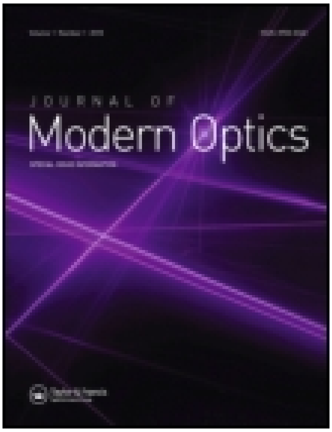

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Enhancement of the Uniformity and Rotation of Large Aperture, Permanent Magnet, Tunable Faraday Rotators

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Enhancement of the uniformity and rotation of large aperture, permanent magnet, tunable Faraday rotators

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Abstract. We present new methods for increasing the magnitude and uniformity of rotation of a Faraday rotator with a large clear aperture. We show theoretically and experimentally that the amount of rotation and the uniformity of rotation across the aperture can be simultaneously increased by introducing a small separation between adjacent, oppositely oriented magnets. Furthermore we show that the uniformity can be increased by displacing the rod of rotator glass longitudinally from the centred position. We have constructed such a device and obtained an isolation ratio of 45 dB at 1·06 μm.

1. Introduction

Faraday rotators are important in many applications [1, 2]. It is often desirable that the clear aperture of the rotator be quite large [3]. In designing Faraday rotators with large apertures it is difficult to maintain the uniformity of the rotation across the entire aperture. In this study we demonstrate two methods to optimize the uniformity for fixed as well as tunable wavelength Faraday rotators, while keeping the aperture and magnet radii fixed.

Previous studies have shown that the rotation produced by a rod of rotator glass inside a magnet is increased by the addition of two flanking magnets, each oriented to repel the central magnet [4–6]. Additionally it has been shown that making the central magnet longer than the glass rotator rod increases the uniformity of rotation across the aperture of the rotator [7]. In this paper we present new theoretical predictions and experimental data on the optimum magnet spacing and rod position. We propose two methods for increasing the uniformity of rotation across the aperture of the Faraday rotator; one of these methods increases the angle of rotation of the plane of polarization as well.

2. Theory

The rotation angle of the polarization can be found by adding the products of the Verdet constant and the difference in scalar potential across the length of the

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given rotator rod for each rod in the Faraday rotator [7]. The on-axis magnetic potential Φ, due to each pole face, can be calculated as follows. Each on-axis point z is equidistant from rings of points on the pole face, the centre of which is taken to be at the origin. If we integrate over all concentric rings of width dρ with radii ranging from $\rho = 0$ to $\rho = R$, where R is the radius of the magnet, we obtain

$$\Phi = M \int_0^R \frac{2\pi\rho \,\mathrm{d}\rho}{(\rho^2 + z^2)^{1/2}} = 2\pi M[(z^2 + R^2)^{1/2} - z], \tag{1}$$

where M is the magnetization of the magnet, which is assumed uniform. The term $(z^2 + R^2)^{1/2}$ can be expanded using the binomial series; for $z < R$ one obtains

$$(z^2 + R^2)^{1/2} = R\left(1 + \frac{z^2}{R^2}\right)^{1/2} = R\left[1 + \frac{1}{2}\left(\frac{z^2}{R^2}\right) + \frac{\frac{1}{2}(-\frac{1}{2})}{2!}\left(\frac{z^2}{R^2}\right)^2 + \frac{\frac{1}{2}(-\frac{1}{2})(-\frac{3}{2})}{3!}\left(\frac{z^2}{R^2}\right)^3 + \dots\right]. \tag{2}$$

At all points in space away from the pole faces the potential Φ must satisfy Laplace's equation $\nabla^2\Phi = 0$ and thus can be expressed in the form

$$\Phi(r, \theta) = \sum_{l=0}^{\infty} [A_l r^l + B_l r^{-(l+1)}] P_l(\cos\theta).$$

Here $P_l(\cos\theta)$ is the lth-order Legendre polynomial. To find the coefficients A_l and B_l, we set $\theta = 0$ (so that $r = z$), in equation (2) and match equal powers of z. The non-physical situation of an infinite potential is automatically avoided since $B_l = 0$ for the case $r < R$, and $A_l = 0$ for the case $r > R$. The final results for the two cases are:

$$\begin{aligned} \Phi(r, \theta) &= 2\pi M\left[R - r\cos\theta + R\sum_{l=0}^{\infty} \frac{P_{2(l+1)}(\cos\theta)(2l)!(-1)^l}{2^{2l+1}l!(l+1)!}\left(\frac{r}{R}\right)^{2(l+1)}\right], \quad r < R, \\ \Phi(r, \theta) &= 2\pi M r\sum_{l=0}^{\infty} \frac{P_{2l}(\cos\theta)(2l)!(-1)^l}{2^{2l+1}l!(l+1)!}\left(\frac{R}{r}\right)^{2(l+1)}, \quad r > R. \end{aligned} \tag{3}$$

Note that $P_l(1) = 1$ for all orders l. Using the superposition principle, the total potential at a point due to the entire stack is found by adding the potentials due to all pole faces. The potential due to each pole face is found by again making use of the superposition principle as follows: the potential for a solid disc of radius R is first calculated using equation (3). Next the effect of the hole is included by subtracting the potential of a solid disc with the same radius as the hole by again using equation (3). The theoretical curves shown in the figures below were obtained by implementing this procedure.

3. Seven-magnet Faraday rotator

Our design for increasing the magnitude and uniformity of the rotation of the Faraday rotator is shown in figure 1. We refer to it as the seven-magnet Faraday rotator to differentiate between it and a three-magnet design for shorter wavelengths discussed below. The seven-magnet Faraday rotator rotates the polarization of 1 µm light by 45°. The use of multiple magnets rather than one single, large magnet decreases the cost of the device as well as produces a more uniform rotation across the aperture than the conventional single-magnet design. As shown in figure 1, the

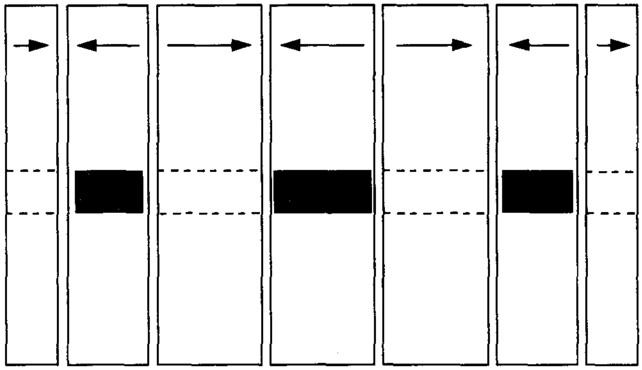


Figure 1. Seven-magnet, three-rotator-rod Faraday rotator used in the first part of this study. In the second part of our work only the middle three magnets and one rod were used. Shaded rectangles represent rods. The centre rod is 25 mm long. Other rods are 17 mm long. In this configuration starting with the magnet on the far left the magnet lengths are; 12·7, 19, 25·4, 25·4, 25·4, 19 and 12·7 mm.

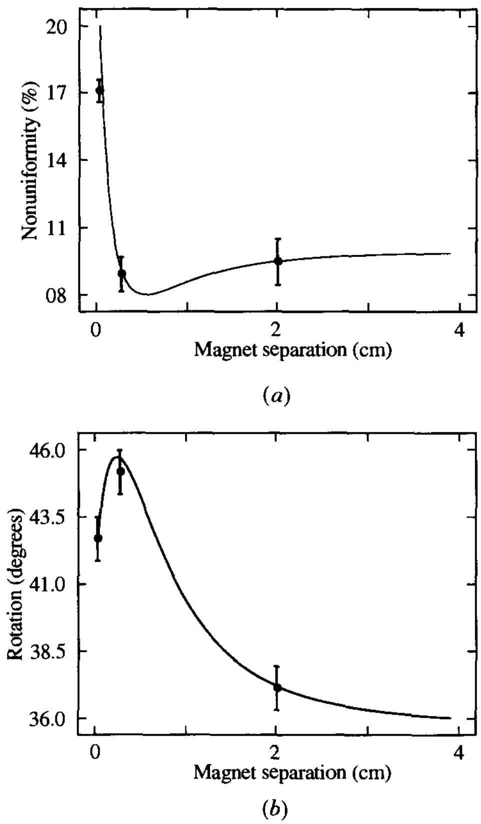


Figure 2. Theoretical predictions and experimental data for the seven-magnet Faraday rotator. Per cent non-uniformity (*a*) and rotation angle (*b*) are shown against magnet separation.

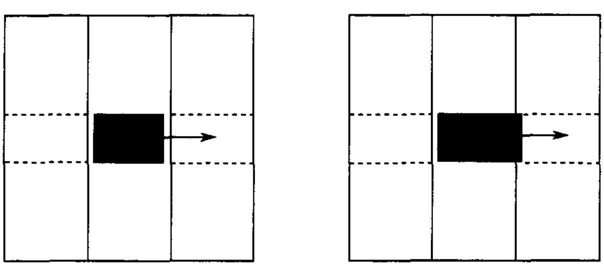
glass rods are cut smaller that the magnets that surround them and there is a slight separation between the magnets; this separation increases both the uniformity and the angle of rotation of the plane of polarization. The rotator has a 1 cm clear aperture and the magnets have an outer diameter of 25·4 mm. The lengths of the magnets are annotated on the figure. The magnets [8] are Sm_2Co_{17} permanent magnets with residual magnetic inductions of 1 T. The rotator glass [9] contains the paramagnetic ion terbium and has a Verdet constant of $-1{\cdot}285°\ (\mathrm{kOe\,cm})^{-1}$. The transmission of the Faraday rotator is 95%. We tested the isolation ratio for three different beams. A beam with a flat intensity profile that covered the entire clear aperture was found to have an isolation ratio of 37·7 dB. A Gaussian beam which was 1 cm in diameter at the $1/e^2$ point was found to have an isolation ratio of 41·3 dB. A Gaussian beam of 1 mm diameter was found to have an isolation ratio of over 45 dB.

Figure 2 (*a*) shows that the rotation first increases and then decreases with magnet separation for the seven-magnet design. There is also an ideal non-zero magnet separation for minimum non-uniformity, as is evident in figure 2 (*b*). Here we define non-uniformity as the difference of the polarization rotation on axis and at the edge of the aperture divided by the rotation on axis. The magnet separation that gives the largest rotation is not far from the separation that gives the smallest non-uniformity. For our seven-magnet design the largest rotation occurs with a magnet spacing of 3 mm.

4. Tunable Faraday rotator (three-magnet Faraday rotator)

By displacing the central magnet, the operating wavelength of the Faraday rotator described above can be tuned. For ease in experimental and computational work in demonstrating tunability we have chosen to use the simpler three-magnet, one-rod Faraday rotator, shown in figure 3 for the second part of our study. The three-magnet Faraday rotator consists of the central three magnets from the seven-magnet Faraday rotator with one glass rod in the central magnet. In practice the seven-magnet Faraday rotator that we have built would be used for wavelengths from 1·06 µm to 0·65 µm, and the three-magnet Faraday rotator would be used for wavelengths shorter than 0·65 µm.

For a fixed wavelength it has been shown that a central magnet longer than the rotator rod gives excellent uniformity as well as large rotation [7]. When tunability



(*a*) (*b*)

Figure 3. Effect of tuning the isolation wavelength by displacing the glass rod from its symmetric position for (*a*) a rod shorter than and (*b*) a rod equal in length to the central magnet. In (*a*) the right end of the short rod approaches a magnet–magnet interface leading to the degradation of the uniformity, in (*b*) both ends of the rod move away from the interfaces.

is desired, however, the rod must be displaced from its centred position to produce 45° rotation at the shorter wavelengths. Since the Verdet constant scales approximately as λ^{-2}, the displacement needed to produce the correct rotation at the new wavelength can be significant even for small shifts in wavelength. As can be seen in figure 3, this displacement brings one end of the short rod closer to the magnet–magnet interface. The non-uniformity increases rapidly as a rod end nears the interface. Our solution to this problem is to use a rod equal in length to that of the central magnet, but already displaced at the long-wavelength limit of the range of tunability for the Faraday rotator. When shorter wavelength isolation is needed, the rod is displaced still farther, moving both rod ends away from the interfaces. In this manner the non-uniformity is always decreased from the long-wavelength value as the Faraday rotator is tuned for isolation at shorter wavelengths.

Experimental and theoretical verification of this effect is shown in figure 4. The data presented in figure 4 were found using two rod lengths of 25 mm and 17 mm. Figure 5 (*a*) is a photograph of the minimum energy through the three magnet isolator when one end of the 17 mm rod is at the magnet–magnet interface. Figure 5 (*b*) shows transmitted intensity using the 25 mm rod offset to give the same rotation as that achieved with the 17 mm rod; note the very uniform intensity unlike that seen in figure 5 (*a*) when the shorter rod was used. Due to the highly uniform rotation of the axis of the polarization, and the excellent extinction of the beam, it was necessary to detune the crossed polarizers from the point of maximum extinction to obtain the photograph shown in figure 5 (*b*). However, the maximum intensity of the beam in each photograph is the same giving a good qualitative comparison of the two designs.

We have calculated the rotation and non-uniformity for a 25 mm rod and a 20 mm rod in the configuration shown in figure 4. A 25 mm rod offset 3 mm in a three-magnet stack, each magnet of which is 25·4 mm long, has the same rotation as a centred 20 mm rod in the same stack. The longer rod, however, has a non-uniformity of only 7·52%, whereas the shorter rod has a non-uniformity of 9·23%. The non-uniformity decreases monotonically with further displacement for the long rod. For the shorter rod the non-uniformity goes through a maximum with displacement. For example, at its highest non-uniformity of 13·8%, the shorter rod has a rotation of 95% of its maximum value. The longer rod has a non-uniformity of 5·8% with this same rotation.

In conclusion we have designed, modelled, and built two new multiple-magnet Faraday rotators. We have shown that the rotation and uniformity can be increased by slightly separating the magnets in the stack. Additionally we have shown that a highly uniform tunable rotator can be made by initially displacing the rod off-centre within the magnet stack. Our designs have greater uniformity than existing rotators using the same materials. In both of our investigations we have excellent agreement between theory and experiment.

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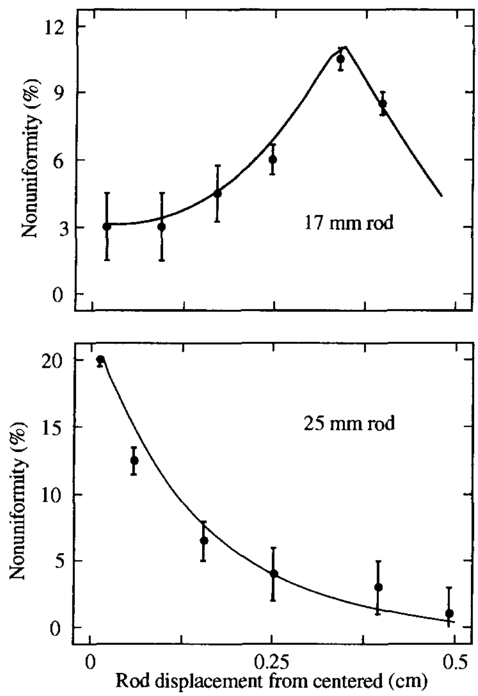
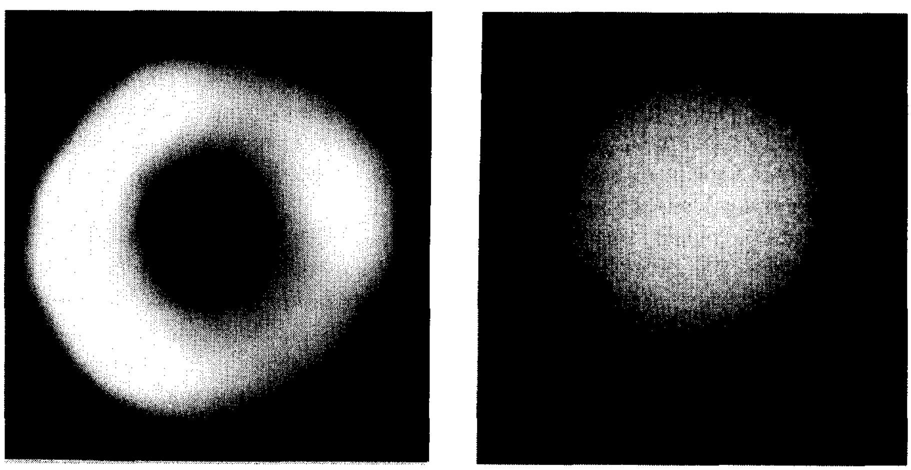


Figure 4. Non-uniformity against displacement of rod from centre position for two different rod lengths in a three-magnet Faraday rotator.



(*a*) (*b*)

Figure 5. Photographs of the output of three-magnet Faraday rotator. (*a*) 17 mm rod with one end at magnet–magnet interface. The analyser is rotated to reject as much light as possible. (*b*) 25 mm rod offset to give same on axis rotation as (*a*). Here the analyser is rotated to let light through in order to expose film.

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