF SIMULATION FOR REFLECTIVE FILTERS

We bias the grating to obtain the effective index: $N_{LC} = 1.4827$. The curve in reflection for a 4000 period long grating (about 1 cm long) is shown in Figure 4. The bandwidth at -3 dB is 0.11 nm, and 0.7 nm at -20 dB. Figure 5 shows that beyond 500 periods the 3 dB bandwidth is lower than 1 nm, and gets stable for more than 1500 periods. Tuning the bias, the bandwidth and the peak wavelength change. Figure 6 shows the tuning capability, about the operation point where the peak wavelength is 1.55 μm (bias down to 0 V voltage, *i.e.*, the index of the liquid crystal being the ordinary index 1.5108). The tuning range can thus be determined given the specifications on the side-lobes levels and filter bandwidth for a specific application.

RESULTS OF SIMULATION FOR FILTERS IN TRANSMISSION

In transmission, the device behaves as a notch filter. The curve corresponding to an effective index $N_{LC} = 1.4827$ and a length of 4000

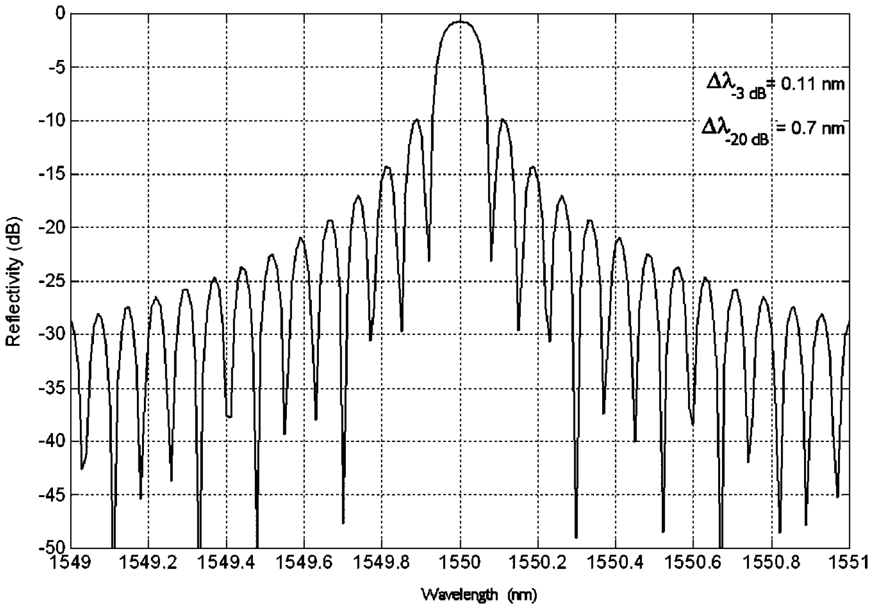

FIGURE 4 Reflectivity for an effective-index contrast of 5×10^{-4}.

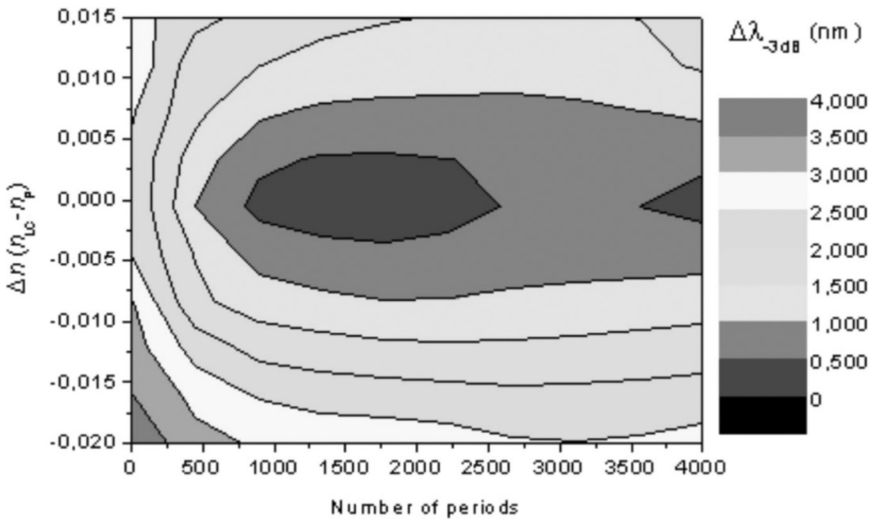

FIGURE 5 Bandwidth versus grating length and index contrast. (See COLOR PLATE XXXVIII)

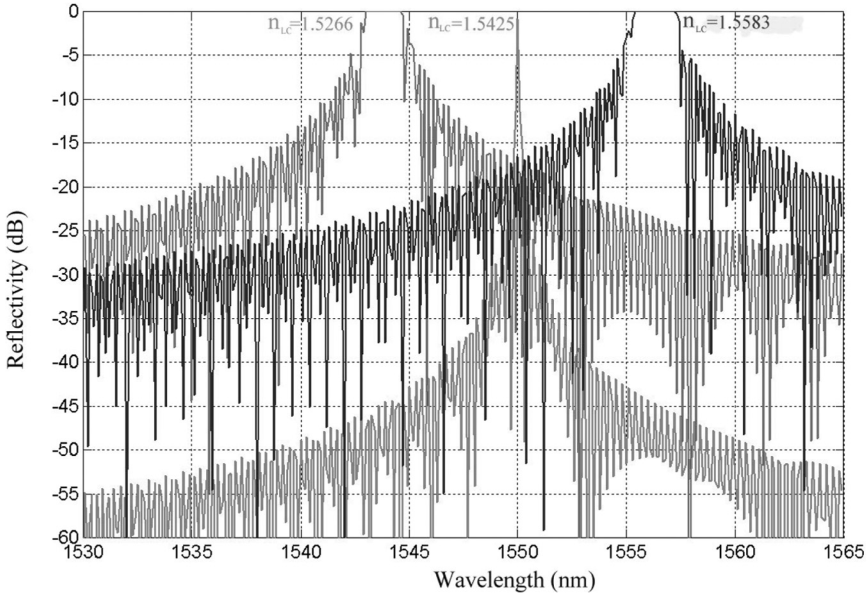

FIGURE 6 Tunability in reflection for 3 different indices of the liquid crystal. (See COLOR PLATE XXXIX)

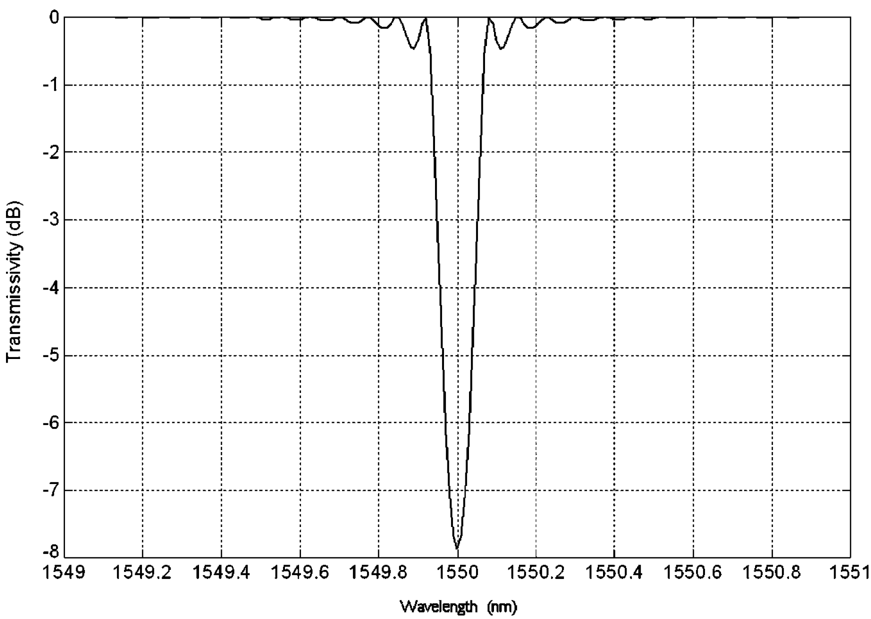

FIGURE 7 Transmissivity for an effective-index contrast of 5.10^{-4}.

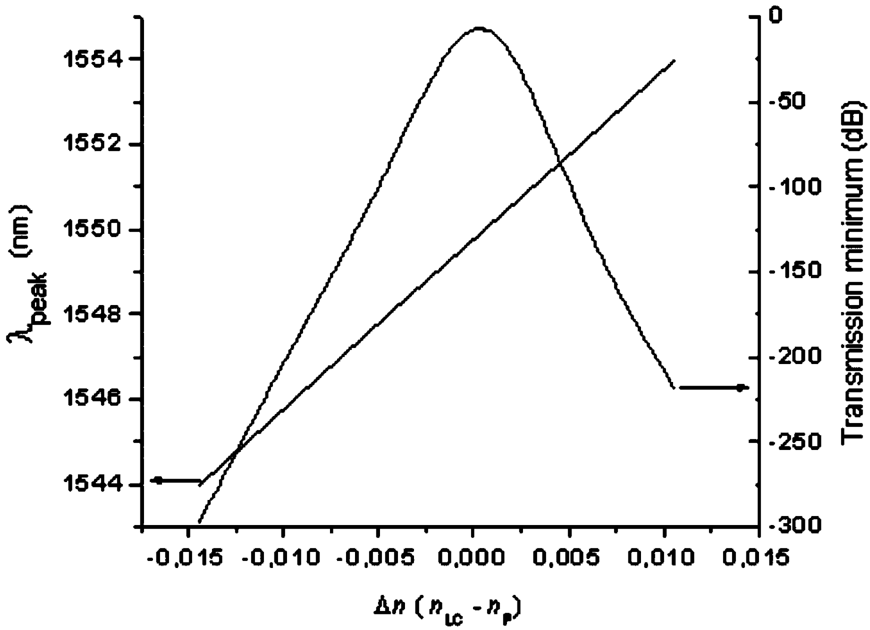

FIGURE 8 Position of the peak and its extinction versus the index contrast.

periods is shown on Figure 7. The bandwidth at –3 dB is 0.11 nm, but the extinction is only 8 dB because the refractive index of the LC is very close to the one of the polymer. Figure 8 shows that the extinction increases dramatically with the index contrast, while the bandwidth can be kept narrow with a relatively short grating, as indicated in Figure 9.

In Figure 10, four different filtered wavelengths are represented, within the tuning range of 7 nm.

Gratings can be designed (stacked, chirped or apodized) in order to produce specific shape filter or even bandpass filters.

MODELLING THE ELECTRO-OPTICAL EFFECT

The effective index of the Liquid Crystal slices was calculated by modal analysis from the refractive index profile. The latter can be derived from the director orientation as calculated by using LC3D software (director calculation software provided by the Liquid Crystal Institute at Kent State University), which minimizes the free-energy of the LC. The elastic constants were considered $\kappa_{11} = 6.4\,\text{pN}$,

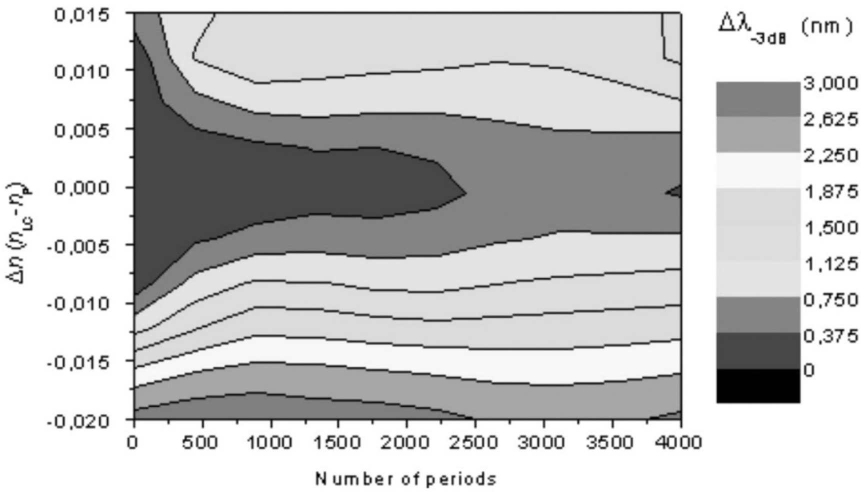

FIGURE 9 Bandwidth versus the index contrast and the grating length. (See COLOR PLATE XL)

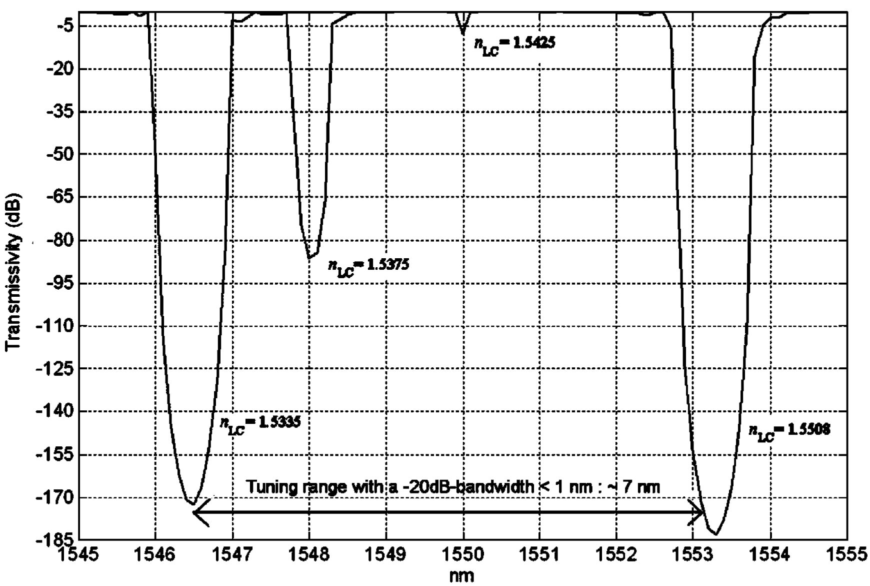

FIGURE 10 Tunability in transmission.

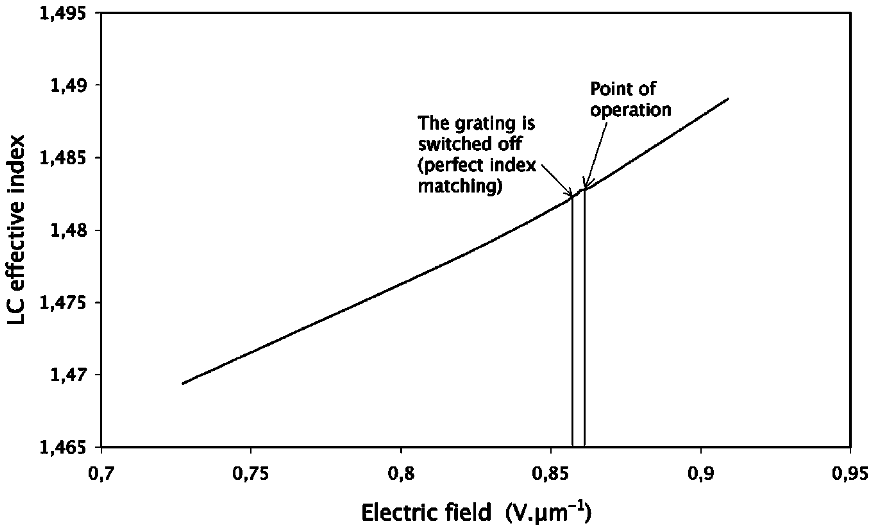

FIGURE 11 LC effective index versus the applied electric field.

$\kappa_{22} = 4$ pN, $\kappa_{33} = 10$ pN, dielectric anisotropy $\Delta\varepsilon = 11.8$, and pretilt angle of 2°. As shown in Figure 11, the operation point results from a small variation of the applied voltage, typically some 10 mV from the bias at about 3 V. The dependency of the LC effective index on the external electric field is:

$$\frac{\partial N_{LC}}{\partial E} = 0.087\,\mu\text{m} \cdot \text{V}^{-1}$$

CONCLUSION

Using a model based on the method of lines, we have calculated the response for TM-polarized light of a POLICRYPS monomode waveguide grating in reflection and transmission, in the C-band.

We have shown that such a grating can exhibit narrow filtering properties and can be tuned just by varying of few mV the bias voltage of only 3 V.

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