A new design of a broadband optical isolator, composed as a sequence of ordinary Faraday rotators and achromatic quarter-wave plates (QWPs), is presented. In particular, we demonstrate that by using four Faraday rotators and six achromatic QWPs, rotated at specific angles, optical isolation better than 15 dB over the range from 700 to 1000 nm can be achieved. The measured transmittance (corrected for absorption and reflection) in the forward direction over the same wavelength range shows broadening of the transmission spectrum compared with the one of a single Faraday rotator. © 2013 Optical Society of America

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Efficient broadband composite optical isolator

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Optical isolators (OIs) play an important role in laser technology to protect lasers and optical amplifiers from the detrimental effects of backreflected light, such as to suppress oscillations due to unwanted optical feedback [1,2]. Commercial OIs [3,4] consist of an input polarizer, a Faraday rotator (FR) tuned to rotate the polarization vector of light at 45°, and an output polarizer, rotated at 45° with respect to the input polarizer. The angle of rotation of the polarization vector by the FR reads

\[ \theta(\lambda) = \nu(\lambda)BL, \]

where B is the external magnetic field, L is the length of the magneto-optical element of the FR, \( \nu(\lambda) \) is the Verdet constant of the material, and \( \lambda \) is the light wavelength.

The Verdet constant, which is a key characteristic of the magneto-optically active medium, is wavelength dependent. Therefore, the isolation efficiency of OIs is limited to a narrow wavelength window: typical Faraday isolators achieve optical isolation of 30–40 dB in a range of 20–30 nm around a specified wavelength.

Faraday isolators can be made wavelength adjustable either by rotating the polarizers, by moving the optical active element in and out of the magnetic field, or by changing the magnetic field. In the first case the tuning range can be made as large as 60 nm, while in the second case it can be extended to about 200 nm. Although tuning of the central wavelength can even be automated, in some special cases (e.g., to preserve the temporal profile of short light pulses) application of broadband OIs could be essential.

In contrast to the adjustable OIs, dispersion compensated Faraday isolators operating over an extended spectral range have been demonstrated [5–7] and are now commercially available. In addition to
the (nonreciprocal) FR, broadband OIs make use of an optically active material, such as quartz, as a reciprocal rotator with 45° rotation to achieve the desired wavelength dependence compensation. The result is nearly flat broadband optical isolation better than 30 dB. Although this type of OI can operate in a wide wavelength range of more than 150 nm, they can not be made adjustable and have to be produced for a specific central wavelength. Moreover, this approach is limited to materials with a proper chosen dispersion and cannot be applied for all magneto-optically active mediums of FRs.

An alternative to dispersion compensation has been proposed theoretically by Berent et al. [8], in which, instead of a single FR, a sequence of FRs and achromatic quarter-wave plates (QWPs) are used. In this way, systematic errors from various sources are canceled by the destructive interference of their effects in each of the optical elements. This scheme makes use of the analogy between the equations driving the evolution of the polarization Jones vector and the quantum state vector [9–13] and thereby adapt the technique of composite pulses in nuclear magnetic resonance [14,15] to polarization optics for the development of an achromatic Faraday isolator.

In this paper, we report an experimental demonstration of a broadband OI, assembled according to the theoretical work of Berent et al. [8] as a sequence of ordinary FRs and achromatic QWPs.

In the Faraday magneto-optical effect, the external magnetic field induces an anisotropy of the refractive index for the light of left and right circular polarizations. In the left–right circular polarization basis, the Jones matrix of Faraday rotation at angle θ is

$$\mathbf{J}(\theta) = \begin{bmatrix} e^{-i\theta} & 0 \\ 0 & e^{i\theta} \end{bmatrix}. \quad (2)$$

and the Jones matrix of an achromatic QWP rotated at an angle α with respect to the fast optical axis is

$$\mathbf{J}(\alpha) = \begin{bmatrix} \cos(\pi/4) & -ie^{i\alpha}\sin(\pi/4) \\ -ie^{-i\alpha}\sin(\pi/4) & \cos(\pi/4) \end{bmatrix}. \quad (3)$$

We wish to design a broadband FR and then use it as part of an OI that operates over a broad range of wavelengths $\lambda$. Therefore, we consider a sequence of four commercial FRs and six achromatic QWPs rotated at angles $\alpha_k$ with respect to their fast polarization axes, as shown in Fig. 1. The Jones matrix $\mathbf{J}_f$ for that system has the form (read from right to left)

$$\mathbf{J}_f(\theta) = \mathbf{J}(\alpha_6)\mathbf{J}(\alpha_5)\mathbf{J}(\alpha_4)\mathbf{J}(\alpha_3)\mathbf{J}(\alpha_2)\mathbf{J}(\theta) \times \mathbf{J}(\theta)\mathbf{J}(\alpha_2)\mathbf{J}(\alpha_1), \quad (4)$$

for the forward direction and

$$\mathbf{J}_b(\theta) = \mathbf{J}(\alpha_1)\mathbf{J}(\alpha_2)\mathbf{J}(\alpha_3)\mathbf{J}(\alpha_4)\mathbf{J}(\theta) \times \mathbf{J}(\theta)\mathbf{J}(\alpha_2)\mathbf{J}(\alpha_1), \quad (5)$$

for the backward direction. Then we expand the composite Jones matrices around the rotation angle $\theta_0 = 45°$,

$$\mathbf{J}_k(\theta) = \mathbf{J}_k(\theta_0) + \mathbf{J}_k'(\theta_0)(\theta - \theta_0) + \frac{1}{2}\mathbf{J}_k''(\theta_0)(\theta - \theta_0)^2 + \ldots, \quad (6)$$

where $k = f, b$. In the next step, we set $\mathbf{J}_f(\theta_0) = \mathbf{J}_b(\theta_0) = \mathbf{J}_0$, where $\mathbf{J}_0$ is the target Jones matrix of the composite FR,

$$\mathbf{J}_0 = \begin{bmatrix} e^{-i\pi/4} & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}. \quad (7)$$

and we nullify as many derivatives as possible,

$$\frac{\partial^s}{\partial \theta^s} \mathbf{J}_f(\theta_0) = 0 \quad \text{and} \quad \frac{\partial^s}{\partial \theta^s} \mathbf{J}_b(\theta_0) = 0, \quad (8)$$

for $s = 1, 2, 3$. There are many solutions to this problem, some of which are listed in Table 1.

We have tested the proposed composite OI with the rotation angles listed in Table 1 experimentally. The experimental setup used commercial optical elements mounted onto an optical bench, as shown in Fig. 1. The arrangement consisted of a source of white light and an analyzing system, positioned about 0.8 m apart, and the composite OI was assembled in between. The source of white light S was a 10 W Halogen–Bellaphot (Osram) lamp with

![Experimental setup](image1)

Fig. 1. Experimental setup. The white light beam is formed by light source S, iris I, and lens L1; the analyzing part consists of the second lens L2 focusing the light beam onto the entrance of an optical fiber connected to the spectrometer for observation of the light spectrum. The investigated composite FR is designed by six achromatic QWPs $Q_k$ and four ordinary FRs $F_k$. $P_1$ and $P_2$ are polarizers. For more details see the text.
stabilized DC power supply. A collimated light beam was obtained by using a variable iris \( I \) with an aperture less than 0.5 mm, positioned at the focus of a plano–convex lens \( L_1 \) with \( f = 150 \) mm. The diameter of the beam, measured at a distance of 2 m, was about 2 mm. The analyzing system consisted of a plano–convex lens \( L_2 \) with \( f = 20 \) mm and a two-axis micropositioner to couple the light to be measured with the optical fiber entrance of an AvaSpec-3648 grating spectrometer. This spectrometer was equipped with a UA grating, with a 25 \( \mu \)m slit and a detector in the spectral range 200–1100 nm. AvaSoft 7.5 control software was used for data acquisition. Measurements were performed with an integration time of 4 ms, and the spectra discussed below are the result of 100 averaged scans.

The composite OI was assembled by using two polarizers, four commercial FRs, and six achromatic QWPs. The composite FR was made of three stacks, each of them composed of an ordinary FR (\( F_i \)) sandwiched between two achromatic QWPs (\( Q_i \)) (see Fig. 1). All the FRs used were based on terbium gallium garnet crystals as the active medium, adjusted for 45° of polarization rotation. Two of the FRs (\( F_2 \) and \( F_3 \)) were combined to serve as the required 90° FR. The QWPs were 02WRM063 (Melles Griot) mica-type with 20 mm aperture, broadband in the 700–1100 nm range. As with an ordinary OI, input and output polarizers, rotated to 45° relative to each other, were added to the composite FR in order to complete the composite OI device. Both polarizers, \( P_1 \) and \( P_2 \), were N101-0520 (Glan-Taylor, 210–1100 nm), borrowed from a Lambda-950 spectrometer. The polarizers and QWPs were assembled onto RSP1 (Thorlabs) rotation mounts. The optical axes of all the QWPs were determined with an accuracy of 1°. The QWPs were mounted slightly tilted with respect to the light beam to reduce unwanted reflections. Using this setup we were able to obtain reliable spectral transmittance data in the range of 600–1000 nm.

Before starting the assembly of the composite OI, we checked the central wavelength of the four FRs. For this purpose the input polarizer \( P_1 \) was mounted and set to polarize the white light horizontally. The transmission spectrum of each of the FRs with mounted polarizer \( P_1 \) and removed output polarizer \( P_2 \) was recorded and used as a reference. Then \( P_2 \), set at 45° with respect to \( P_1 \), was mounted in the optical chain. The spectrum of the light transmitted through \( P_1 -FR-P_2 \) was set to have its maximum of optical isolation at 800 nm, adjusting the magnetic field for each of the FRs. We checked out the rotation angle of the polarization after the twin FR, and the expected rotation of 90° at 800 nm was confirmed.

A series of measurements was performed to check the composite OI isolation efficiency with the different QWP rotation angles from Table 1. Prior to the measurements of the composite OI forward and backward transmission, the respective reference transmission spectra were recorded. For this, the QWPs were rotated at the theoretically calculated angles \( \alpha_t \) relative to the slow axis. The output polarizer \( P_2 \) was removed and the transmitted light spectrum was recorded and used as a reference. After mounting \( P_2 \) set to 45° back in the optical chain, the transmitted light through the composite OI was recorded and rescaled to the reference, which represented the forward composite OI transmittance spectrum.

In order to analyze the backward transmittance spectra, the experimental setup was readjusted. It was more convenient to just swap the places of the source of polarized white light and the analyzing system. As above, first the reference was recorded and then the transmittance spectra of the composite OIs were determined in the backward direction. The isolation was calculated as

$$dB = 10 \log \left( \frac{T_f}{T_b} \right),$$

where \( T_f \) and \( T_b \) are the transmittances in the forward and backward directions, respectively.

Representative experimental data for composite OI transmittance are shown in Fig. 2 (upper frame). The set of rotation angles used for the QWPs is taken from the set of angles (a) in Table 1. For comparison, we also recorded data for an isolator with a single FR. The spectrum obtained for the composite OI is slightly noisy due to the lower intensity of our white light.

![Fig. 2. (Top) Transmission spectra of the composite Faraday isolator (red curve) and a single FR (blue curve) versus the light wavelength. (Bottom) Isolation properties of the composite Faraday isolator (red curve) as compared to the isolator based on a single rotator (blue curve) versus its wavelength. The spectra for the designed and presented composite OI are representative and correspond to the set of angles (a) in Table 1.](image-url)
light source in the longer wavelength range as well as the overall transmission of the composite OI.

Figure 2 (lower frame) compares the isolation of a composite OI to that of an OI with a single FR. The asymmetry relative to the central wavelength (800 nm) stems from the fact that the Faraday rotation angle depends nonlinearly on the wavelength. The maximum isolation is about 25 dB over a region of some 100 nm, while in the wings the isolation slightly decreases to 15 dB or less. As can be seen, the isolation properties of the designed composite OI extends over a much broader spectral range (about 275 nm on the level of 15 dB) compared to the ordinary single OI.

In conclusion, we have demonstrated a broadband composite Faraday isolator with the use of four commercial 45° FRs and six achromatic QWPs, achieving isolation higher than 15 dB over a 275 nm bandwidth. These results are in good agreement with the theoretical expectations [8]. The obtained results for the efficiency of the composite OI could be even better if higher-quality achromatic QWPs and polarizers are used. Further improvement can be achieved if more precise mechanical adjustments are possible. On the other hand, the broadband feature of the composite isolator can still be achieved by using ordinary (nonachromatic) waveplates, if in Eq. (3) the wavelength dependence is taken into account and the corresponding optimization is carried out.

This composite approach is highly versatile and can be applied to numerous configurations. The bandwidth of the composite OI is limited by the number of FRs and achromatic QWPs used in the stack to compensate for the Verdet constant dispersion. On the other hand, one has to bear in mind that increasing the number of optical elements will lead to higher reflection and absorption losses. In many cases, this could be tolerated in particular applications, such as light sources of sufficiently high intensity.

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