Polarization changes at Lyot depolarizer output for different types of input beams

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Lyot depolarizers are optical devices made of birefringent materials used for producing unpolarized beams from totally polarized incident light. The depolarization is produced for polychromatic input beams due to the different phase introduced by the Lyot depolarizer for each wavelength. The effect of this device on other types of incident fields is investigated. In particular two cases are analyzed: (i) monochromatic and nonuniformly polarized incident beams and (ii) incident light synthesized by superposition of two monochromatic orthogonally polarized beams with different wavelengths. In the last case, it is theoretically and experimentally shown that the Lyot depolarizer increases the degree of polarization instead of depolarizes.

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1. INTRODUCTION

Polarization is one of the most important properties of light for various optical devices such as liquid crystals, optical isolators, and unconventional polarizers and for applications in astronomy, some optical fiber communication systems that use polarization coding techniques, optical manipulation, optical microscopy, etc. However, there are other situations in which it is desirable that the light is depolarized to get good results, for example, in pumping sources for fiber optic amplifiers, in depolarized fiber optic gyros, and in various applications of spectroscopy. Many researchers have studied the properties of unpolarized light, and several methods for depolarizing light can be found in the literature; see for example [1–7]. A device used for this purpose is the Lyot depolarizer (LD). Since the introduction of this device a long time ago [8], many theoretical and experimental works has been devoted to the study of the LD [9–13], and several applications have recently been proposed [14–17]. They are manufactured with two parallel synthetic crystal quartz plates assembled with their optic axes lying in the plane of the plates and forming a 45° angle (see Fig. 1). The LD was designed in this way because the depolarization was effective for broad spectrum light of any state of polarization. However, this device does not depolarize uniformly and totally polarized monochromatic beams. For this reason, the LD is generally used with polychromatic incident beams that can be thought as a superposition of monochromatic components with different wavelengths. This device adds a different phase to each spectral component of the superposition, so the degree of polarization of the output beam is always lower than the degree of polarization of the input beam and approximately zero. The LD has been investigated assuming specific cases of polychromatic light with different spectral characteristics. All previous works consider the polychromatic incident beams that come from a single light source and assume that all the spectral components are uniformly polarized across the beam section and with the same state of polarization.

In recent years, there has been an intensive research on the proposal and synthesis of light beams with special characteristics of polarization. For example, beams with a state of polarization that varies across the transverse section, like radially and azimuthally polarized fields, as well as fields which can be represented as an uncorrelated superposition of beams with the same or different states of polarization have been studied and/or synthesized [18–23]. On the other hand, several spectral-beam-combining schemes have been developed in order to obtain an efficient power scaling of laser radiation; see for example [24,25]. This suggests a detailed analysis of the behavior of the LD for input beams with different spectral and polarization properties.

In order to determine the changes in the polarization characteristics at the output of the LD, the standard degree of polarization is generally considered. However, beams can be globally depolarized but locally totally polarized. In these cases more detailed information of the beam polarization is necessary, and other parameters proposed in the literature [26], such as the local degree of polarization, as well as the weighted degree of polarization and the weighted azimuth and ellipticity, can be used.

In this paper we investigate the behavior of the LD through the parameters listed above by analyzing the polarization output beam characteristics when different types of incident beams are considered. The paper is structured as follows. After the introduction given in this section, the formalism used to study the LD effect on incident light will be described in Section 2. In Section 3, the LD output characteristics of polarization for a monochromatic input beam with nonuniform distribution of polarization across the transverse section, orthogonal to the propagation direction, will be studied. In Section 4, the degree of polarization at the output of the LD when the incident light is a superposition of monochromatic beams, with different degrees and states of polarization and different wavelengths, will be introduced. The particular case of superposition of two uniformly, totally, and orthogonally polarized beams will be theoretically and experimentally analyzed in detail in Section 5. Finally, the main conclusions of this work will be summarized in Section 6.

2. PRELIMINARIES

Let us consider a collimated and monochromatic beam of wavelength λ propagating along the z direction with a degree and state of polarization that vary from one point to another across the transverse section. The beam polarization characteristics can be given by the Stokes vector:

$$S(\mathbf{r}) = \begin{pmatrix} s_0(\mathbf{r}) \\ s_1(\mathbf{r}) \\ s_2(\mathbf{r}) \\ s_3(\mathbf{r}) \end{pmatrix} = \begin{pmatrix} P_{ss}(\mathbf{r}) + P_{pp}(\mathbf{r}) \\ P_{ss}(\mathbf{r}) - P_{pp}(\mathbf{r}) \\ 2\,\mathrm{Re}\{P_{sp}(\mathbf{r})\} \\ 2\mathrm{Im}\{P_{sp}(\mathbf{r})\} \end{pmatrix}, \tag{1}$$

where $\mathbf{r}$ denotes a point in the transverse section of the beam and where the subindexes s and p refer to the components of the field, orthogonal to the propagation direction. The Stokes parameters are given in terms of the elements $P_{jk}(\mathbf{r})$ of the polarization matrix, $\hat{P}$, defined as follows [27,28]:

$$\hat{P}(\mathbf{r}, \mathbf{r}, z) = \begin{pmatrix} P_{ss}(\mathbf{r}) & P_{sp}(\mathbf{r}) \\ P_{ps}(\mathbf{r}) & P_{pp}(\mathbf{r}) \end{pmatrix}, \tag{2}$$

with

$$P_{jk}(\mathbf{r}) = \langle E_j^*(\mathbf{r}; t) E_k(\mathbf{r}; t) \rangle \tag{3}$$

being $E_j^*(\mathbf{r})$ with $j, k = s, p$, the components of the field and $\langle\rangle$ representing a temporal average. The diagonal elements of $\hat{P}$ represent the irradiances associated to each component of the beam; meanwhile, the off-diagonal terms are the correlations between s and p components at a point $\mathbf{r}$.

The Stokes parameters are measurable quantities and can be determined from the irradiances at the output of a quarter-wave phase plate and a linear polarizer. In such a case [29],

$$S(\mathbf{r}) = \begin{pmatrix} s_0(\mathbf{r}) \\ s_1(\mathbf{r}) \\ s_2(\mathbf{r}) \\ s_3(\mathbf{r}) \end{pmatrix} = \begin{pmatrix} I_{0°}(\mathbf{r}) + I_{90°}(\mathbf{r}) \\ I_{0°}(\mathbf{r}) - I_{90°}(\mathbf{r}) \\ I_{45°}(\mathbf{r}) - I_{135°}(\mathbf{r}) \\ I_{\lambda/4,45°}(\mathbf{r}) - I_{\lambda/4,135°}(\mathbf{r}) \end{pmatrix}, \tag{4}$$

where $I_\theta(\mathbf{r})$ and $I_{\lambda/4,\theta}(\mathbf{r})$ are the irradiances at each point across the transverse section of the beam, the subindex θ refers to the angle of the transmission axis of the polarizer, and s direction and $\lambda/4$ indicates the presence of the quarter-wave phase plate. $s_0(\mathbf{r})$ represents the irradiance at each point $\mathbf{r}$; $s_1(\mathbf{r})$ is equal to the difference between linearly polarized light at 0° with respect to linearly polarized light at 90°. The meaning of $s_2(\mathbf{r})$ is similar to $s_1(\mathbf{r})$ but with linearly polarized light at 45° and 135°. Finally, $s_3(\mathbf{r})$ gives the difference between left- and right-handed circularly polarized light at $\mathbf{r}$.

From the Stokes parameters, the local degree of polarization is defined as

$$P(\mathbf{r}) = \sqrt{\frac{s_1(\mathbf{r})^2 + s_2(\mathbf{r})^2 + s_3(\mathbf{r})^2}{s_0(\mathbf{r})^2}}. \tag{5}$$

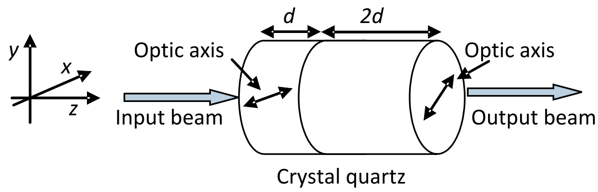


Fig. 1. (Color online) Scheme of the LD.

The inequality $0 \le P(\mathbf{r}) \le 1$ stands for $P(\mathbf{r})$. If $P(\mathbf{r}) = 1$, we have a totally polarized field, and for $P(\mathbf{r}) = 0$ the beam is unpolarized at the point $\mathbf{r}$.

For totally polarized fields, we can define the local azimuth, $\psi(\mathbf{r})$, and the ellipticity, $\chi(\mathbf{r})$, at each point of the transverse section of the beam as

$$\psi(\mathbf{r}) = \frac{1}{2} \arctan\left[\frac{s_2(\mathbf{r})}{s_1(\mathbf{r})}\right], \tag{6}$$

$$\chi(\mathbf{r}) = \frac{1}{2} \arcsin\left[\frac{s_3(\mathbf{r})}{s_0(\mathbf{r})}\right], \tag{7}$$

with the conditions $0 \le \psi(\mathbf{r}) < \pi$ and $-\pi/4 < \chi(\mathbf{r}) \le \pi/4$.

Usually global information about the beam polarization characteristics is required. In such a case, the standard degree of polarization, defined as [29]

$$P_{\mathrm{st}} = \sqrt{\frac{\bar{s}_1^2 + \bar{s}_2^2 + \bar{s}_3^2}{\bar{s}_0^2}}, \tag{8}$$

with

$$\bar{s}_i = \iint s_i(\mathbf{r}) \mathrm{d}\mathbf{r}, \qquad i = 0, 1, 2, 3, \tag{9}$$

is generally used. In terms of the parameters given by Eqs. (5)–(7), the Stokes vector for each wavelength is given by

$$S(\mathbf{r}) = \begin{pmatrix} s_0(\mathbf{r}) \\ s_1(\mathbf{r}) \\ s_2(\mathbf{r}) \\ s_3(\mathbf{r}) \end{pmatrix} = \begin{pmatrix} s_0(\mathbf{r}) \\ s_0(\mathbf{r})P(\mathbf{r}) \cos 2\psi(\mathbf{r}) \cos 2\chi(\mathbf{r}) \\ s_0(\mathbf{r})P(\mathbf{r}) \sin 2\psi(\mathbf{r}) \cos 2\chi(\mathbf{r}) \\ s_0(\mathbf{r})P(\mathbf{r}) \sin 2\chi(\mathbf{r}) \end{pmatrix}. \tag{10}$$

Some useful parameters for globally characterizing the beam polarization are the weighted degree of polarization, the weighted ellipticity, and the weighted azimuth, given by

$$\tilde{P} = \frac{\iint P(\mathbf{r}) s_0(\mathbf{r}) \mathrm{d}\mathbf{r}}{\int s_0(\mathbf{r}) \mathrm{d}\mathbf{r}}, \tag{11}$$

$$\tilde{\psi} = \frac{\iint \psi(\mathbf{r}) s_0(\mathbf{r}) \mathrm{d}\mathbf{r}}{\int s_0(\mathbf{r}) \mathrm{d}\mathbf{r}}, \tag{12}$$

$$\tilde{\chi} = \frac{\iint \chi(\mathbf{r}) s_0(\mathbf{r}) \mathrm{d}\mathbf{r}}{\int s_0(\mathbf{r}) \mathrm{d}\mathbf{r}}. \tag{13}$$

Note that $\tilde{P}$, $\tilde{\psi}$, and $\tilde{\chi}$ give information about the predominant values of the degree of polarization, azimuth, and ellipticity in the region where the irradiance is significant.

On the other hand, the LD consists of two birefringent phase plates (see Fig. 1). The first phase plate has its optic axis along the x direction and adds a δ phase. The second phase plate is exactly twice the thickness of the first one so adds a 2δ phase. Its optic axis forms a 45° angle with the x axis. Within the Stokes formalism, the LD is given by a Müller matrix, which is calculated combining two Müller matrices corresponding to both phase plates, resulting in

$$\mathrm{LD} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\delta & \sin 2\delta \sin \delta & -\sin 2\delta \cos \delta \\ 0 & 0 & \cos \delta & \sin \delta \\ 0 & \sin 2\delta & -\sin \delta \cos 2\delta & \cos 2\delta \cos \delta \end{pmatrix}. \quad (14)$$

In this equation, δ is the phase difference between the s and p components after propagating through the thinnest phase plate of the LD for each wavelength,

$$\delta = \frac{2\pi}{\lambda} |\Delta n(\lambda)| d, \quad (15)$$

where d is the first phase plate thickness and $\Delta n(\lambda) = n_o(\lambda) - n_e(\lambda)$, with n_o and n_e the ordinary and extraordinary refraction indexes, respectively.

3. INCIDENT BEAM: MONOCHROMATIC NONUNIFORMLY PARTIALLY POLARIZED BEAMS

Let us consider a nonuniformly and partially polarized (NUP) beam of wavelength λ whose degree of polarization and state of polarization of the totally polarized component can vary from one point to another across the transverse section of the beam. The Stokes vector, $S^{\mathrm{in}}_{\mathrm{NUP}}$, describing the beam polarization of the incident beam is given by Eq. (1). After propagating through the LD, the new Stokes vector, $S^{\mathrm{out}}_{\mathrm{NUP}}$, results:

$$S^{\mathrm{out}}_{\mathrm{NUP}}(\mathbf{r}) = \mathrm{LD} S^{\mathrm{in}}_{\mathrm{NUP}}(\mathbf{r}) = \begin{pmatrix} s_0(\mathbf{r}) \\ s_1(\mathbf{r}) \cos 2\delta + s_2(\mathbf{r}) \sin 2\delta \sin \delta - s_3(\mathbf{r}) \sin 2\delta \cos \delta \\ s_2(\mathbf{r}) \cos \delta + s_3(\mathbf{r}) \sin \delta \\ s_1(\mathbf{r}) \sin 2\delta - s_2(\mathbf{r}) \sin \delta \cos 2\delta + s_3(\mathbf{r}) \cos 2\delta \cos \delta \end{pmatrix}. \quad (16)$$

By simple calculations, it is demonstrated that the local, standard, and weighted degree of polarization at the output of the LD are identical to the input beam:

$$P^{\mathrm{out}}(\mathbf{r}) = P^{\mathrm{in}}(\mathbf{r}), \quad (17)$$

$$P^{\mathrm{out}}_{\mathrm{st}} = P^{\mathrm{in}}_{\mathrm{st}}, \quad (18)$$

$$\tilde{P}^{\mathrm{out}} = \tilde{P}^{\mathrm{in}}. \quad (19)$$

Note that the output beam still shows a degree and a state of polarization that can vary from one point to another in the beam cross section. The LD does not change the degrees of polarization of the input beam; it just modifies the state of polarization at each point of the transverse section.

In order to put this fact into evidence, let us consider a particular case of nonuniformly and totally polarized (NUTP) beam: the spirally polarized beam (SPB) [22,23,30]. An SPB can be represented by the following Stokes vector:

$$S^{\mathrm{in}}_{\mathrm{SPB}}(\mathbf{r}) = \begin{pmatrix} s_0(\mathbf{r}) \\ -s_0(\mathbf{r}) \cos(2\theta + 2\alpha) \\ -s_0(\mathbf{r}) \sin(2\theta + 2\alpha) \\ 0 \end{pmatrix}, \quad (20)$$

where $\mathbf{r} = (r, \theta)$ is the position vector across the plane and α is a constant angle. Note that the polarization state is not defined at the center of the profile; then $s_0(\mathbf{r})$ must be chosen in such a way that the amplitude vanishes at $\mathbf{r} = 0$. The polarization of an SPB field is linear at any point and symmetric around the propagation axis, as shown in Fig. 2(a) for the case of $\alpha = \pi/6$. The electric field lines are logarithmic spirals whose growth parameter depends on the value of α [30]. By varying α, we range from azimuthal (when $\alpha = 0$) to radial (when $\alpha = \pi/2$) polarization.

The Stokes vector after the LD is

$$S^{\mathrm{out}}_{\mathrm{SPB}}(\mathbf{r}) = \begin{pmatrix} s_0(\mathbf{r}) \\ s_0(\mathbf{r})(-\cos(2\theta + 2\alpha) \cos 2\delta - \sin(2\theta + 2\alpha) \sin 2\delta \sin \delta) \\ -s_0(\mathbf{r}) \sin(2\theta + 2\alpha) \cos \delta \\ s_0(\mathbf{r})(-\cos(2\theta + 2\alpha) \sin 2\delta + \sin(2\theta + 2\alpha) \sin \delta \cos 2\delta) \end{pmatrix}, \quad (21)$$

which remains an NUTP beam, but now the polarization state has changed at each point across the section. The local polarization state of the output beam has been plotted in Fig. 2(b) for an LD with $\delta = \pi/2$. In this case we have

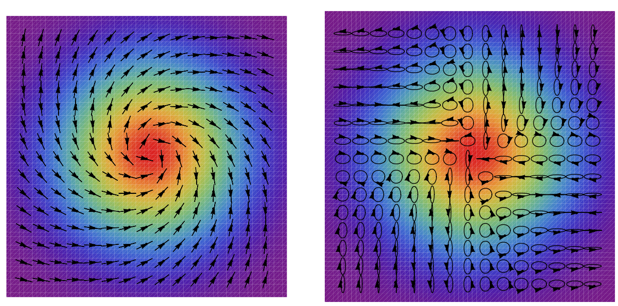
$$P^{\mathrm{out}}(\mathbf{r}) = P^{\mathrm{in}}(\mathbf{r}) = 1, \quad (22)$$

$$P^{\mathrm{out}}_{\mathrm{st}} = P^{\mathrm{in}}_{\mathrm{st}} = 0, \quad (23)$$

$$\tilde{P}^{\mathrm{out}} = \tilde{P}^{\mathrm{in}} = 1, \quad (24)$$

which yields to a locally totally polarized but globally depolarized output beam (given by P_{st}). Its azimuth and ellipticity vary across the transverse section. By using an LD, it is possible to modify the polarization distribution across the beam profile, obtaining a beam that is circular, linear, or elliptically polarized depending on the observation point.

An example of SPB is the so-called radially polarized beam (RPB) which has attracted high attention in past years due to its usefulness in several applications. This type of beam is linearly polarized with its azimuth oriented in the radial direc-



(a) (b)

Fig. 2. (Color online) (a) Polarization distribution of an input SPB with $\alpha = \pi/6$. (b) Polarization distribution at the output of an LD with $\delta = \pi/2$.

tion. The Stokes vector is given as function of the coordinate θ as

$$S^{\text{in}}_{\text{RPB}}(\mathbf{r}) = s_0(\mathbf{r})\begin{pmatrix} 1 \\ \cos 2\theta \\ \sin 2\theta \\ 0 \end{pmatrix}. \tag{25}$$

When an RPB propagates through an LD with $\delta = \pi/2$, the output beam Stokes vector results:

$$S^{\text{out}}_{\text{RPB}}(\mathbf{r}) = \begin{pmatrix} 1 \\ -\cos 2\theta \\ 0 \\ \sin 2\theta \end{pmatrix}, \tag{26}$$

which does not represent an RPB, but the local, standard, and weighted degree of polarization remain unchanged for the input and output beam. On the contrary, the azimuth and ellipticity have changed from the initial values, given by

$$\psi^{\text{in}}(\mathbf{r}) = \theta, \tag{27}$$

$$\chi^{\text{in}}(\mathbf{r}) = 0, \tag{28}$$

to final values

$$\psi^{\text{out}}(\mathbf{r}) = 0, \tag{29}$$

$$\chi^{\text{out}}(\mathbf{r}) = \theta. \tag{30}$$

With regard to the global polarization characteristics, the input and the output beams have $\tilde{\chi}^{\text{in}} = \tilde{\chi}^{\text{out}} = 0$ and $\tilde{\psi}^{\text{in}} = \tilde{\psi}^{\text{out}} = 0$. There is not a predominant azimuth in the input beam or a predominant ellipticity in the output beam. On the other hand, it should be noticed that, due to $s_3(\mathbf{r}) \neq 0$ after the LD, we have a spin contribution to the angular momentum at each point in the transverse section, and it could be useful, for example, for manipulating molecules locally.

4. INCIDENT BEAM: SUPERPOSITION OF MONOCHROMATIC UNIFORMLY AND PARTIALLY POLARIZED BEAMS WITH DIFFERENT WAVELENGTHS AND STATES OF POLARIZATION

Spectral beam combining is a recently developed method for efficient power scaling of laser radiation [24,25]. In applications where depolarized light it is necessary or convenient, one wonders if an LD could be useful to depolarize a spectral beam combined superposition of lasers.

Let us now consider as incident beam a finite superposition of monochromatic uniformly and partially polarized beams with different wavelengths and states of polarization. The local, the averaged, and the standard degree of polarization have the same value for uniformly polarized beams. Because of this fact, in the following only the standard degree of polarization will be analyzed. For a superposition of uncorrelated beams, the Stokes vector of the input beam is given by the sum of the Stokes vectors of each component (in the following, the wavelength dependence will be explicit):

$$S^{\text{in}} = \sum_{\lambda} S^{\text{in}}(\lambda), \tag{31}$$

and at the output of the LD, we have

$$S^{\text{out}} = \sum_{\lambda} S^{\text{out}}(\lambda), \tag{32}$$

where $S^{\text{in}}(\lambda)$ is given by Eq. (1) and $S^{\text{out}}(\lambda)$ by Eq. (16). Dependence on $\mathbf{r}$ has been omitted because, in the following, only uniformly polarized beams will be considered. For this superposition as input beam, the degree or polarization at the output of the LD can be modified by varying properly the input beam characteristics and the LD dephases.

The specific situation of input beam in which the spectral components of the superposition are uniformly and completely polarized $[P^{\text{in}}(\mathbf{r}) = P^{\text{in}}_{\text{st}} = \tilde{P}^{\text{in}} = 1]$ with the same state of polarization, for example, linear, and different wavelengths has been previously studied in [10–15], where uniformly polarized polychromatic beams emitted by a single source are considered. In this case, at the output of the LD, $P^{\text{out}}_{\text{st}}$ is close to zero, and then the beam is locally and globally depolarized. A simple case that has not been studied yet, to our knowledge, is an incident beam synthesized with a superposition of two monochromatic and uniformly totally polarized components with different wavelengths and different states of polarization. This case will be analyzed in Section 5.

5. INCIDENT BEAM: SUPERPOSITION OF TWO MONOCHROMATIC UNIFORMLY AND ORTHOGONALLY POLARIZED BEAMS WITH DIFFERENT WAVELENGTHS

In order to show in a simple way the effect of the LD on the input beams given by Eq. (31), let us consider the simple case of two monochromatic beams of wavelengths λ_1 and λ_2 linearly polarized at 0° and 90° with respect to the incidence plane, respectively, and with powers $s_0(\lambda_1)$ and $s_0(\lambda_2)$. Then the incident Stokes vector is given by

$$S^{\text{in}} = S^{\text{in}}(\lambda_1) + S^{\text{in}}(\lambda_2) = s_0(\lambda_1)\begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} + s_0(\lambda_2)\begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix}. \tag{33}$$

The standard degree of polarization for this input beam is

$$P^{\text{in}}_{\text{st}} = \frac{|s_0(\lambda_1) - s_0(\lambda_2)|}{s_0(\lambda_1) + s_0(\lambda_2)}, \tag{34}$$

which is a globally and locally partially polarized beam. For the particular situation of $s_0(\lambda_1) = s_0(\lambda_2)$, the degree of polarization at the input is $P^{\text{in}}_{\text{st}} = 0$, and the beam is unpolarized.

After propagating through the LD, the new Stokes vector results:

$$\begin{aligned} S^{\text{out}} &= S^{\text{out}}(\lambda_1) + S^{\text{out}}(\lambda_2) \\ &= s_0(\lambda_1)\begin{pmatrix} 1 \\ \cos 2\delta_1 \\ 0 \\ \sin 2\delta_1 \end{pmatrix} + s_0(\lambda_2)\begin{pmatrix} 1 \\ -\cos 2\delta_2 \\ 0 \\ -\sin 2\delta_2 \end{pmatrix}, \end{aligned} \tag{35}$$

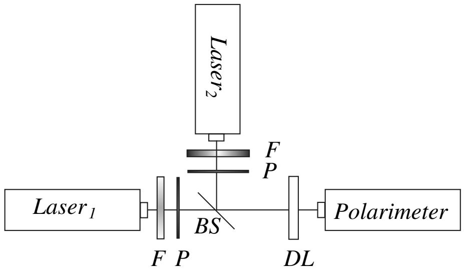


Fig. 3. Experimental setup for synthesizing the input beam described in Section 5 and for measuring the standard degree of polarization at the input and output of the LD. F, neutral filter; P, linear polarizers; and BS, beam splitter.

where δ_i with $i = 1, 2$ is the phase difference given by Eq. (15) for each wavelength. The standard degree of polarization at the output of the LD results in

$$(P_{\mathrm{st}}^{\mathrm{out}})^2 = (P_{\mathrm{st}}^{\mathrm{in}})^2 + \frac{2s_0(\lambda_1)s_0(\lambda_2)[1 - \cos(2\delta_1 - 2\delta_2)]}{[s_0(\lambda_1) + s_0(\lambda_1)]^2}. \quad (36)$$

This expression reduces to $P_{\mathrm{st}}^{\mathrm{out}} = |\sin(\delta_1 - \delta_2)|$ when $s_0(\lambda_1) = s_0(\lambda_2)$.

As can be seen from Eq. (36), the degree of polarization depends on the difference phase for each wavelength. When both beams have the same wavelengths, δ_1 and δ_2 are equals, and the degree of polarization does not change. The beam remains unpolarized. From Eq. (36), it is inferred that $P_{\mathrm{st}}^{\mathrm{out}}$ will be greater than or equal to $P_{\mathrm{st}}^{\mathrm{in}}$. At the output of the LD, a minimum value of the degree of polarization $P_{\mathrm{st}}^{\mathrm{out}} = P_{\mathrm{st}}^{\mathrm{in}}$ is obtained for $\delta_1 - \delta_2 = m\pi$, with m an integer. When $\delta_1 - \delta_2 = (2m + 1)\pi/4$, then

$$(P_{\mathrm{st}}^{\mathrm{out}})^2 = \frac{s_0^2(\lambda_1) + s_0^2(\lambda_2)}{[s_0(\lambda_1) + s_0(\lambda_2)]^2}, \quad (37)$$

and for $\delta_1 - \delta_2 = (2m + 1)\pi/2$, then $P_{\mathrm{st}}^{\mathrm{out}} = 1$. For all other cases, the values of $P_{\mathrm{st}}^{\mathrm{out}}$ will be ranged between $P_{\mathrm{st}}^{\mathrm{in}}$ and 1. For the given superposition of beams at the input, the degree of polarization at the output of the depolarizer is greater than (or equal to) the degree of polarization at the input of the LD; that is to say, the depolarizer increases the degree of polarization.

An incoherent superposition of orthogonally linearly polarized beams as the one described by Eq. (33) has been used by Gorodetski *et al.* [31] for testing the performance of their proposed polarimeter when measuring the degree of polarization of partially polarized light. For a more general test, a superposition of elliptically polarized beams could be useful, and the introduction of an LD is an easy way for obtaining such a superposition [see Eq. (35)].

Table 1. Characteristics of the Input Beams

λ (nm)	ψ (deg)	χ (deg)	$P_{\mathrm{st}}^{\mathrm{in}}$
632.8[a]	89.9	0.54	0.98
632.8[b]	0.04	−0.025	0.99
594	0.01	−0.08	0.99
532	0.08	−0.26	0.99

[a]He–Ne laser from Spectra-Physics.
[b]He–Ne laser from Uniphase.

In order to experimentally check Eqs. (34) and (36), the setup shown in Fig. 3 was designed. Two lasers were used to synthesize the input beam. The laser labeled laser$_1$ was always an intensity- and frequency-stabilized mode red He–Ne laser source ($\lambda_1 = 632.8$ nm), Model Spectra-Physics 117A. For the laser labeled as laser$_2$, three different type of lasers were used: a red He–Ne Uniphase ($\lambda_2 = 632.8$ nm), a yellow He–Ne laser Uniphase ($\lambda_2 = 594$ nm), and a green diode laser Alpec ($\lambda_2 = 532$ nm). In order to control the irradiance, neutral filters (F) at the output of each laser were used. The polarization state (linear polarization along the x and y directions) at the output of the lasers was obtained by means of linear polarizers (P). A beam splitter (BS) was used to combine both beams. The LD was the LDPOL-B from Thorlabs of quartz phase plates with thicknesses of 2 and 4 mm. A polarimeter (Thorlabs, PAX5710) was used for measuring the standard degree of polarization, and a powermeter (Digital powermeter Model 815 series from Newport) was inserted between the BS and the LD for measuring the beam powers.

The experimental characteristics of each isolated beam at the input of the LD are shown in Table 1. These values together with Eqs. (10), (16), (31), and (32) were used for computing the theoretical values of the standard degree of polarization.

Theoretical and measured values of the standard degree of polarization, both at the input and at the output of the LD, are compared in Table 2.

As can be seen from Table 2, there is good agreement between theoretical values and experimental measurements. For identical wavelengths of the two lasers, the input and output degrees of polarization are close to zero. Both beams are depolarized. When the yellow (594 nm) or the green (532 nm) lasers were used as laser$_2$, the input was unpolarized, and the output was partially polarized with $P_{\mathrm{st}}^{\mathrm{out}} \approx 0.20$ or $P_{\mathrm{st}}^{\mathrm{out}} \approx 0.30$, respectively. The slight discrepancies are higher when the values of the degree of polarization are nearly zero. In the particular case of the green laser, the differences between theoretical and experimental results of the degree of polarization

Table 2. Theoretical and Experimental Values of the Standard Degree of Polarization for Different Combinations of Laser$_1$ and Laser$_2$

				$P_{\mathrm{st}}^{\mathrm{in}}$		$P_{\mathrm{st}}^{\mathrm{out}}$	
Laser$_1$ λ_1 (nm)	Laser$_2$ λ_2 (nm)	Power$_1$ (mW)	Power$_2$ (mW)	Theory	Experiment	Theory	Experiment
632.8[a]	632.8[b]	0.322	0.330	0.017	0.015	0.017	0.014
632.8[a]	594	1.500	1.286	0.068	0.011	0.197	0.195
632.8[a]	532	0.938	0.860	0.050	0.090	0.220	0.300

[a]He–Ne laser from Spectra-Physics.
[b]He–Ne laser from Uniphase.

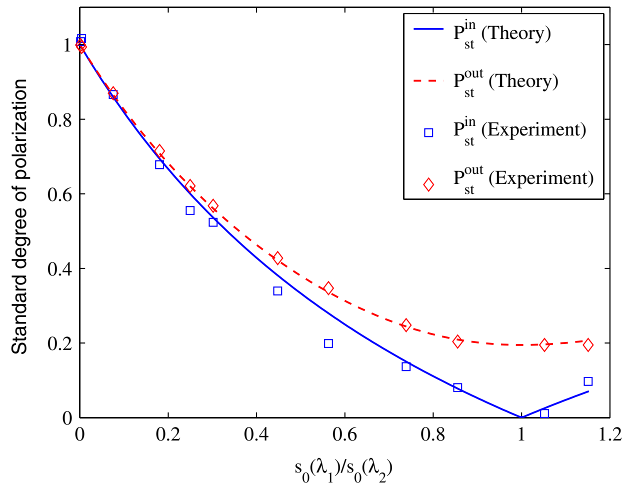


Fig. 4. (Color online) Theoretical and experimental values of the degree of polarization at the input and the output of the LD.

at the output of the LD are high, and it could be due to the intensities instabilities of this laser.

On the other hand, Eqs. (34) and (36) show that the degree of polarization, both at the input and at the output of the LD, vary from 0 to 1 just by varying the two laser irradiances ratio $s_0(\lambda_1)/s_0(\lambda_2)$. The experimental setup of Fig. 3 was used with red (632.8 nm) and yellow (594 nm) lasers and with several neutral filters in order to show the dependence of P_{st}^{in} and P_{st}^{out} on the laser irradiance ratio. Theoretical curves together with the experimental values of the degree of polarization, P_{st}^{in} and P_{st}^{out}, are shown in Fig. 4. It can be seen that the predicted relation $P_{st}^{in} < P_{st}^{out} < 1$ is always satisfied, and a good agreement between theory and experiment is observed.

Finally, note that, in this section, we have reported an experimental method for synthesizing, in a simple way, a field with a propagation-invariant spectrum and degree of polarization that can be chosen at will.

6. CONCLUSIONS

LDs are optical devices used to produce polychromatic output beams with standard degree of polarization near to zero from polychromatic and uniformly totally polarized input beams. In this work, the polarization characteristics at the output of this device are investigated when other types of incident beams are considered. For monochromatic NUP beams, the LD only modifies the distribution of polarization across the beam transverse section but does not change the degree of polarization. In contrast, for totally polarized overlapping beams with different polarization and different wavelengths, the degree of polarization at the output depends on the specific characteristics of the input beams and of the LD. The degree of polarization can be increased. In particular, it has been shown theoretically and experimentally that, when the incident beam is a superposition of two uniformly and orthogonally polarized beams with different wavelengths, the LD polarizes instead of depolarizes.

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