Efficient composite broadband polarization retarders and polarization filters

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Abstract. A new type of broadband polarization half-wave retarder and narrowband polarization filters are described and experimentally tested. Both, the retarders and the filters are designed as composite stacks of standard optical half-wave plates, each of them twisted at specific angles. The theoretical background of the proposed optical devices was obtained by analogy with the method of composite pulses, known from the nuclear and quantum physics. We show that combining two composite filters built from different numbers and types of waveplates, the transmission spectrum is reduced from about 700 nm to about 10 nm width.We experimentally demonstrate that this method can be applied to different types of waveplates (broadband, zero-order, multiple order, etc.).

1. Introduction

Optical half-wave and quarter-wave retarders belong to the standard equipment of every optical laboratory. An optical retarder is an optical plate, made of birefringent material, which introduces a phase shift $\varphi=2\pi\delta_n L/\lambda$ of the light wave travelling through it. Here, λ is the light wavelength, δ_n is the birefringence and L is the thickness of the birefringent optical medium of the retarder. In the case of half-wave plates (HWP) the phase shift is $\varphi=(k+1)\pi$ and k=0, 1, 2, 3, ... while for the quarter-wave plates (QWP) $\varphi=(k+1/2)\pi$. The waveplates can be zero-order (k=0) or multiorder (k>0). Waveplates (WP) exhibit wavelength dispersion, due to the wavelength dependence of the phase shift and are thus manufactured for particular wavelength ranges.

Applications of waveplates are measurements with ultrashort laser pulses, e.g. terahertz time-domain spectroscopy [1, 2], microwave polarimetry [3, 4 and 5], etc. demand wider wavelength range of nearly constant phase retardation. Broadband (BB), also called achromatic, retarders are well known from the literature and are already commercially available. For instance, quarter- or half- wave plates with wide spectral range can be constructed using two or more waveplates of different birefringence [6], or waveplates with different thickness [7], or stacks of a number of equal waveplates [8, 9], twisted to specific angles, optimized to obtain nearly flat spectral response. The last mentioned case is an example that generally, a birefringent network having any required transfer function can be constructed if a proper method for the determination of the respective waveplates rotation angles is available.

Stacked composite plates can be seen as mathematically equivalent to composite pulses in quantum physics, a technique widely used in nuclear magnetic resonance (NMR) [10] and since recently, in quantum optics [11, 12]. This similarity is derived from the formal analogy between the Schroedinger equation for a two-state quantum system and the equation for the Jones polarization matrix evolution [13]. Ardavan [14] proposed to use the broad band (BB) and narrow band (NB) composite pulses of Wimperis [15] to design BB and NB WPs, respectively. In a recent work [16], the analogy between the polarization Jones vector and the quantum state vector was used to propose a calculation method to derive the twisting angles of the retarders in a stack with predefined wavelength range and polarization conversion fidelity. Recently, composite BB and NB WPs composed of stacked zero-order WPs were proposed [16] and experimentally demonstrated [17] in a double-pass setup. Both BB retarders and NB optical filters, constructed using a set of stacked standard multi-order WPs were presented in [18].

The theoretical background and calculation method used to design our polarization BB retarders and NB filters have been presented in details in [16, 18] and will not be discussed here. In the present work we will demonstrate that the wavelength range of a commercial broadband half WP can be further extended by combining it with further BB HWPs, building a composite half-wave plate. Furthermore, varying the twisting angles of the single WPs in the stack the wavelength range of the composite HWP can be even made narrower for possible applications as narrow optical polarization filter.

2. Experimental setup

2.1. Optical setup

We have used an optical breadboard to set up the experiments, cf. figure 1. The setup consisted of i) a light source, ii) the composite retarder under test, and iii) the transmission spectra recorder.

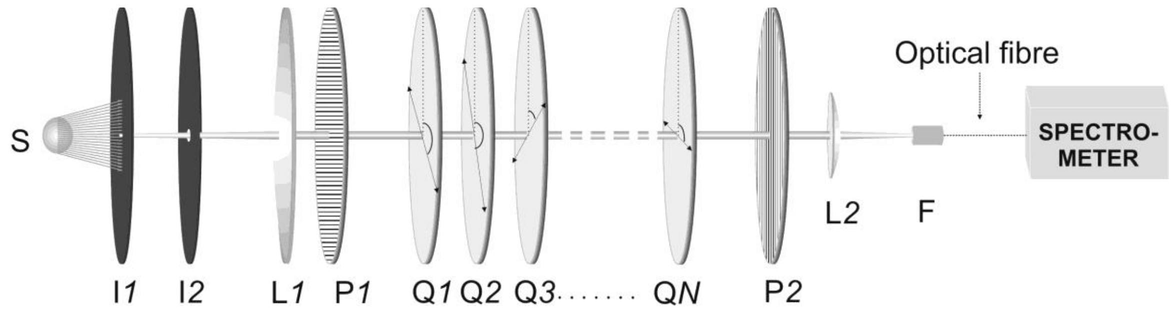

Figure 1. Experimental setup. The source S, irises I1 and I2, lens L1 and polarizer P1 form a beam of white polarized light. Polarizer P2 and lens L2 focus the analyzed beam of output light onto entrance F of an optical fibre connected to spectrometer. The investigated composite retarders are designed by stack of multiple order waveplates WPs (Qn).

As source of collimated polarized light with continuous spectrum we used a 10 W Halogen-Bellaphot (Osram) lamp, S, powered by a stabilized DC supply. For good collimation an iris I*1* with an aperture less than 0.5 mm was used, serving as a point light source, placed in the focus of a plano-convex lens L*1* (f=150 mm). A second iris diaphragm I*2* was used to collimate and thus further improve the beam so that its diameter, measured along a distance of 2 m was about 2 mm. The two polarizers P*1* and P*2* were N101-0520 (Glan-Taylor, 210-1100 nm), borrowed from a Lambda - 950 spectrophotmeter. The stack of waveplates, WP_n, to be investigated for their performance as a composite retarder was build-up of single broadband HWPs (WRM053-mica, 700-1100 nm, aperture 20 mm, Melles Griot), using RSP1 rotation mounts (Thorlabs Inc.). The optical axes of all the used waveplates could be preset to *1°* accuracy. Composite retarders consisting of up to 9 waveplates were assembled and their respective optical axes were preset to angles calculated using the model described elsewhere [16]. The waveplates were slightly tilted around the vertical axis to eliminate effects due to reflections [17].

The light passing through the composite retarder was focused by a plano-convex lens L*2* (f=20 mm) and a two-axes micro-positioner onto the optical fibre entrance "F". The later is used to feed the light to the input slit of a portable grating spectrophotometer Model AvaSpec-3648, spectral range 200 - 1100 nm, slite – 25 µm, grating – UA, controlled by AvaSoft 7.5 software.

2.2. Measurement procedure

The composite retarders were stacks of half-waveplates, assembled and adjusted according to the respective series of optical axes angle-of-rotation data delivered from the numerical calculations. For all experiments the first step was to parallel the axes of the polarizer P*1*, the analyzer P*2* and the slow axes of the waveplates which build-up the composite retarder under test. In this configuration the transmitted light spectrum was measured and stored as a reference. Thus, losses due to reflections and absorptions from all the single waveplates are taken into account. In a next step, the plates were rotated to the relative angles of their slow optical axis, according to the respective data from table 1. The analyzer P*2* was rotated to 90° with respect to its initial position. The transmission spectrum of the obtained composite retarder was recorded in respect to the reference spectrum. Thus, the measured spectrum will characterize the effective retardance of the stack of waveplates.

3. Experimental results

The theoretical model described in [16] has been applied to calculate a number of sets of rotation-angles for 3, 5, 7 and 9 BB HWPs, respectively and to construct the composite broadband retarders and composite narrowband polarization filters. Up to 10 different sets of rotation-angles for each type of composite retarders have been tested, recording their respective transmission spectra. In all cases the obtained spectra were nearly identical. Thus, we will present here only representative results for the composite retarders we have tested (see table 1).

Table 1. Calculated sets of rotation angles for construction of composite broadband polarization rotators (a) and polarization filters (b) by 3, 5, 7 and 9 BB half-wave plates (HWPs).

angles vs. waveplates	(α1, α2, α3, α4, α5, α6, α7, α8, α9)
(a)	**broadband polarization retarder**
a) 9 HWPs	(5.7, 12.5, 22.7, 34.3, 48.2, 61.5, 72.4, 81.3, 86.8)
b) 7 HWPs	(22.2, 67, 86.7, 44, 3.7, 24.5, 69.9)
c) 5 HWPs	(46.6, 0.2, 47.1, 88.9, 39.5)
d) 3 HWPs	(14.6, 44.9, 75.2)
e) 1 HWP	(45)
(b)	**polarization filter**
a) 9 HWPs	(166.4, 43, 7, 136.8, 165.2, 15.6, 43.1, 177.8, 126.7)
b) 7 HWPs	(175.6, 4.3, 170.6, 6.8, 169, 3.2, 174)
c) 5 HWPs	(7.5, 172.5, 14.2, 172.9, 8.6)
d) 3 HWPs	(14.7, 164.4, 14.7)
e) 1 HWP	(45)

3.1. Broadband composite retarders

As expected from the theory [16] and as already shown [18] a stack of identical commercial waveplates can be used effectively either as a broadband or as a narrowband composite retarder if the

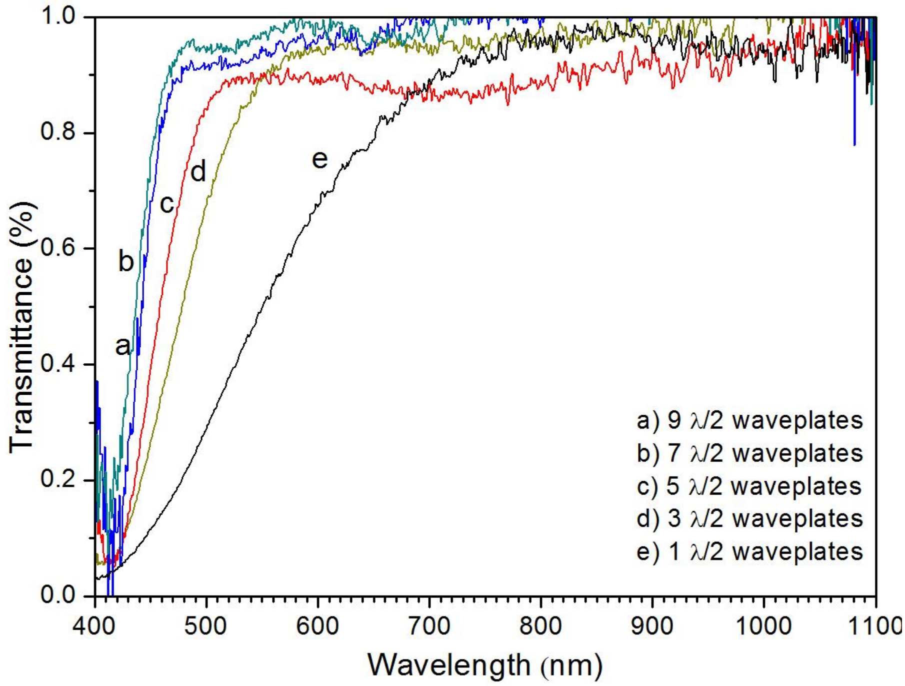

Figure 2. Transmission spectra of broadband composite retarders a), b), c) and d) assembled, respectively, by 9, 7, 5 and 3 broadband half-wave plates according to table 1(a). Each curve corresponds to the first set of angle data for the respective number of waveplates used. For comparison curve (e) presents the spectrum of one half-wave plate.

constituent WPs are arranged in a proper way. We will first show the possibility to extend the retardation of a HWP in a wider wavelength range, i.e. we will demonstrate composite BB HWPs.

Figure 2 presents the transmission spectra obtained with composite retarders assembled with different number of broadband half–wave plates, with each of them rotated to a specific angle of the slow axes according to the data from table 1 (a). It can be easily seen that with increasing number of waveplates the transmission and retardance spectra, respectively, become broader and steeper compared to the spectrum of one waveplate, cf. curves (a-e). Unfortunately, due to the experimental limitations (lamp spectrum) we were missing reliable spectral data for $\lambda \geq 1000$ nm. Thus, we do not see on the figures data for longer wavelengths.

3.2. Narrowband composite retarders

As mentioned above, according to the theoretical predictions, the wavelength range of nearly constant retardation of a composite retarder can be adjusted on demand using properly arranged stack of waveplates. In this subsection we will present representative results from a series of measurements intended to verify the possibility to produce retarders with narrower wavelength band.

Sets of rotation angles, presented in table 1(b) for composite retarders with narrow wavelength range were calculated. Although, it does not seem to be very useful for a retarder, it could be an excellent example of how a narrow band polarization optical filter can be assembled. Using the same experimental technique as described above, narrowband composite retarders were assembled with different number of broadband half-wave plates and respective angles of the slow axes from table 1(b).

Experimental transmission spectra of composite half-wave plates (HWPs) assembled with 3, 5, 7 and 9 HWPs, respectively, are shown on figure 3. On this figure the spectrum of a single half-wave plate is depicted for comparison, curve (e). The progressive narrowing of the transmission band with growing number of waveplates without significant altering of the central wavelength is clearly

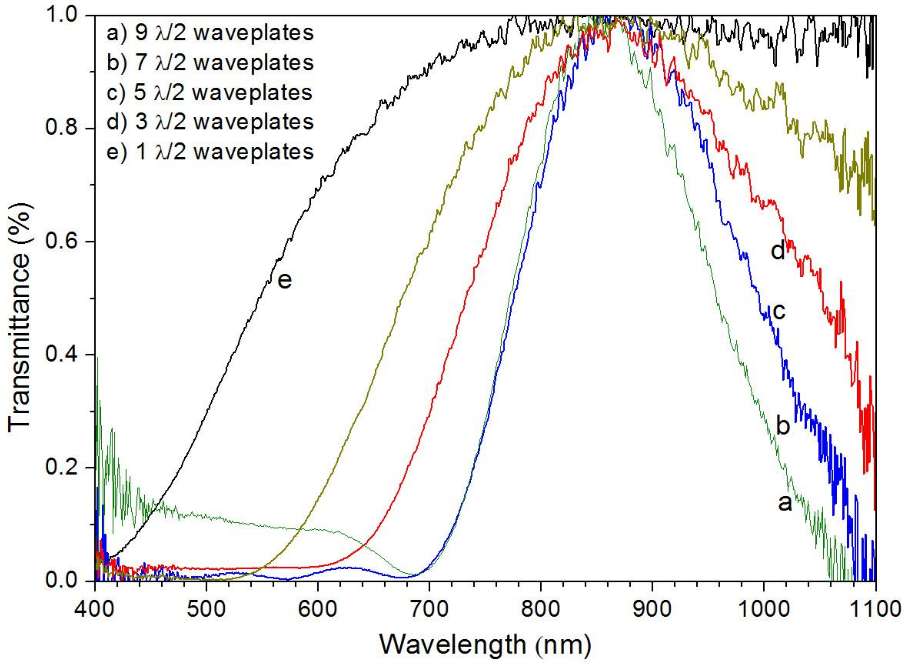

Figure 3. Transmission spectra of narrowband composite retarders assembled by 3, 5, 7, and 9 broadband half-wave plates according to table 1(a). Each curve corresponds to the first set of angle data for the respective number of waveplates used. For comparison curve (e) presents the spectrum of one half-wave plate.

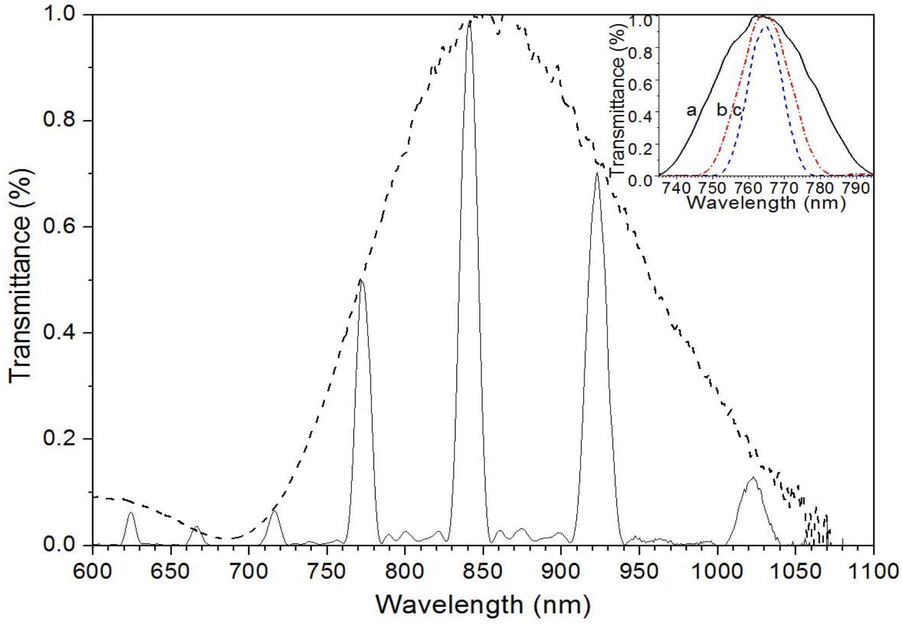

Figure 4. Transmission spectra (solid line) of a narrowband composite retarder assembled by two consecutive composite polarization filters: 9 broadband HWPs and 5 multiorder HWPs according to table 1(b). The dash curve corresponds to curve a from figure 2. The inset presents the effect of narrowing of the spectra of 1, 3 and 5 multiorder half-wave plates, curves a, b and c, respectively.

demonstrated. Thus, practical applications of composite retarders as narrowband optical filters appear to be feasible. It is also seen, that the transmission spectra show relatively low side lobes (cf. figure 3). Unfortunately, increasing the number of waveplates leads to more pronounced appearence of side lobes in the lower wavelength range.

The theoretical method used for the calculation of the rotation angles does not depend on the nature of the birefringent material. The effect of narrowing the transmission spectrum by using two consecutive composite polarization filters (CPFs) is presented in figure 4. As a result the transmission spectrum (with width of ca. 700 nm) is reduced to three peaks each with FWHM of about 10 nm. The first composite polarization filter is designed by BB HWPs with mica glass used as birefringent material while for the second composite filter a set of 5 quartz multiorder QWPs (780 nm) is used, working as HWPs at 763, 840 and 925 nm. The squeezing spectrum effect of the second CPF is presented in the inset. In both CPFs the rotation angles are taken from table 1.

Conclusion
We have demonstrated the possibility for practical realization of a new type of broadband polarization half-wave retarder plates and narrowband polarization filters, designed as composite stacks of commercial achromatic optical half-wave plates. The obtained results can be seen as further support for the calculation method described in [16].

Acknowledgments
This work was supported by the Bulgarian NSF Grant DRila-01/4 and the European Community's Seventh Frame - work Programme under grant agreement no. 270843 (iQIT).

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