Broadband and ultra-broadband polarization rotators with adiabatic modular design

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Received 3 March 2015, revised 9 May 2015
Accepted for publication 14 May 2015
Published 2 July 2015

Abstract
We experimentally demonstrate broadband and ultra-broadband spectral bandwidth polarization rotators with modular design. The presented polarization rotators comprise arrays of half-wave plates rotated at different angles. We give the general recipe to determine the exact values of the rotation angles as follows: align the fast polarization axis of the first half-wave plate with the incoming polarized light, and then rotate each subsequent half-wave plate at a gradually increasing angle until the fast polarization axis of the last half-wave plate is parallel with the desired polarization rotation angle. We show that the broadband and ultra-broadband performance of the polarization rotators is due to the adiabatic nature of the evolution of the light polarization. In this paper we experimentally investigate the performance of broadband and ultra-broadband polarization rotators comprising ten multi-order half-wave plates and ten commercial achromatic half-wave plates, respectively.

Keywords: broadband polarization rotator, adiabatic evolution, piecewise adiabatic passage, modular design

1. Introduction
Rotating the orientation of linearly polarized light by an angle of choice is one of the key operations in polarization optics, which is achieved by using optical polarization rotators [1–4]. These rotators are traditionally based on either the Faraday effect, total internal reflection, or the birefringent effect [3, 4]. The so-called Faraday rotators use the Faraday effect [3, 4] to create a difference in the refractive indices for right and left circularly polarized light and, as a result, the linear polarization plane is rotated irrespective of its initial orientation. In contrast, double Fresnel rhombs, which use total internal reflection [5, 6], and twisted nematic cells, which use the birefringent effect [7], require an initial alignment between the polarization plane of the incoming light and the optical instruments.

Two advantages of double Fresnel rhombs [5, 6] are the extremely large bandwidth of operation (~1000 nm) and relative low-cost. However, they are able to rotate the linear polarization plane only by 90° and cannot be used for a rotation at an arbitrary angle. Similarly, twisted nematic cells [7], which rotate the linear polarization plane of light by following the twisted structure, can operate over a wide range of wavelengths but rotate the polarization by a fixed angle, typically 45° or 90°. It is possible to create a twisted nematic cell for any desired polarization rotation angle [9], however, this rotation angle cannot be subsequently changed due to the nonlinear dependence of the twist on the applied voltage and temperature [10]. A device consisting of three liquid-crystal cells that is capable of rotating a linear polarization state of light by a certain angle for a wide range of wavelengths was demonstrated by Zhuang et al. [11] and later optimized by Aharon and Abdulhalim [12]. However, to the best of our knowledge, a polarization rotator for any desired rotation angle based on twisted nematic cell has not been demonstrated yet.

In this paper, we report an experimental demonstration of broadband and ultra-broadband polarization rotators based on modular design comprising ten multi-order half-wave plates and ten commercial achromatic half-wave plates,
respectively. For both polarization rotators the constituent half-wave plates are rotated gradually from an alignment between the fast-polarization axis of the first half-wave plate with the incident linearly polarized light to an alignment of the fast-polarization axis of the last half-wave plate with the desired linear polarization orientation. By design, our scheme shares a close connection with twisted nematic cells, where the relative rotation of the fast-polarization axis of each subsequent half-wave plate takes the part of the twisted structure. Thus, the proposed rotators can be viewed as discrete alternatives of twisted nematic cells. Major advantages of our modular polarization rotators are their achromaticity and easy adjustability to rotate the linear polarization state of light by any desired angle. Furthermore, they can be assembled in any modern laser lab at no additional cost by simply using optical elements that are already available. Therefore, the proposed broadband and ultra-broadband polarization rotators with modular design hold the promise to be of significant interest and application.

2. Theory

Consider the propagation of a plane electromagnetic wave along the z-axis through a lossless medium. The polarization evolution is then given by the torque equation for the Stokes vector [13–16]:

$$\frac{d}{dz} S(z) = \Omega(z) \times S(z),$$  \hspace{1cm}(1)

where $z$ is the distance along the propagation direction, $S(z) = [S_1(z), S_2(z), S_3(z)]$ is the Stokes vector, and the driving torque $\Omega(z) = [\Omega_1(z), \Omega_2(z), \Omega_3(z)]$ is the birefringence vector of the medium. When the medium is not optically active and when it is uniaxial with the slow and fast axes in the $xy$ plane, the components of the birefringence vector $\Omega(z)$ are given by

$$\Omega_1(z) = \Omega_0 \cos(2\varphi),$$  \hspace{1cm}(2)

$$\Omega_2(z) = \Omega_0 \sin(2\varphi),$$  \hspace{1cm}(3)

$$\Omega_3(z) = 0,$$  \hspace{1cm}(4)

$$\Omega_0 = \frac{2\pi}{\lambda} (n_e - n_o).$$  \hspace{1cm}(5)

Here, $n_e$ and $n_o$ are the refractive indices along the fast and the slow axis, respectively, $\lambda$ is the light wavelength, $\Omega_0$ is the rotary power, and $\varphi$ is the angle of rotation between the fast (slow) axis and the x (y) Cartesian axis.

Assume that the Stokes vector $S(z)$ is initially parallel to the birefringence vector $\Omega(z)$, such that $\Omega(z) \times S(z) = 0$. If then the angle $\varphi$ is changed slowly (adiabatically), the Stokes vector will also follow an adiabatic evolution according to equation (1). For example, if linearly polarized light is initially in the horizontal plane, i.e., the Cartesian axes $x$ and $y$ coincide with the fast and slow optical axes and $S(z_i) = (1, 0, 0)$, and $\varphi(z_i) = 0$, then the birefringence vector $\Omega(z)\parallel S(z)$. Following an adiabatic evolution, the final angle of linear polarization will be $\varphi(z_f)$. This adiabatic approach to rotating the linear polarization state of light has the advantage of being robust with respect to large intervals of values for $\Omega_0$ and is therefore, broadband.

Here, we introduce an alternative modular scheme to induce adiabatic evolution of the Stokes vector using similar technique to piecewise adiabatic passage from quantum optics [22–27]. The presented technique is based on an analogy between the Poincaré space and the Bloch space, which are used for the description of the light polarization state and the state of two-level quantum systems, respectively [17–21]. We propose that the angle $\varphi$ is not changed continuously, as described in the previous paragraph, but in a sequence of discrete steps. Experimentally, we realize this by a sequence of $N = 10$ birefringent crystals, each rotated at an angle $\varphi_i$, with respect to the chosen Cartesian coordinate system (illu-

3. Experiment

3.1. Optical setup

We performed several experiments using the presented broadband and ultra-broadband polarization rotators to rotate the linear polarization state of light to 45°, 60°, 75° and 90° degrees. We assembled the polarization rotators using a sequence of ten half-wave plates, which were rotated at different angles $\varphi_i$, with respect to the chosen Cartesian coordinate system, as shown in figure 1.
The experimental setup included a 10 W Halogen-Bellaphot (Osram) lamp with dc power supply, which we utilized as a light source with continuous spectrum in the range from 450 to 1100 nm (figure 2). Additionally, we used an iris, two lenses and a polarizer to produce a collimated polarized light beam. The iris \( I \) was placed in the focus of a plano-convex lens \( L_1 \) with \( f = 35 \) mm, thus imitating a point light source. The resulting beam was additionally collimated by a second lens \( L_2 \) with \( f = 150 \) mm. Lastly, a polarizer \( P \) (Glan–Taylor, 210–1100 nm, borrowed from a Lambda-950 spectrometer, Perkin Elmer) linearly polarized the white light in the horizontal plane.

We used two types of half-wave plates to realize broadband and ultra-broadband optical rotators. For the broadband optical rotator we used a set of ten ordinary multi-order quarter-wave plates (WPMQ10M-780, Thorlabs), which perform as half-wave plates at \( \lambda = 763 \) nm. For the ultra-broadband optical rotator we replaced the ordinary half-wave plates with achromatic half-wave plates (WRM053-mica, 700–1100 nm, Melles Griot). Each wave plate (aperture of 1″) was assembled onto a separate RSP1 rotation mount, which can realize a 360° rotation. The scale marked at 2° increments allowed for precise positioning and fine angular adjustment.

We analyzed the characteristics of the light transmitted through the sequence of \( N \) wave plates. We rotated each of them at the estimated angle according to the formula:

\[
q_m = (m - 1) \cdot \frac{\alpha}{(N - 1)},
\]

where \( m \) is the sequential number of the waveplate and \( N = 10 \) in the present experiment. We note that the chosen rotation angles \( q_m \) are just one possible choice and any other set of angles, which change gradually from an alignment between the fast-polarization axis of the first half-wave plate with the incident linearly polarized light to an alignment of the fast-polarization axis of the last half-wave plate with the desired final linear polarization orientation, will

**Figure 2.** Experimental setup. A source \( S \), an iris \( I \), lenses \( L_1 \) and \( L_2 \), and a polarizer \( P \) produce a collimated beam of white polarized light. After passing through the polarization rotator, the light beam is focused by an analyzer \( P_2 \) and a lens \( L_3 \) onto the entrance \( F \) of an optical fiber connected to a spectrometer. The polarization rotators with modular design comprising ten half-wave plates rotate the linear polarization of the light to any desired angle in the broadband and ultra-broadband spectra.

### 3.2. Measurement procedure

We assembled the broad and ultra-broad spectral bandwidth linear polarization rotators by means of ten identical multi-order half-wave plates and ten identical achromatic half-wave plates, respectively, as described in section 3.1. The waveplates were slightly tilted to reduce unwanted reflections. For the analysis of the experimental data we used a single-beam spectrometer. To account for noise and losses due to light transmission, reflection and absorption in different media, we measured the light and dark spectra for all experiments. Furthermore, we used the dark spectrum, which is measured with the light path completely blocked, for correction of hardware offsets. The reference spectrum is usually taken with the light source on and a blank sample instead of the sample of interest measured. In our case, however, we measured the transmission spectrum of the already assembled polarization rotator, but the axes of the polarizer \( P \), the analyzer \( P_2 \) and the fast axis of each half-wave plate were all set to be parallel. We used the measured light spectrum as a reference for the subsequent measurements.

A linearly polarized light beam was transmitted through the sequence of \( N \) wave plates. We rotated each of them at the estimated angle according to the formula: 

\[
q_m = (m - 1) \cdot \frac{\alpha}{(N - 1)},
\]

where \( m \) is the sequential number of the waveplate and \( N = 10 \) in the present experiment. We note that the chosen rotation angles \( q_m \) are just one possible choice and any other set of angles, which change gradually from an alignment between the fast-polarization axis of the first half-wave plate with the incident linearly polarized light to an alignment of the fast-polarization axis of the last half-wave plate with the desired final linear polarization orientation, will...
lead to adiabatic evolution of the Stokes vector. We then measured the linear polarization rotation for each of the arbitrarily chosen angles $\{45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ and collected the data with an analyzer $P_2$ rotated at angles $\alpha$ and $(\alpha + 90^\circ)$. 

3.3. Experimental results

We experimentally demonstrated a broadband polarization rotator comprising ten multi-order half-wave plates. The measured transmittance spectra for four arbitrary chosen angles $\alpha = \{45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ and collected the data with an analyzer $P_2$ rotated at angles $\alpha$ and $(\alpha + 90^\circ)$. 

Even more broadband effect was achieved when we replaced the ten multi-order half-wave plates by ten achromatic half-wave plates, thereby creating ultra-broad bandwidth linear polarization rotator. We measured the transmittance of the rotator for the same rotation angles $\alpha$. 

The experimental results are shown in figure 4(a). Again, to verify that the proposed device is a linear polarization rotator we also measured the transmittance spectra for the orthogonal angles $(\alpha + 90^\circ)$, which are presented in figure 4(b). We observed that the wavelength after which there was no more signal detected was 1000 nm.

It is important to note that there are two effects, which give rise to the oscillations in the transmittance in figures 3 and 4. First, the noise present in our setup was in part due to the light signal since the spectrum of the halogen lamp was not uniform. Second, the adiabaticity of the evolution depends on the number of wave-plates and on the rotation angle $\alpha$. That is, for smaller rotation angles $\alpha$ the setup is more adiabatic and the oscillations are smaller, while for larger rotation angles $\alpha$ the setup is less adiabatic and the oscillations are larger, as is clearly seen in figures 3 and 4.
4. Conclusion

In this paper we demonstrated an experimental application of piecewise adiabatic passage, a concept introduced by Shapiro et al in quantum optics [22–24], for optical broadband and ultra-broadband polarization rotators. The broadband and ultra-broadband polarization rotators have modular design and comprise sequences of multi-order half-wave plates or commercial achromatic half-wave plates. Following the polarization manipulation principle from twisted nematic cells, the waveplates are rotated gradually from an initial alignment of the fast polarization axis of the first half-wave plate with the polarization of the incident light to the angle of the desired linear polarization rotation. The experimental results show clear broadening of the bandwidth of the polarization rotators compared to a single waveplate, which is maintained for different arbitrary rotation angles. The presented adiabatic polarization rotators offer robustness against variations of the parameters of both the crystal and the light field. These include the wavelength of the electric field, the crystal length, and the angle of incidence. In addition, the proposed rotators are of significant interest due to their adjustability, as they allow us to manipulate the polarization orientation of light only by varying the rotation angles of the individual half-wave plates.

Acknowledgments

ED acknowledges financial support by Bulgarian National Science Fund Grant: DRila 01/4. AR and EK acknowledge financial support by SUTD start-up Grant No. SRG-EPD-2012-029, SUTD-MIT International Design Centre (IDC) Grant No. IDG31300102.

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