Polarization-controlled wavelength modulation by a resonant transmission or reflection filter

Mario Ivanov and Paul Rochon
Royal Military College of Canada, Department of Physics, P.O. Box 17000, Station Forces, Kingston, Ontario K7K 7B4, Canada
E-mail: mario.ivanov@rmc.ca

Abstract. A relief diffraction grating is holographically recorded in azo-polymer. The polymer layer under the grating serves as a waveguide for the light coupled by the grating. When a guiding condition is met, sharp minima appear in the transmitted spectrum and sharp maxima appear in the reflected spectrum. Since the resonance conditions for transverse electric (TE) and transverse magnetic (TM) polarized waves occur at different wavelengths, the effect can be used for fast wavelength encoding of a binary signal. The speed of such a device would be limited only by the speed of the encoding part, which changes the azimuth of the input linearly polarized light.
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1 Introduction

Corrugated waveguides exhibit resonance-enhanced optical transmission and reflection properties and have been of interest as devices that can be used to modulate light in the visible and near infrared (NIR). In these devices, a surface relief diffraction grating is inscribed on a slab waveguide, or a grating structure is embedded in a waveguide. In either case, the complete structure acts as an effective waveguide with well-defined guiding modes. The gratings act to couple light into the guided modes, which results in sharp peaks in the transmission and reflection spectra under plane wave illumination.[1] The observed peaks depend on the wavelength and angle of incidence of the light hitting the structure.

These resonance-type anomalies have been studied for many years[2–5] and have been successfully modeled using rigorous coupled-wave theory.[6] The fabrication of the gratings is usually quite demanding[7,8] and can be a drawback in practical applications; however, recent developments in polymer research could ease this problem. It has been demonstrated by us and others[9–11] that high-efficiency surface gratings can be directly inscribed onto the surface of thin polymer films using a low-power laser beam. The ease of fabrication using polymer films makes this medium attractive for use in optical devices.

In the present study, we demonstrate a simple structure and method for fast wavelength modulation based on the fact that the resonances for "TE and TM" guided modes in a slab waveguide occur at different wavelengths for light incident at a fixed angle. Thus, a binary signal, for example, can be coded by frequency rather than by amplitude.

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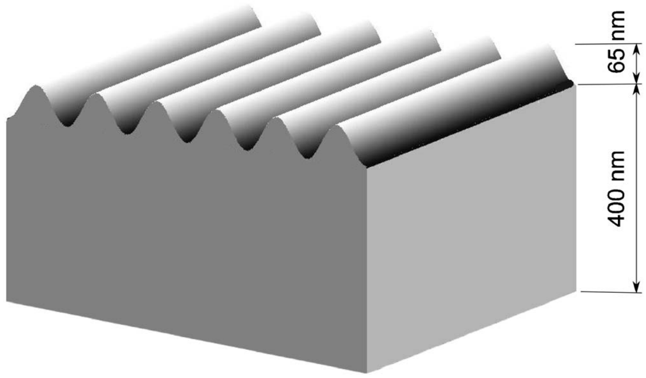

Fig. 1 Relief grating holographically recorded in an azo-polymer. The polymer layer under the corrugated zone serves as a waveguide.

2 Experimental Setup

The polymer used in this study is an azobenzene side chain polymer synthesized as described elsewhere.[12] The optical structure is prepared by spin-casting a 2% or 5% w/w of the azo-dye, pDR1M, dissolved in dichloromethane on clean CaF_2 plates. The film is then dried in an oven at 60°C for an hour to remove any remaining solvent. The resultant high-quality films have a thickness of 130 nm and 400 nm, respectively. To record the gratings, we exposed the material to an interference pattern made by a 750 mW/cm^2, λ =532 nm laser. The gratings have a sinusoidal relief with a depth of 50 to 100 nm and a period of 400 nm. The relief is stable at room temperature since the glass transition temperature of the polymer is about 130°C. The polymer film has a refractive index of 1.65 and thus acts as a slab waveguide with a corrugated surface, as illustrated in Fig. 1.

The sample was mounted on a rotation stage with a step precision of 0.01 deg. White light from an incandescent lamp was focused by a mirror onto the sample, as illustrated in Fig. 2. A linear polarizer was placed between the sample and the mirror. A 3-mm-wide slit was placed in front of the converging mirror in order to limit the angular spread of the beam onto the grating. The light that was transmitted through the sample or reflected by the sample

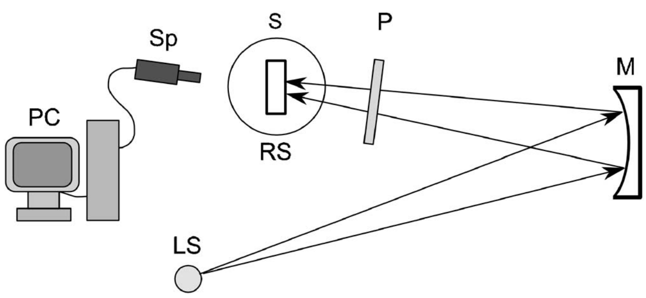

Fig. 2 Experimental setup. LS—light source, M—converging mirror, P—polarizer, RS—rotation stage, S—sample, Sp—minispectrometer, PC—personal computer.

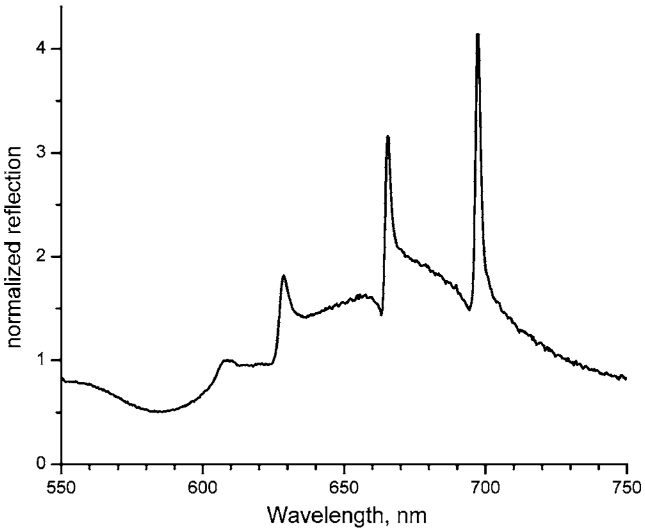

Fig. 3 Normalized reflection spectrum. Thickness of the guiding layer—400 nm, angle of incidence—5 deg, s-polarization. The sharp peak at 700 nm has a half width of 3 nm.

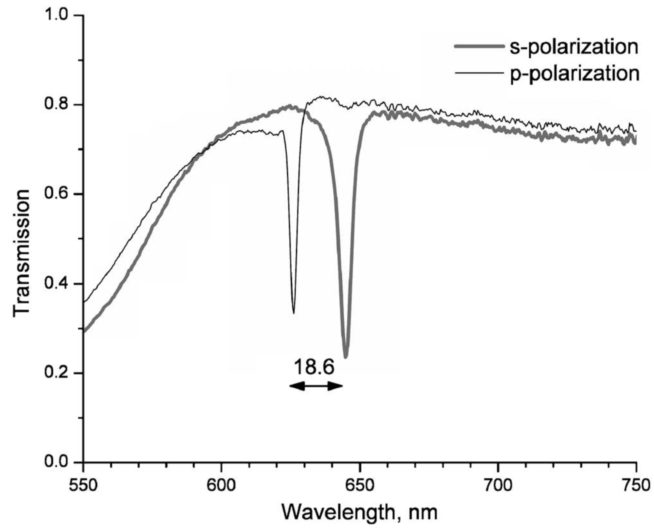

Fig. 5 Transmittance spectrum for the s- and p-polarized waves. Only a single mode exists in this spectral region. The guiding layer is 130 nm thick, and the angle of incidence is 12.9 deg.

was focused onto the entrance optical fiber of a BWTEK mini-spectrometer, connected to a personal computer.

3 Results

Typical reflection and transmission spectra of our samples are shown in Figs. 3–5. The resonances are quite narrow; for example, the peak at 700 nm in Fig. 3 is 2-nm wide, while the precision of our spectrometer is 1.3 nm. The resonances in Figs. 3 and 4 are at different wavelengths because these spectra were taken at different angles of incidence. When the polymer layer under the grating is 400 nm, it supports multiple modes for the visible spectrum, and in accordance with the theory,[1] for a fixed angle of incidence the guided modes for TE and TM polarizations are at different wavelengths (8-nm difference is shown in Fig. 4). When the guiding layer is 130 nm, only one mode exists. In the latter case, the peaks become deeper and the separation is larger, ca. 18.6 nm (Fig. 5). In that case, a higher angle of incidence is required in order to work in the same spectral region (12.9 deg).

Depending on the angle of incidence, it is possible to tune a convenient wavelength for the particular application, as well as determine whether one or more modes exist in a given spectral range. For small angles, the resonances depend quasi-linearly on the angle, as illustrated in Fig. 6. There we take the left couple of peaks shown in Fig. 3 and plot their positions while changing the angle of incidence. Because at angles different from zero, there are forward- and backward-coupled modes, each peak splits into two. Figure 6 also shows that the wavelengths for the two polarizations are well separated. Thus, by switching the input

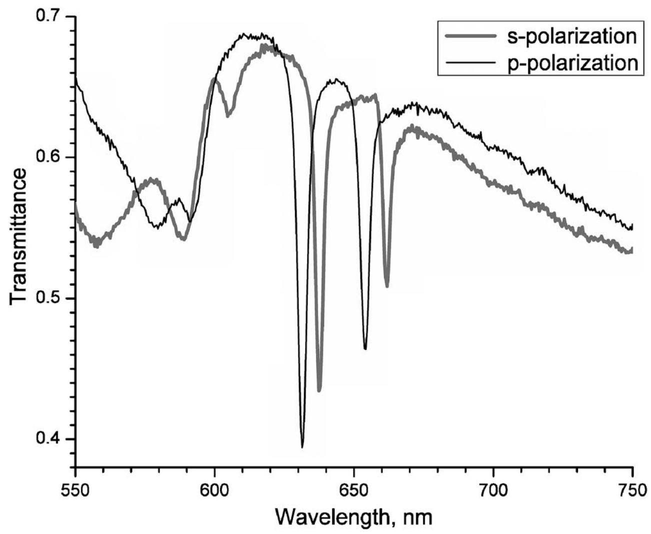

Fig. 4 Transmittance spectrum for the s- and p-polarized waves. Two modes exists in this spectral region. The guiding layer is 400 nm; the angle of incidence 2.3 deg.

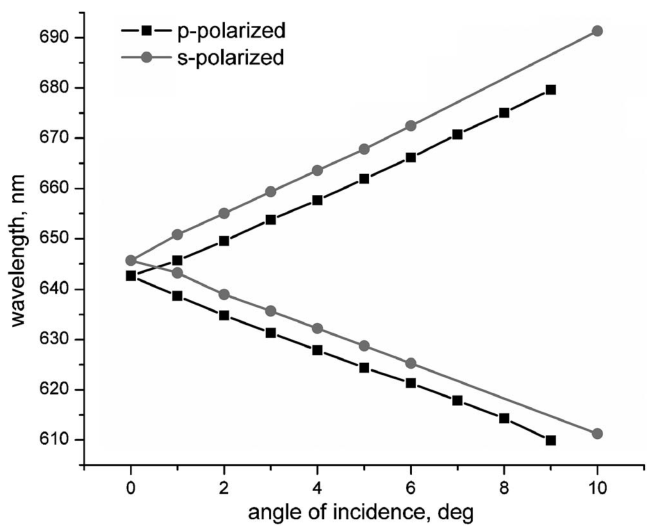

Fig. 6 Wavelength position of the transmittance minimums vs the angle of incidence. The dependence is linear for that range of angles. Each single peak at 0 deg splits into two peaks for angles different from zero. The guiding layer is 400 nm thick.

polarization, one can control the output wavelength. If the presence of λ_1 is 1 and the presence of λ_2 is 0, one can have a binary encoding device.

In our reflection spectra, the intensities of the peaks were up to 2.5 times that of the baseline. This could act as a polarization-frequency selective mirror. The speed at which the frequency could be switched was limited by our ability to change the polarization of the incident light. For presently available electro-optical devices for control of the polarization of light, a typical switch time could be as low as 1 ns.

4 Conclusion

A method for fast and reliable binary wavelength encoding is proposed. The main advantage is that, in principle, its speed is limited only by the electronics. As an active element, we propose a diffraction grating recorded holographically in a polymer material. The preparation is simple because only a single polymer layer is coated on the substrate. The desired wavelengths of operation are adjusted by the angle of incidence. Transmission or reflection modes of operation are possible.

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