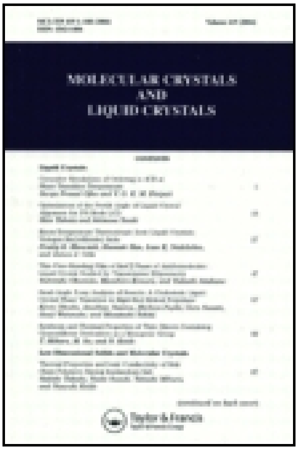


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# Optical Characterization at Wavelengths of 632.8 NM and 1549 NM of Policryps Switchable Diffraction Gratings

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# OPTICAL CHARACTERIZATION AT WAVELENGTHS OF 632.8 NM AND 1549 NM OF POLICRYPS SWITCHABLE DIFFRACTION GRATINGS

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*Optical characterization at the wavelengths of 632.8 nm and 1549 nm of an electrically switchable POLICRYPS grating sample is reported. The sample consists of a 10 μm thick cell made of ITO coated glass filled with a mixture of 30% nematic liquid crystal 5CB and pre-polymer NOA61. The grating with a period of 1.34 μm was written by laser curing at wavelength of 351 nm. A self-aligning setup both for visible and for infrared was used for the characterization. At the Bragg angle the grating starts to be switched off by applying an electric field of 2.5 V/μm and complete switching occurs at about 5 V/μm both at visible and at infrared. The grating shows a switching time of about 4 ms for both wavelengths. A FWHM of about 7° was measured at 1549 nm, corresponding to an optical bandwidth of about* $\Delta\lambda = 266$ *nm.*

*Keywords*: optical switches; diffraction gratings; polymers; liquid crystal

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## INTRODUCTION

Liquid crystal switchable diffraction gratings are interesting devices which can be used as basic components to implement a wide variety of functions in WDM telecommunications systems, such as optical switching, wavelength routing, filtering and spectral equalization, or for other applications such as flat panel displays, beam steering in laser radar and tunable diffractive filters. Several experiments using different mixtures have been carried out, exploiting the possibility offered from liquid crystal (LC) composites to obtain refractive index modulation by the director axis reorientation effect. In particular laser induced gratings can be created in dye-doped nematic liquid crystals [1–4], or in polymer-dispersed liquid crystals (PDLCs) [5–8]. The common goal especially for devices to be used in optical communications is to reach high diffraction efficiency in gratings obtainable by simple and cheap processes.

A new technique has been recently explored [9] to create permanent switchable gratings in structures called POLICRYPS (POlymer LIquid CRYstal Polymer Slides). A laser curing process is used in a nematic liquid crystal (NLC) and polymer mixture to obtain a grating composed of a sequence of aligned LC layers separated by polymer layers. The control of the parameters involved in the polymerization process and in the used mixture allows to reach a nearly complete separation polymer-LC. Such gratings show high diffraction efficiency, with a reduction of scattering losses and switching voltages in comparison with PDLC gratings. A diffusion model has been presented to explain the formation of the POLICRYPS diffraction gratings and experimental results seem to be consistent with theoretical interpretation [10].

In this paper preliminary experimental measurements of a POLICRYPS cell are reported. The measurements were carried out by means of probing beams both at the visible wavelength of 632.8 nm and at the infrared wavelength of 1549 nm . The behavior of the diffraction efficiency of the first diffraction order versus the applied electric field, the extinction ratio, and the switching time, for the two wavelengths are reported. The angular grating selectivity at 1549 nm is also reported to evaluate the bandwidth of the device for its use in WDM systems.

The working principle of a POLICRYPS grating is based on the possibility to align the LC molecules along an applied electric field. This effect implies to a variation of the liquid crystal refractive index for the incident beam. At the electric field value for which a perfect matching between the LC refractive index $n_{LC}$ and the polymer refractive index $n_{pol}$ is reached, there is a temporary deletion of the grating, which can be restored by removing the applied field. Therefore when no electric field $\mathbf{E}$ is applied ($n_{LC} \neq n_{pol}$) a fraction of the beam incident on the grating is diffracted (Fig. 1a), while

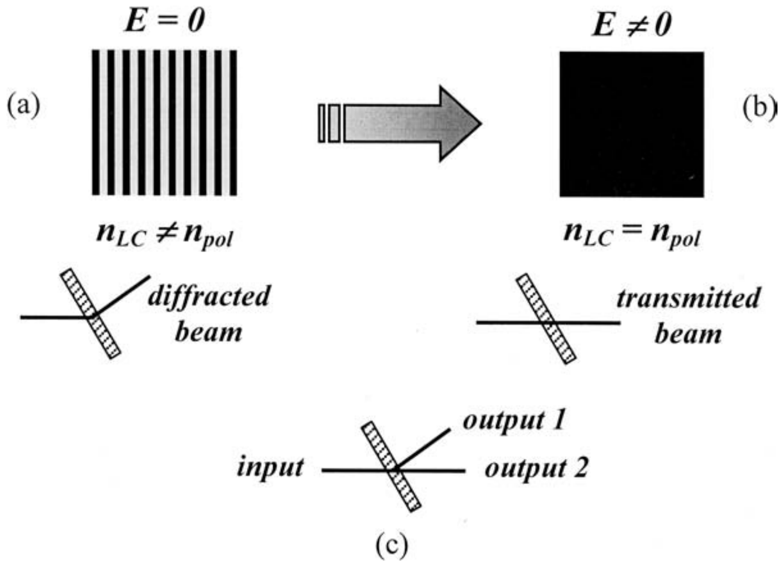


**FIGURE 1** Working principle of a POLICRYPS grating with $\mathbf{E} = 0$ (a), with $\mathbf{E} \neq 0$ (b) and application as an optical switch (c).

with the **E** field applied ($n_{LC} = n_{pol}$), the diffracted beam is switched off (Fig. 1b). If the diffraction efficiency is high enough (almost 100%), the grating can be used as a an optical switch $1 \times 2$ (one input-two outputs) as sketched in Figure 1c.

From the optical point of view, the POLICRYPS samples behave as Bragg diffraction gratings. In Figure 2 a sketch of the experimental geometry is reported. The Wavevectors $\mathbf{K}_{1,2}$ represent the curing beams while $\mathbf{K}_{P,D}$, indicate respectively the probe and the diffracted ones. The **K** wavevector is related to the second order diffraction maximum and $\Delta$ is its wave mismatch. The diffracted beam angle $\theta$ can be simply evaluated using the relation:

$$\Lambda = \frac{\lambda}{2 \sin \theta} \tag{1}$$

where $\Lambda$ is the grating fringe spacing and $\lambda$ the probe wavelength.

## SAMPLE PREPARATION

The POLICRYPS grating used for our measurements was realized in a cell with a thickness of 10 μm (measured by a standard spectroscopic technique before filling the sample). The sample consisted of two ITO coated

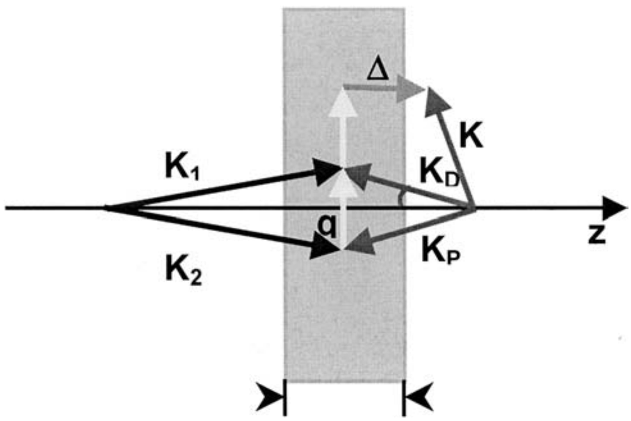


**FIGURE 2** Sketch of the experimental geometry. $\mathbf{K}_{1,2}$: UV curing beam wave vectors, **q**: grating wave vector, $\mathbf{K}_{P,D}$: probe and 1st diffraction order wave vectors, $\theta$: diffraction angle, **K**: 2nd diffraction order wave vector, $\Delta$: 2nd order wave mismatch, **L**: sample thickness, **x,z**: cartesian axes. $\mathbf{n}_0$ represents the alignment of LC director, perpendicular to the grating fringes.

glass slabs separated by mylar spacers. The initial mixture was prepared by diluting the NLC 5CB in the pre-polymer system Norland Optical Adhesive NOA-61. The NLC load was about 30% by weight of the total concentration. The particular pre-polymer system utilized in the mixture is photo-sensitive to UV radiation: the exposure of this system to such radiation induces a polymerization reaction in it. This process is usually referred to as curing. In order to obtain a diffraction grating, the sample is, in general, cured by the inhomogeneous intensity pattern produced by two interfering laser beams. The experimental set-up for the UV curing process is presented in Figure 3.

A single (transverse) mode beam from an Ar-ion laser operating at the wavelength $\lambda_B = 351\,\text{nm}$ (Coherent Innova 90 C), is broadened by the beam expander (BE) up to a diameter of about 25 mm. Further, it is divided into two beams of nearly the same intensity ($I_1/I_2 = 0.95 \pm 0.02$) by the beam splitter (BS). The intensity either of the main beam or of the one reflected by the BS are controlled by a half wave plate followed by a polarizer (PP). These two beams intersect at the entrance plane of the sample, thus providing an interference pattern whose spatial period is $\Lambda = 1.34\,\mu\text{m}$. An aperture A of 4 mm diameter is placed immediately before the entrance slab of the sample to provide a uniform intensity of the curing radiation all over the exposed part of the sample; the light polarization is s-type, i.e. with the electric vector **E** aligned along the fringes of the pattern.

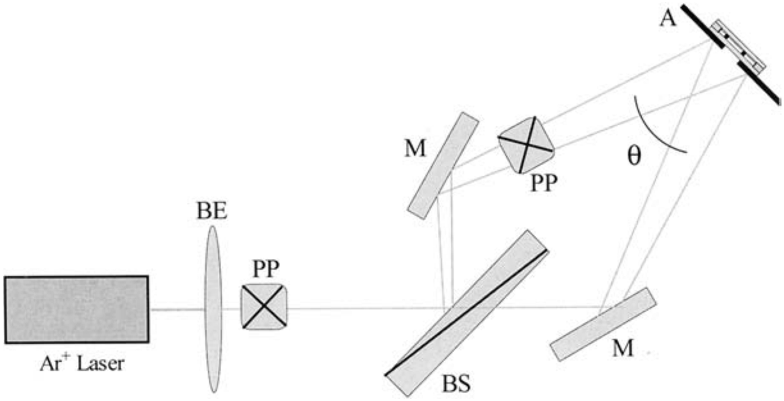


**FIGURE 3** Optical set-up for curing gratings. BE: Beam Expander, PP: half wave plate and polarizer, BS: Beam splitter, M: Mirror, A: Aperture.

The curing intensity was about 6 mw/cm$^2$. This intensity was experimentally found out to be optimal from the viewpoint of resulting diffraction efficiency of the grating obtained (see also [10]). As for exposure time, it was always 1000 s, which was found to be enough for the completion of polymerization reaction (no long term changes of the grating properties after exposition). Polarized optical microscope and probe laser beam analysis of the grating show that the fringes containing LC molecules present a well aligned continuous nematic phase with the LC molecules homeotropically aligned with respect the polymeric walls.

## MEASUREMENTS AND EXPERIMENTAL RESULTS

The preliminary optical characterization of one POLICRYPS grating was carried out by using the setup sketched in Figure 4. The sample was positioned on a rotatory-translation stage driven, by a dedicated software, in order to find the angle of incidence for best diffraction efficiency defined as the ratio between the power of the first diffraction order and the total transmitted power. The measurement setup included single-mode optical fibers with FC connectors and two different lasers, an He-Ne emitting at the visible wavelength of 632.8 nm and a DFB quantum well infrared laser emitting at 1549 nm. In the setup a self-alignment system allowed to switch from visible to infrared characterization, just by changing the fiber in section A of Figure 4. The polarization of light emitted by the DFB laser and outcoming from collimator 2 was controlled by a pigtailed polarization controller. Zero-th and first order diffracted beams were collected by a silicon photodetector for visible light and by an indium gallium arsenide

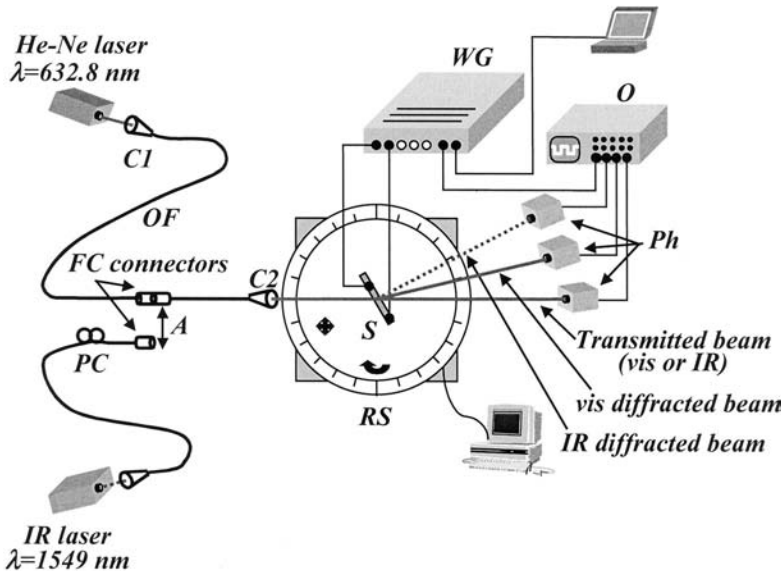


**FIGURE 4** Characterization setup operating at infrared and visible wavelengths. WG: Waveform generator, O: Oscilloscope, Ph: Photodetector, RS: Rotary stage, S: Sample, PC: Polarization controller, C1: Collimator1, C2: Collimator2, OF: single-mode optical fiber.

photodetector for the infrared respectively, positioned at two different Bragg angles for the two corresponding different wavelengths. A digital oscilloscope was used to visualise the photodetector's outputs. An arbitrary waveform generator driven by a computer through a dedicated software supplied the voltage signal to switch the LC and to delete the grating. The characterization was carried both for visible and infrared wavelengths using p polarization.

Figure 5 shows the diffraction efficiency at 632.8 nm, with the sample positioned at the Bragg angle of 13.6°, at 25.5°C, for different values of the electric field applied to the cell in order to estimate the device switching features. The used driving voltages were square waveforms of 1 kHZ frequency and amplitude ranging from 0 V to 60 V. At the Bragg angle the diffraction efficiency with no voltage applied was 83.7%. The optical response shows that switching of this cell begun by applying 2.5 V/μm. An increase of the electric field caused the decrease of the diffracted beam intensity, till a minimum of the diffraction efficiency of 0.75% when the applied electric field was 5.6 V/μm.

Diffraction efficiency at 1549 nm for different applied electric fields, at the same temperature of 25.5°C, and with the cell tilted by an angle of

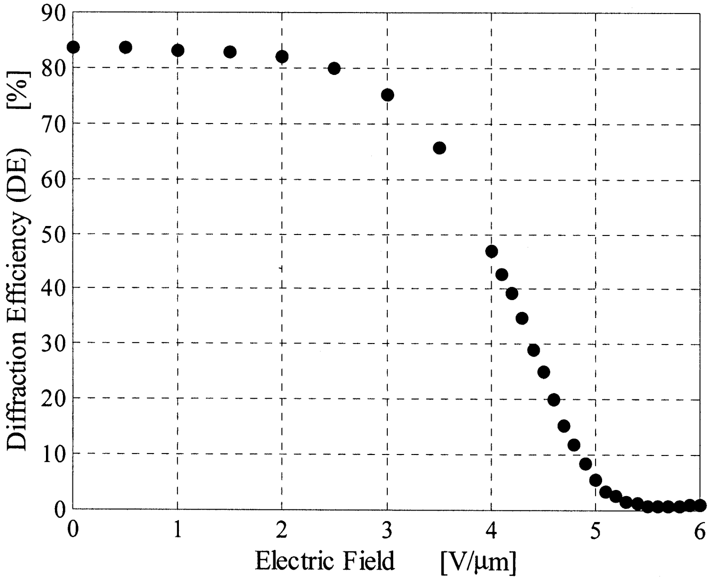


**FIGURE 5** Diffracted efficiency of a POLICRYPS grating versus electric field at 632.8 nm.



about 35.8° (Bragg condition at 1549 nm) with respect to the incident beam are reported in Figure 6. The diffraction efficiency when no field is applied was 14.3%. In this case the switching begun with an electric field of about 2 V/µm, reaching the minimum of the diffraction efficiency of 1.22% with 5.2 V/µm. Moreover at higher electric fields the intensity of the diffracted beam re-increased due to the fact that when the molecules axis are almost perpendicular to the cell plane, so that the refractive index of the liquid crystal is different from that one of the polymer.

Measurements of the diffraction efficiency at 1549 nm with no field applied, at the Bragg angle, with lower temperatures show an improvements reaching a value of about 17% at 20.3°C.

A parameter to evaluate an optical switch is the on-off extinction ratio defined as the ratio (in dB) between the power P of the diffracted beam with the voltage applied and the power $P_{off}$ of the same beam without voltage:

$$ER = 10 \log \frac{P}{P_{off}} \tag{2}$$

The extinction ratio measured for different electric field intensities is reported in Figure 7, at the wavelength of 632.8 nm and at 1549 nm.

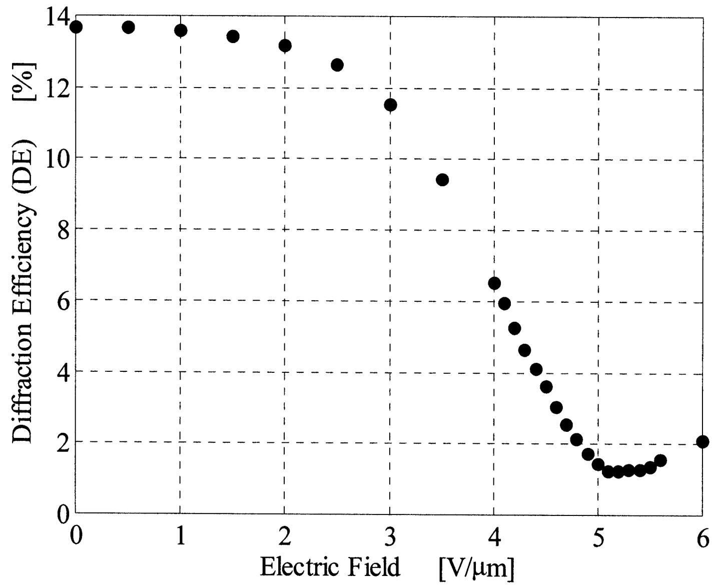


**FIGURE 6** Diffracted efficiency of a POLICRYPS grating versus electric field at 1549 nm.

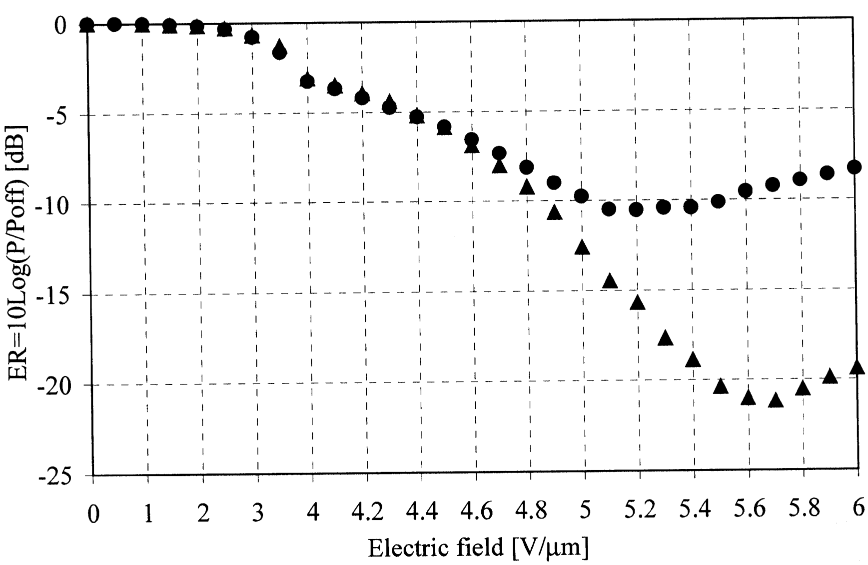


**FIGURE 7** Extinction ratios in the visible (triangles: $\lambda = 632.8\,nm$) and in the infrared (circles: $\lambda = 1549\,nm$) versus electric field.

A minimum of ER = −21.17 dB at 632.8 nm and ER = −10.54 dB at 1549 nm can be observed.

In order to test the possibility to use POLICRYPS gratings as optical switches, another important measurement that was performed is the switching time, defined as the time required for the optical response signal to rise from 10% to 90% of the maximum intensity. The switching time at 632.8 nm was bout 4 ms. It was measured applying a burst of bipolar rectangular pulses of 1 kHz frequency and electric field of 4.7 V/μm applied at the sample. The same value of about 4 ms was measured also at the infrared wavelength of 1549 nm by applying a train of square waves of 1 kHz and electric field of 4.4 V/μm. Figure 8 reports the oscilloscope trace of the diffracted beam intensity with signal applied to the sample to measure the switching time at 1549 nm.

The experimental setup of Figure 4 was also used to measure the diffraction efficiency with no voltage applied to the cell, for a set if incident angles centered at the Bragg angle of about 35.8°. These measurements are reported in Figure 9, where the angular grating bandwidth defined as full width half maximum (FWHM) is $\Delta\vartheta_{FWHM} \cong 7°$. Differentiating the Bragg condition (1) is possible to obtain a grating optical bandwidth of:

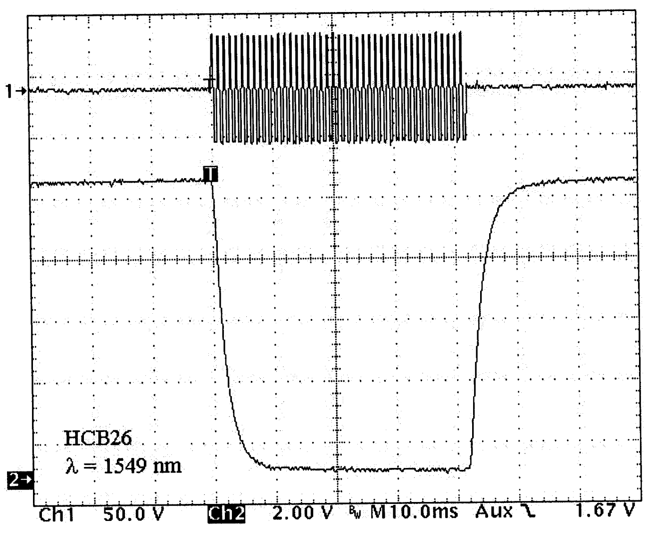


**FIGURE 8** Optical response (lower trace) of the diffracted beam intensity by applying a burst of bipolar rectangular pulses (upper trace) to evaluate the switching time at $\lambda = 1549$ nm.

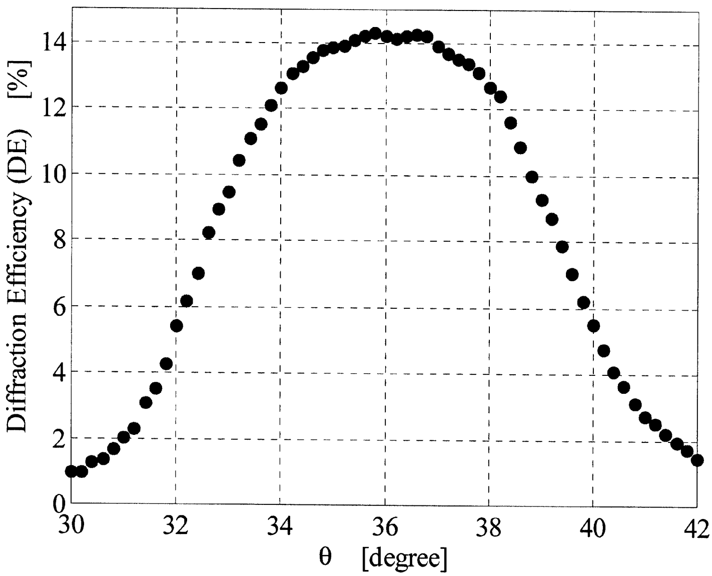


**FIGURE 9** Diffraction efficiency (DE) versus incident angle at $\lambda = 1549\,\text{nm}$.

$$\Delta\lambda = 2\Lambda \cos \vartheta \Delta\vartheta \cong 266\,\text{nm} \tag{3}$$

The optical bandwidth is quite large, which means that the device could be used as optical switch over a wide spectrum which includes conventional C–band (1530–1560 nm) of optical fibers used in the long haul fiber optic networks.

## CONCLUSIONS

A first characterization at the wavelengths of 632.8 nm and at 1549 nm of a POLICRYPS switchable diffraction grating was carried out. The switching time was just 4 ms, extinction ratios were over 20 dB in the visible and over 10 dB in the infrared, and optical bandwidth of about 266 nm. At this preliminary stage we can conclude that POLICRYPS behave as a large bandwidth optical switches whose performance can be improved to meet requirements also for optical communication systems.

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