A different optical composition for a broadband linear polarization rotator

Hristina Hristova¹, Stefano Ognyanski¹, Andon Rangelov² and Emiliya Dimova¹

¹ Institute of Solid State Physics, Bulgarian Academy of Sciences, 72 Tsarigradsko Chaussee Blvd., 1784 Sofia, Bulgaria
² Department of Physics, Sofia University, James Bourchier 5 blvd., 1164 Sofia, Bulgaria
E-mail: hhristova@issp.bas.bg, e.dimova@issp.bas.bg

Abstract. We suggest and experimentally demonstrate a broadband polarization rotator. Our device consist of a Fresnel’s rhomb retarder and a composite broadband half-wave plate with relative rotation $\alpha$ between their fast polarization axis. Such a optical device rotate the polarization plane of a linearly-polarized light at angle $2\alpha$ over a wide range of wavelengths.

1. Introduction

Being fundamental property of light [1–5], the polarization became an important tool for many optical measurement techniques used in stress measurements, ellipsometry, physics, chemistry, biology, astronomy and others [6–8]. The ability to manipulate light polarization is highly desirable for practical applications. For example, display and telecommunications technologies rely on the ability for controlled rotation of the light polarization [9]. For the purpose optical polarization rotators, which rotate the light polarization plane at a desired angle [1–5], ordinary are used.

Two types of polarization rotators are commercially available. First of them exploits the effect of circular birefringence. The main advantages of this type are independence of the angle of light polarization rotation via rotation of the rotator around its own optical axis, and low price. On the other hand, they can be used only for a limited range of wavelengths. The second type of rotators are those for which polarization plane rotation is achieved through consecutive reflections, for example, Fresnel rhombs [1–5]. They can operate over a wide range of wavelengths but are quite expensive. Due to their features both of the types are used for measurements [10].

There are also schemes to enlarge the spectral width of a light polarization plane rotation - for several fixed wavelengths simultaneously using up to four half-wave plates in a series, suggested by Koester [11], and using two wave plates of the same material, shown by Kim and Chang [12].

The approach of Kim and Chang [12] can be extend in combination with the Koester idea [11] allowing to design an arbitrary broadband polarization rotator [13, 14]. The presented scheme consists of two crossed half-wave plates, where the angle between their fast axes is half the angle of polarization rotation. Due to the the analogy with the composite phase gates [15], the usage of composite half-wave plates ensures broadband and stability with respect to wavelength variations.
In this paper, we propose an alternative design for a broadband polarization rotator and demonstrate the device working. The main difference from [13, 14] consists in using of a Fresnel’s rhomb instead of one of the both composite half-wave plates.

2. Theory

Using the Jones calculus, any reversible polarization transformation can be considered as a composition of a retarder  and a rotator  Jones matrices [16], represented in the horizontal-vertical basis as,

\[
R(\theta) = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta 
\end{bmatrix}, \quad J(\varphi) = \begin{bmatrix}
e^{i\varphi/2} & 0 \\
0 & e^{-i\varphi/2}
\end{bmatrix},
\]

(1)

where \(\theta\) is the angle of rotation, the phase shift is \(\varphi = 2\pi L(n_f - n_s)/\lambda\), with \(\lambda\) being the vacuum wavelength, \(n_f\) and \(n_s\) the refractive indices along the fast and slow axes, correspondingly, and \(L\) the thickness of the retarder. The Fresnel’s rhombs and the wave plates are used as retarders. The performance of the wave plates is usually limited to a narrow range of wavelengths around \(\lambda\).

A broadband rotator can be constructed as a sequence of two broadband half-wave plates with an additional rotation between them. In references [13, 14, 17] the main steps in derivation of the Jones matrices for the composite half-wave plate(CHWP) are shown and broadband rotator composed of two CHWPs. But there is another possibility for creation of a broadband rotator, namely, to replace one of the CHWPs in the sequence with a half-wave Fresnel’s rhomb (HWFR).

For a single half-wave plate rotated at angle \(\theta\), the Jones matrix \(J\) has the form

\[
J_{\theta}(\pi) = R(-\theta)J(\pi)R(\theta) = \begin{bmatrix}
i \cos(2\theta) & -i \sin(2\theta) \\
-i \sin(2\theta) & -i \cos(2\theta)
\end{bmatrix}.
\]

(2)

Considering a simple sequence of two ordinary half-wave plates rotated at angles \(\theta_1\) and \(\theta_2\) respectively, multiplication of the Jones matrices gives the total propagator

\[
J_{\theta_1}(\pi)J_{\theta_2}(\pi) = -\begin{bmatrix}
\cos(2\alpha) & \sin(2\alpha) \\
-\sin(2\alpha) & \cos(2\alpha)
\end{bmatrix},
\]

(3)

where \(\alpha = \theta_1 - \theta_2\) denoted the relative rotation between the fast axes of the two waveplates. The last matrix represents a Jones matrix for a rotator up to unimportant \(\pi\) phase (minus sign), which is not broadband. For our purpose to extend the range of operation of the rotator, we replace the two ordinary half-wave plates with a HWFR, described again by equation 2, and a CHWP, respectively. With a relative rotation of \(\alpha/2\) between them, the final propagator is described again by equation3.

3. Experimental setup

Using commercially available optical elements, a broadband linear polarization rotator is developed.

The constructed rotator is composed by two types optical components. First is a half-wave Fresnel’s rhomb retarder (FR600HM, ThorLabs) and the second one is an ultra-broadband CHWP. The last one is developed by using the quantum-optical analogies. The composite half-wave plate is built as a stack of ordinary achromatic half-wave plates (WRM053-mica, 700-1100nm, aperture 20mm, MellesGriot) which respective optical axes are adjusted according to the procedure described in [17]. In such a way it plays as half-wave plate for ultra-broadband spectral range, covering whole visual and near IR spectral region.

The experimental setup, shown on the figure 1, is similar to those in [14,17]. For visualization of the investigated effect we have used white light from a lamp TUNGSRAM powered by a 6V d.c. power supply. The light was collimated in a beam (2 mm diameter for a distance of up to
Figure 1. Experimental setup. A Lamp S, an iris I, lenses $L_1$ and $L_2$, and a polariser $P_1$ produce a collimated beam of white polarized light. After passing through the investigated composite rotator, the light beam is focused by an analyser $P_2$ and a lens $L_3$ onto the entrance $F$ of an optical fibre connected to a spectrometer.

2 m) by a set of an iris and two lenses, $L_1$ (f=35 mm) and $L_2$ (f=150 mm). Good collimation, as well as beam horizontality, are critical to HWFR’s work. The polarisers, $P_1$ and $P_2$, were borrowed from a Lambda-950 spectrometer, Perkin Elmer and were of GlanTayler type with a wide spectral range of 210-1100 nm. The light beam was polarized in the horizontal plane by the polariser $P_1$. $P_2$ was used to analyse the polarization of the output light. The objects under investigation were placed between them. The light after $P_2$ was sent by set of a lens and a fibre to a spectrometer AvaSpec 3648 Fiber Optic Spectrometer, controlled by the proprietary software AvaSoft version 7.5.

The investigating polarization rotator is a composition of a HWFR and a half-wave plate. We investigated three cases. In the first one we used combination between HWFR and a achromatic half-wave plate (WRM053-mica, 700-1100nm, aperture 20mm, MellesGriot), and the other case two half-wave plates, the same type, have been used. The taken transmittance spectra from this two compositions we used for comparison with the one of the developed new construction. The rotator of interest is constructed by HWFR and a ultra - broadband CHWP made by tree achromatic half-wave plates. Each of the optical elements is mounted on a separate RSP1 rotation mount (Thorlabs Inc.), which can be used for 360° rotation. The scale marked at 2° increments allowed for precise, repeatable positioning and fine angular adjustment. The mounted half-wave plates were slightly tilted around their vertical axes in order to avoid the back reflection of the light.

4. Measurement procedure and results
The experimental properties of the composite rotator have been studied by analyzing the polarization of the transmitted light through the investigated object. With the upper explained
setup we can achieve a reliable data in the range 500-1000 nm, because of the properties of the light source.

The measurement procedure was similar to one described in the articles [14, 17]. All experiments started with measurement of the dark and reference spectra. The dark spectrum, taken with the light path blocked, is further used to automatically correct for hardware offsets. The reference spectrum is usually taken with the light source on and using a blank sample rather than the sample under test. In our case, however, we measured the transmission spectrum of the already assembled composite polarization rotator, with the axes of the analyzer P2 and the fast axis of the single wave plates and HWFR all set to be parallel. The measured light spectrum was used as a reference for the subsequent measurements.

First step of our measurement was to built the CHWP. For this experiment we stopped on the CHWP assembled by three ordinary half-wave plates, [17], and by turning the fast axes of the half-wave plates respectively on angles: first half-wave plate: 60°; second half-wave plate: 120° and third half-wave plate: 60°. As a next step, we set the composite rotator in two parts similar to the one reported in the [14]. Instead of a half-wave plate, we used HWFR here and the second component is CHWP, which we have already built. The composed linear polarization rotator was tested at randomly selected angles. For more clear representation of the results, we choose angles 40°, 60°, 90° and 120°.

![Figure 2](image-url)

Figure 2. Experimental results for ultra-broadband spectral bandwidth linear polarization rotator built by half-wave Fresnel’s rhomb and composite achromatic half-wave plates, black solid line. Three single half-wave plates were used to assemble the composite half-wave plate and their respective optical axes were to the respective rotation angles in accordance with angles in table 1 in the article [17]. As reference data the spectra of two types of rotators are also shown. First on is built by HWFR and one half-wave plate (b), blue dash dot line, while the other one is constructed by two half-wave plates (c), red dashed line.
On the figure 2 the spectra of the composed broad-bandwidth rotator at the chosen angles are presented. Each curve is taken with integration time of 10 ms and average of 1000. The comparison with the reference spectra of rotator, composed by a HWFR and a half-wave plate, as well as rotator, composed of two half-wave plates, shows the broadening effect of proposed by us optical construction. We expect that in case of the composite half-wave plates stacked by more number of elements (5, 7, 9), the linear polarization rotator will have effect even at broader spectrum. As the principle of the construction of this type of linear polarisation rotator is universal on the type of the half-wave plates, we can expect a broader application of it.

5. Conclusion
We have presented an approach to construct broadband composite polarization rotator which operates over a wide range of wavelengths. Such a rotator is comprised of a Fresnel’s rhomb and a composite broadband half-wave plates with a relative rotation of $\alpha/2$ between them. Furthermore we prove experimentally that such a polarization rotator is indeed broadband and operate over a wide range of wavelengths, using a double Fresnel’s rhomb and a broadband half-wave plate.

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