A Compound High-Order Polarization-Independent Birefringence Filter Using Sagnac Interferometers

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***Abstract*—Polarization-independent fiber-optic filters are presented that replace the polarizers in traditional birefringence filters with a Sagnac interferometer. The performance of these filters is discussed when Solc and Lyot type birefringence combinations are used. A high-order, compound filter combining these two filters is presented, along with experimental verification.**

***Index Terms*—Optical fibers, polarization.**

NARROW-BAND optical filters are essential elements in the dense wavelength division multiplexer (WDM) systems that are currently used in fiber telecommunications. Birefringence filters are a class of classic filters with both narrow bandwidth and stability, and have been used in the optical spectroscopy community for many years. Solc filters and Lyot filters are the two most common filters in this category [1], [2]. A wide range of intensity transfer functions, as well as dispersion equalizers, can be achieved by orienting linear birefringence elements in a proper way [3]–[5]. A similar idea also has appeared recently to synthesize delay line-based filters [6]. Using this technique, any type of transfer functions can be realized by combining linear birefringence or delay lines.

Although conventional birefringence-based filters can be used for narrow-band applications, they all require polarizers, making them lossy and input-polarization dependent. The input polarization dependence may result in intensity noise, since the incoming polarization state is usually random in fiber telecommunication links. To remove this difficulty, a new filter structure was recently proposed, using a Sagnac interferometer to replace the polarizers in conventional birefringence filters [7]. Based on this technique, a new class of polarization-independent birefringence filters, called *Sagnac birefringence filters*, can be realized. Fig. 1 shows the structure of a general Sagnac birefringence filter, where the coupler is a low-loss 3-dB coupler and the Sagnac loop contains an arbitrary chain of linear birefringence elements. If the input polarization state at port 1 is assumed to be

$$E_{\text{in}} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} \tag{1}$$

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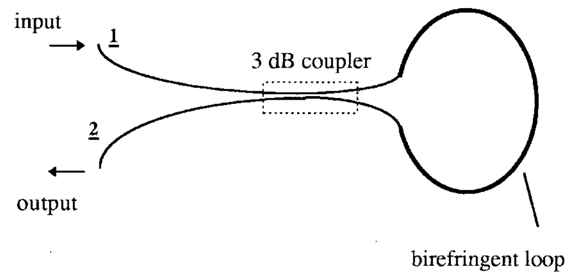


Fig. 1. A Sagnac interferometer with a loop birefringence element.

according to the reciprocity of the Jones matrix, the output field at port 2 will be given by [7]

$$E_{\text{out}} = i\,\text{Im}(B)\begin{bmatrix} E_y \\ E_x \end{bmatrix} \tag{2}$$

where $\text{Im}(B)$ represents the imaginary part of B, which is the coupling term (off-diagonal) of the Jones matrix of the loop birefringence.

Two conclusions can be made based on (2). Firstly, the magnitude response of the transfer function is independent of the input polarization state and is solely determined by the imaginary part of element B. Secondly, the output polarization state is a rotationally transformed version of the input state and can be converted back to its original state by traveling through a second loop. The intensity transfer function of the new filter can be obtained from (2), and is given by

$$T = (\text{Im}(B))^2. \tag{3}$$

To design a filter with particular spectral-selective properties, one must specify a birefringence combination that has the desired imaginary part of B. An important property of this new filter structure is that no polarizers are employed and the transfer function is independent of input polarization. Birefringence configurations derived from conventional Solc and Lyot filters are chosen in this letter as examples.

The Jones matrix of a fan-Solc filter has been analyzed in [1]. By inserting this birefringence configuration (without polarizers) into the Sagnac loop and using (3), the transfer function of the resulting Solc–Sagnac filter is given by

$$T = \sin^2\left(\frac{\Gamma}{2}\right)\frac{\sin^2 N\chi}{\sin^2 \chi} \tag{4}$$

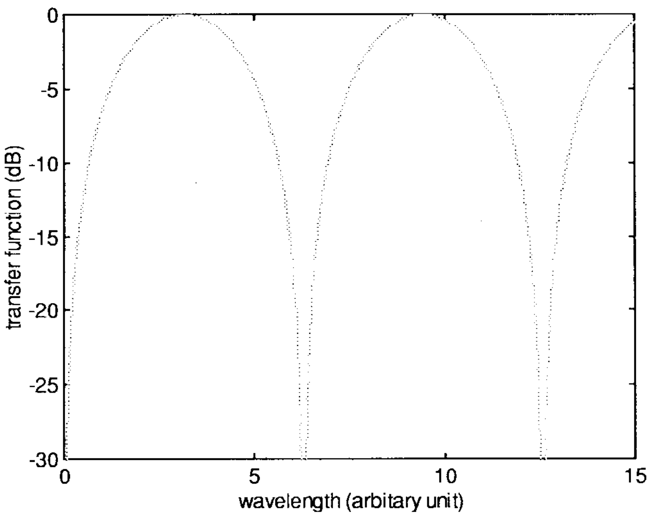


Fig. 2. Calculated intensity transfer functions of the first-order Solc–Sagnac filter.

where Γ is the retardation of a single element in a Solc filter, N is the number of elements, χ is determined by

$$\cos\chi = \cos(2\rho)\ \cos\left(\frac{\Gamma}{2}\right) \tag{5}$$

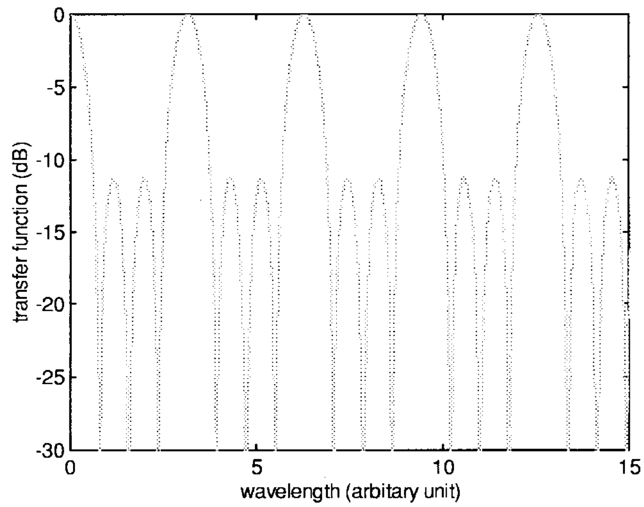
where 2ρ is the rotation angle between any two adjacent birefringence elements, and $2N\rho = \pi/2$. Fig. 2 shows the intensity transfer functions of a first-order ($N = 1$) Solc–Sagnac filter where the retardation of the birefringence is assumed to be *inversely* proportional to the wavelength.

Standard Lyot-type filters, on the other hand, consist of several polarizers and linear birefringence elements of unequal retardation. The retardation of each birefringence element is chosen to be double that of the previous one, with a 45° rotation of the principal axis. In order to implement a Lyot-type birefringence configuration into a Sagnac interferometer, the polarizers are removed from the conventional filter configuration. It can be shown that the intensity transfer function of a first-order Lyot–Sagnac filter (two birefringence elements) is given by

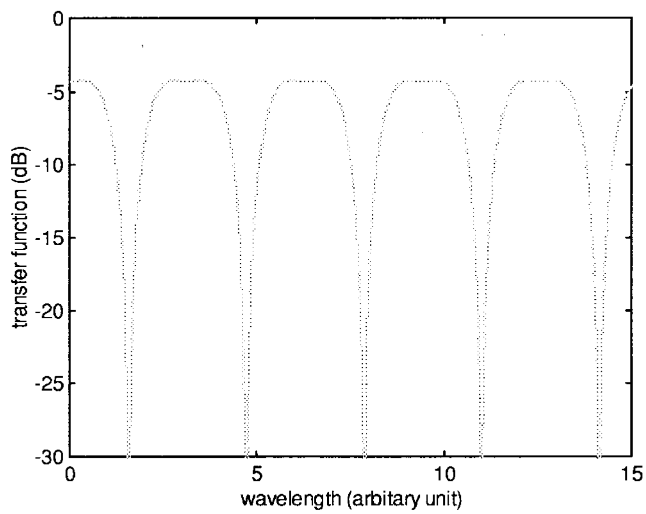
$$T = \sin^2(\varphi/2)\ \cos^2(\varphi) \tag{6}$$

where φ is the phase retardation of the smaller birefringence, and the principal axis of the larger birefringence is within the plane of the Sagnac loop. The peak transmission coefficient is 100%, and the side-lobe level is about -11 dB relative to the peak level. When the principal axes of the loop birefringence are rotated 1.1 rad with respect to the plane of the Sagnac loop, the filter becomes a notch filter, with a transfer function shown in Fig. 3(b).

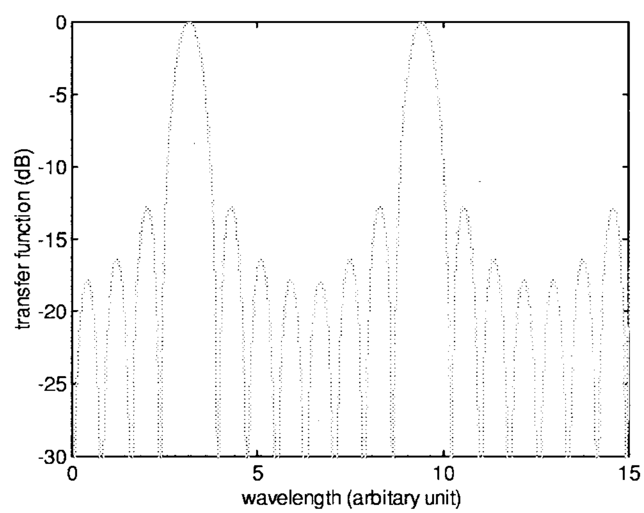
By connecting two low-order filters in cascade, a higher order filter can be constructed. Fig. 3(c) shows an example of a high-order intensity transfer function obtained by connecting the first-order Solc–Sagnac filter [Fig. 2(a)] with the first-order Lyot–Sagnac filter [Fig. 3(a)]. It can be seen from the figure that the Q factor of this compound bandpass filter is doubled compared to that shown in Fig. 3(a), which is a useful property for narrow-band applications. Also, the second Sagnac filter of this compound filter flips the output polarization back to its original state, making the whole device polarization-preserving.



(a)

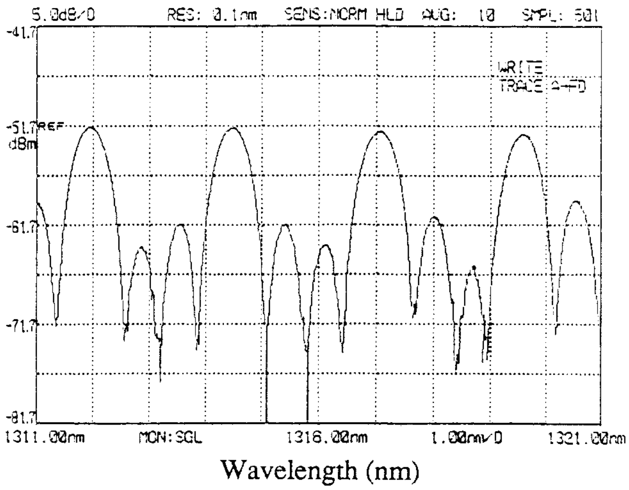


(b)

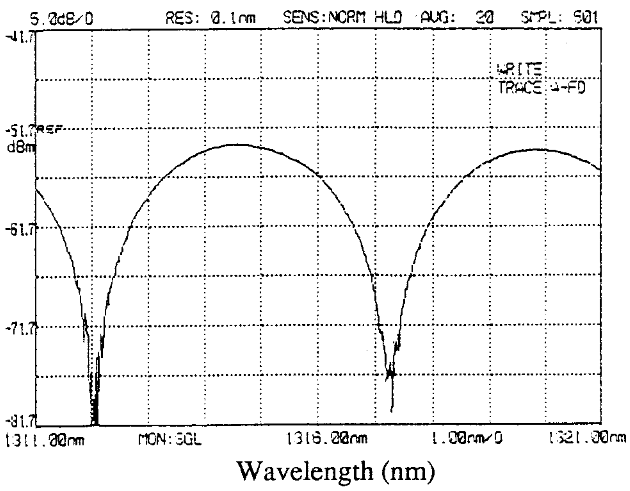


(c)

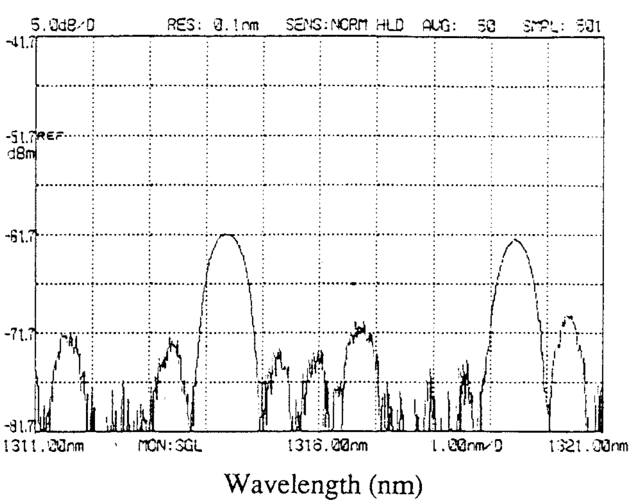
Fig. 3. Calculated intensity transfer functions. (a) First-order Lyot–Sagnac filter. (b) First-order Lyot–Sagnac filter after 1.1 rad of birefringence rotation. (c) Cascade of filters of Fig. 2(a) and Fig. 3(a).



(a)



(b)



(c)

Fig. 4. Measured intensity transfer functions. (a) The first-order Lyot–Sagnac filter. (b) The first-order Solc–Sagnac filter. (c) Two filters in tandem.

In order to verify our theoretical models, a first-order Solc–Sagnac filter and a first-order Lyot–Sagnac filter were built. Linear birefringence was introduced by using Newport polarization maintaining (PM) fibers whose beat length is about 2 mm. The two PM fibers for the Lyot–Sagnac filter were 1- and 2-m long, respectively, and the PM fiber for the first-order Solc–Sagnac filter was 0.5-m long. The fiber couplers used were low-loss 3-dB couplers, and a 1300-nm LED was used as the light source. The intensity transfer functions of the filters were recorded with an optical spectrum analyzer and are shown in Fig. 4. Fig. 4(a) shows the transfer function of the first-order Lyot–Sagnac filter. The asymmetric side lobes in Fig. 4(a) are believed to be caused by inaccuracies in the principal axis alignment and the birefringence relationship between the two PM fibers. Fig. 4(b) shows the transfer function of the first-order Solc–Sagnac filter, where the PM fiber is 0.5-m long with its principal axis 45° relative to the plane within which is the Sagnac loop. Connecting the two filters together produced a higher order filter as shown in Fig. 4(c), where the FWHM is about 0.5 nm and channel spacing is about 5 nm. The high loss is primarily caused by coupling losses between the PM fibers and the ordinary fibers, and can be minimized by using the same type of fibers. The relatively poor signal-to-noise ratio in Fig. 4(c) is due to the low optical power received. Notch filter characteristics similar to that shown Fig. 3(b) were also observed during the experiment. Agreement between the theoretical prediction shown in Figs. 2 and 3 and the experimental results in Fig. 4 validates our theoretical analysis. The polarization independence of the filter was verified by introducing a linearly polarized laser light into the filter and inducing an input-polarization change by bending the lead-in fiber (port 1). No output intensity change was observed.

In conclusion, this letter has shown that high-order polarizer-free birefringence filters can be made from Sagnac interferometers and are polarization independent. A first-order Solc–Sagnac filter and a first-order Lyot–Sagnac filter were built to show the influence of the birefringence configuration on the transfer function of our new filter structure. Future research will concentrate on the development of a synthesis technique to determine the birefringence according to desired transfer functions.

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