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Cellophane film as half wave retarder of wide spectrum

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Abstract

In this work, we introduce the use of a cellophane film as a half wave retarder plate of wide spectrum. Using a commercial arc lamp as a light source, we have characterized a cellophane film as half wave plate retarder in the spectral range from $\lambda = 400$ to 700 nm. In addition, we made similar characterizations for several commercial laser emission lines. Although this film behaves as other commercial half wave plate retarder devices, it has the advantages of a low cost and an easy availability. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Cellophane is a composed word, *cell* is the French abbreviation for *cellulose* and *phane* is a Greek word that means to show [1,2]. Cellophane films are composed of regenerated cellulose extruded into thin, flat transparent sheets. When such sheets are extruded through a small hole or spinneret it produces fiber named rayon. However, the main application for cellulose sheets is to make films to package food and other perishables. Cellophane is also highly impermeable to dry gases, grease, and bacteria. For such uses it is frequently given a mositure-proof coating and sometimes is dyed. The manufacturing process to synthesize cellophane consists of an initial step where an alkaline solution of cellulose fibers usually made of wood or cotton (known as viscose) is extruded through a narrow slit into an acid bath. The acid regenerates the cellulose forming the cellulose film. Further treatments such as washing and bleaching yield, as final product, the cellophane. Such a name is the trademark in many countries where cellpohane has been produced since 1920; its transparency attracted attention at once, beginning a revolution in wrapping materials. Although it is highly sensitive to water and to changes in humidity, cellophane is still very popular. We are interested in the use of cellophane from a different perspective, and we want to study its optical properties as optical phase retarder plate.

An optical phase retardation plate [3–10] is one of the many optical devices or materials that allows a change in the polarization state of light. Usually retarder plates are made of materials such as calcite, quartz or mica [3,4,6]. Recently, we have reported the use of polyester films as efficient quarter wave retarders [11]. Interestingly, we have

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also found that materials such as cellophane films can be used to make half wave retarder plates (HWRP) to be used in a wide range of spectra.

2. Theory

The simplest retardation plate known to date consists of a uniaxial crystal cut to include a crystalline optic axis direction. Within the retarder plate the crystalline optic axis and other axis normal to it are often called fast or slow axis. The classification of such axis depends on whether the uniaxial crystal is positive or negative. The directions of the axis of the retarder plate are a consequence of the inner structure of the crystal. A beam into these devices reads two axis or directions while it is propagating, so it is divided into two components. One of the components oscillates in a direction parallel to the fast axis, while the other oscillates in the normal direction or slow axis. These beams are called ordinary (o wave) and extraordinary (e wave), respectively. As the o and e waves traverse the retarder plate, a phase difference is accumulated. Such a difference is caused by retardation of the slow beam in comparison to the fast beam and is proportional to the distance traveled within the plate. However, once both beams emerge the o and e waves recombine and form an output beam whose polarization is generally different from the one that entered the retarder. The phase difference between o and e waves depends on the thickness of the retarder employed.

A half wave plate is a retardation plate, which introduces a relative phase difference of π radians or 180° between the o and e waves.

The phase difference, $\Delta\Phi$ for a retarder plate of certain thickness d obeys the difference

$$\Delta\Phi = \Delta\Phi_e - \Delta\Phi_o = -\frac{2\pi}{\lambda}(n_e - n_o)d, \quad (1)$$

where λ is the wavelength of the light, n_e and n_o are the extraordinary and ordinary refraction indexes.

Particularly, the HWRP is produced when $|\Delta\Phi| = (2m+1)\pi$ that is when

$$|n_e - n_o|d = (2m+1)\frac{\lambda}{2}, \quad (2)$$

where m is an integer ($m = 0, 1, 2, \ldots$) [4,8].

The change in the horizontal linear orientation of polarized light into vertical one (represented in Fig. 1) was demonstrated by the Stokes vectors and the Mueller or Jones matrices [3,5,8]. For simplicity, we here employed only the Jones formalism, so the matrix of a retarder plate can be represented, assuming normalized vectors (except for constants) for the following equation

$$Mr(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \times \begin{bmatrix} \exp(i\delta/2) & 0 \\ 0 & \exp(i\delta/2) \end{bmatrix} \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}. \quad (3)$$

The matrix $Mr(\theta)$ represents all the possible positions of the fast or slow axes of the retarder. The angle θ corresponds to an arbitrary angle between the horizontal axes and the fast axis of the retarder plate, while δ corresponds to the retarder phase between the o wave and the e wave.

A vertical polarized incident light can be represented by Eq. (4a), and the polarizer with its transmission axis horizontal is represented by Eq. (4b).

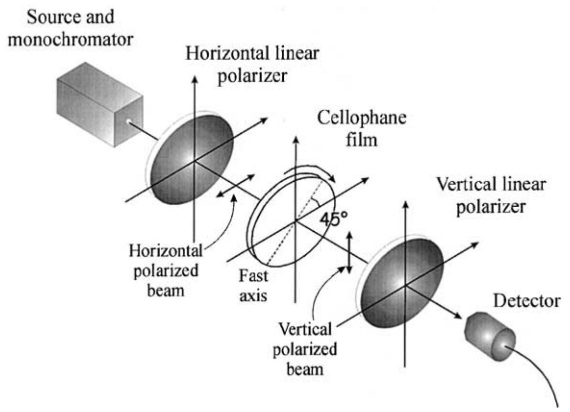

Fig. 1. Schematic illustration of the experimental setup used to characterize the cellophane film. This figure shows the change in the polarization state of a beam from horizontal to vertical, as it goes through the rotating cellophane film. The polarization changes are recorded using a combination of a linear polarizer and a fast detector.

$$E = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad (4a)$$

$$\mathrm{P} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}. \quad (4b)$$

The light behavior through the system represented in Fig. (1) is expressed by Eq. (6).

$$I(\theta, \delta) = |PMr(\theta)E|^2. \quad (5)$$

As expected, Eq. (5) conduces to

$$I(\theta, \delta) = 4|\cos(\theta)\sin(\delta/2)\sin(\theta)|^2. \quad (6)$$

Particularly, when the retarder plate introduces a phase delay of $\delta = \pi$, we obtain

$$I(\theta, \delta) = 4|\cos(\theta)\sin(\theta)|^2. \quad (7)$$

The solid line in Fig. 2 shows the last equation. In this graph the four maximums localized in the corresponding angles for $\theta = \pi/4, 3\pi/4, 5\pi/4, 7\pi/4$ can be easily identified.

3. Results

We have performed a series of experiments to characterize the cellophane as HWRP. The graph showed in Fig. 2 was experimentally reproduced using the setup shown in Fig. 1. As depicted in Fig. 1 the optical retarder plate under examination was localized between two orthogonal polarizers. The optical plate was mechanically rotated, generating the signal (the beam passing through the system) to be detected. In this setup, we used an ultraviolet arc lamp as a source of light (Ealing mod. 27-1031) and a monochromator (Oriel Multispec mod. 77 400) as element to discriminate among wavelengths. The monochromator average power output was ~40 μW over the range of interest.

Using such a system, in Fig. 2 we show the resulting curve when the selected wavelength of the setup was $\lambda = 532$ nm. Also in the same figure, we have compared three data curves corresponding to the cellophane film, a commercial HWRP (made

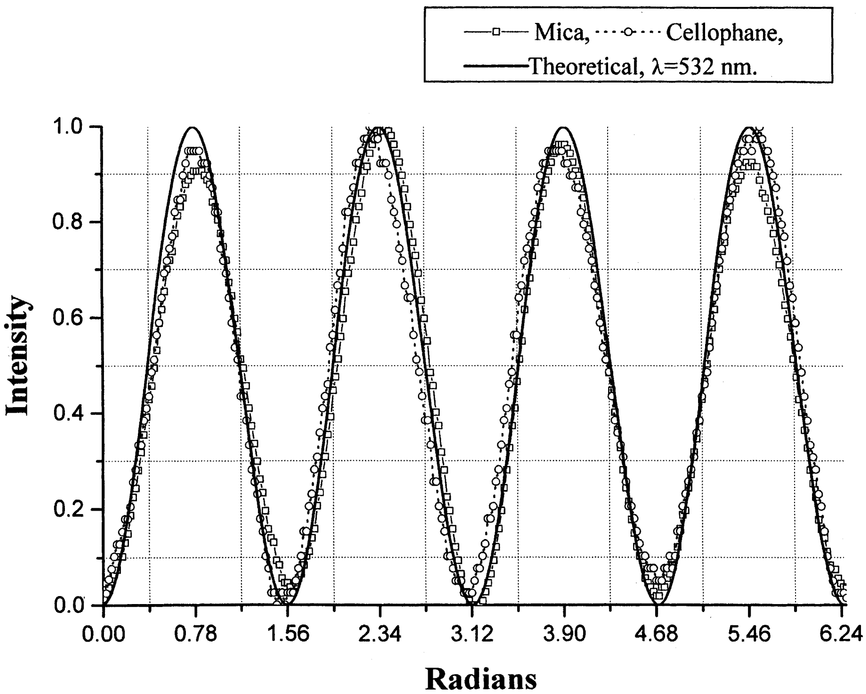

Fig. 2. Dependence of intensity as the cellophane film (- -o- -) and an Oriel HWRP (–□–) are rotated, for the wavelength $\lambda = 532$ nm. The experimental curves are compared with the theoretical curve (–) obtained by Eq. (7).

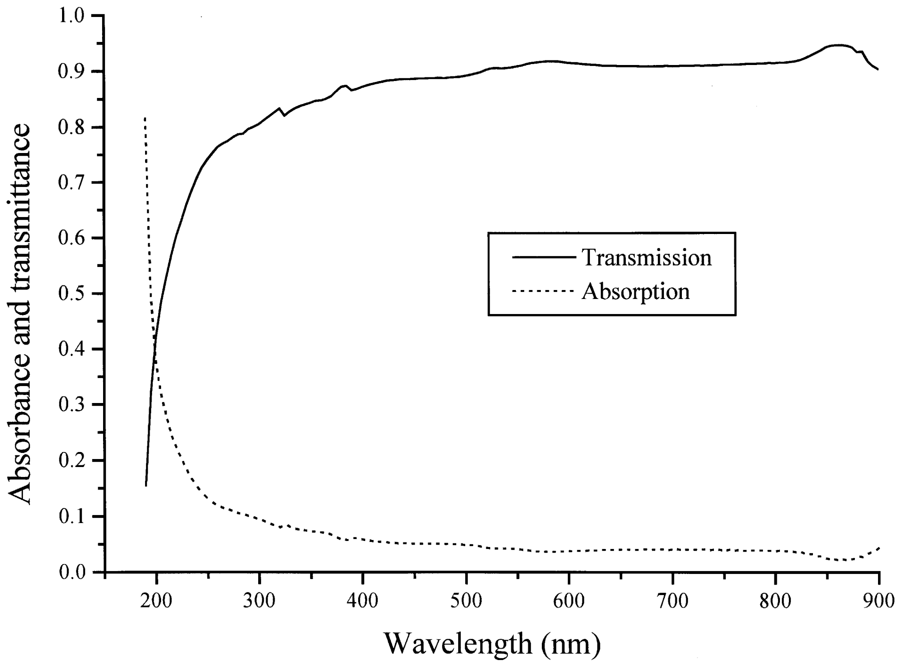

Fig. 3. Wavelength dependence of transmission (–) and absorption (- - -) coefficients of a cellophane film.

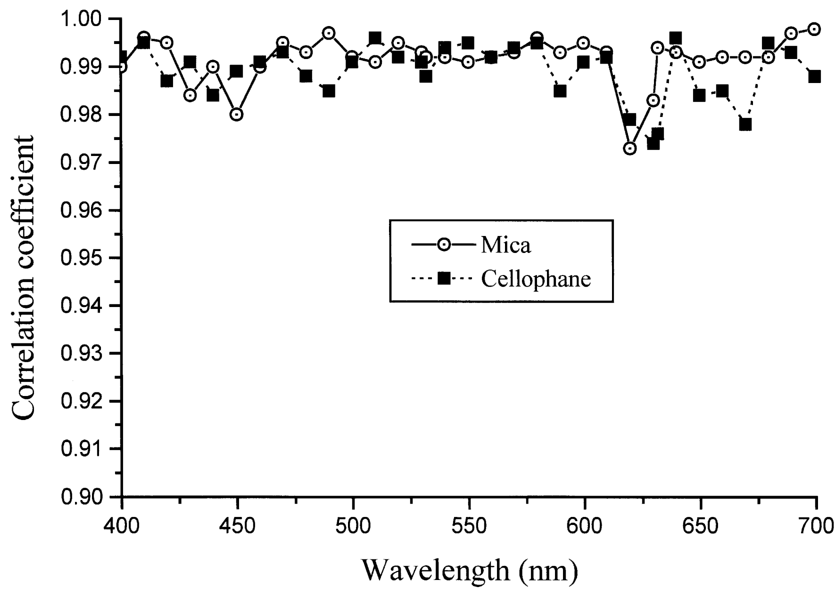

Fig. 4. Wavelength dependence of the Pearson's *r* correlation coefficients. The coefficients are obtained correlating the intensity curves of the cellophane film and the curves corresponding to an ideal retarder plate. Similar dependence is shown for the commercial Oriel HWRP.

of mica, # 25450 distributed by ORIEL©) and the expected theoretical curve. Interestingly all materials share similar behavior. Such a resemblance among the different curves corroborates that cellophane serves as a HWRP at such wavelength.

One of the most attractive and useful properties of the cellophane film is its transparency. In Fig. 3 we show the light transmittance and absorption of cellophane over a wide spectrum of wavelengths (300–900 nm). The transmission coefficient has a maximum variation of a 10% and a 0.90 average value over the total range. Having in mind this transparency property, we have repeated our experiment described above for 30 different wavelengths. A set of 30 data curves were obtained for each one of the samples (the cellophane film and the commercial HWRP mentioned above). In order to quantify our measurements we have compared the experimental and theoretical curves for each wavelength, using the Pearson's r correlation coefficients [12]. Fig. 4 shows the Pearson's r correlation coefficients, for several wavelengths among a family of 30 data curves and their respective expected theoretical curve. In this figure each point corresponds to a different wavelength, starting from $\lambda = 400$ to 700 nm in intervals of 10 nm. In addition, the correlation coefficient for the wavelengths at 488, 532 and 633 nm is also shown. These wavelengths correspond to commercial laser emission lines. In all wavelengths a strong correlation coefficient (0.99 average) was observed. These results allow us to conclude that cellophane in a wide spectrum behaves as a very good HWRP.

This last result was also verified using as the source of light several commercial lasers. The laser emission lines studied were 488, 532, 632.8, and 780 nm and the incident laser intensities used for each wavelength were 0.5 and 1.0 mW. Under such conditions, no major differences were reported. The data curves found were similar to those observed in Fig. 2. A value of 0.96 was obtained as the average of the Pearson's r correlation coefficients for all wavelengths and intensities considered above.

So far our light source has been a beam of very small area, and to spatially verify the optical properties of the cellophane film reported above, an additional technique was used. The experimental setup for the additional technique is shown in Fig. 5(a). The first component of the setup is a glass plate covered with cellophane strips of equal period (adequately oriented) simulating a grating. After grating, we placed an arrangement of orthogonal linear polarizers one next to other. When a vertical linearly polarized white light beam oscillating 45° from the fast axis of the cellophane film passes through the polarizers, the polarization state of the beam changes from vertical to horizontal. Therefore, when such light beam goes through the polarizer arrangement, part of the beam is stopped in those zones where its polarization state is orthogonal to the transmittance axis of the polarizers. As a result, an arrangement

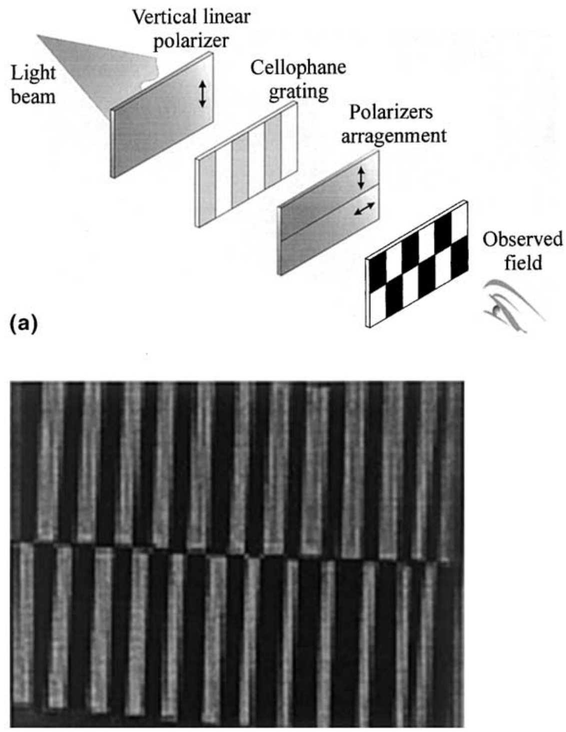

Fig. 5. (a) This schematic representation shows the changes in the polarization state of the beam. The light passing through the cellophane grating and the polarizer's arrangement creates the dark and white areas. (b) Photography of the cellophane grating film between the arrangement of the linear polarizers illuminated by white light.

of clear and dark zones resembling a chessboard is created (see Fig. 5(b)). Similar results were obtained for several commercial laser emission wavelengths ($\lambda = 632,\ 532$ and 488 nm).

4. Conclusions

Several conclusions can be taken from our work. First, the cellophane film can be used as half wave retarder of wide spectrum from $\lambda = 400$ to 780 nm. This film has a relative phase difference of π radians or 180° between the o and e waves. In addition, we have found that this film behaves efficiently and in a similar fashion as HWRP when the intensity from the source is in the order of 10 μW to 1 mW for the wavelengths at 488, 532, 632.8, and 780 nm. Consequently, cellophane films can be used as HWRP retardation plates instead of the other commercial but more expensive plates.

Acknowledgements

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