All-fiber polarization interference filters based on 45°-tilted fiber gratings

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We report all-fiber polarization interference filters, known as Lyot and Lyot-Őhman filters, based on alternative concatenation of UV-inscribed fiber gratings with structure tilted at 45° and polarization maintaining (PM) fiber cavities. Such filters generate comb-like transmission of linear polarization output. The free spectral range (FSR) of a single-stage (Lyot) filter is PM fiber cavity length dependent, as a 20 cm long cavity showed a 26.6 nm FSR while the 40 cm one exhibited a 14.8 nm FSR. Furthermore, we have theoretically and experimentally demonstrated all-fiber 2-stage and 3-stage Lyot-Őhman filters, giving more freedom in tailoring the transmission characteristics.

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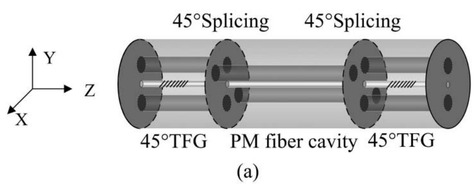
The Lyot filter is a kind of polarization interference filter, which was invented by Bernard Lyot in 1933 [1]. It is formed by placing a birefringence medium (BM) between two parallel polarizers whose axes are aligned at 45° with respect to the axis of the BM. Lyot filters can be used as comb transmission filters, due to the property of continuous wavelength-dependent transmission bands in the spectra. Later, Őhman demonstrated a new monochromator by connecting several Lyot filters in series, which was named as Lyot–Őhman filter [2]. The Lyot filters were widely applied in spectral imaging [3,4], communication [5], and laser [6–7] systems. Because of unavailability of in-fiber components, the majority reported Lyot and Lyot-Őhman filters were constructed using bulk polarizers with a polarization maintaining (PM) fiber, inducing not just high insertion loss but also the chunky structure, which is not compatible with all-fiber systems. Tilted fiber gratings (TFGs) were firstly reported by Meltz *et al.* in 1990 [8]. Owing to their unique polarization function, TFGs have been applied as polarimeter, polarization dependent loss equalizer and so on [9–10]. Recently, we have demonstrated in-fiber polarizers with a high polarization extinction ratio (PER) based on 45°-TFGs UV-inscribed in single mode telecom and photosensitive fibers [11,12]. We have also demonstrated that the 45°-TFGs can be UV-inscribed into PM fibers along the fast or slow axis, leading to linear polarization light output. In this Letter, we propose and demonstrate all-fiber Lyot and Lyot-Őhman filters that are implemented by alternatively concatenating 45°-TFGs and PM fiber cavities with fiber axis at 45° to each other. The bandwidth of the filter is easily controlled by changing the length of PM fiber cavity, while the FSR of transmission bands can be freely tailored by using multistage Lyot filters.

The configuration of an all-fiber Lyot filter using two 45°-TFGs is illustrated in Fig. 1(a). In this structure, the two 45°-TFGs created in PM fiber along the fast axis are used as linear polarizers, and a section of PM fiber is used as a BM with its fast axis aligned 45° to that of the two polarizers.

The working principle of this all-fiber Lyot filter is as follows: the light that passes the first 45° TFG is linearly polarized and then enters the PM fiber at 45° direction and is resolved into two beams with equal intensity travelling along the fast- and slow-axis of the PM fiber, respectively. Because of the birefringence of the PM fiber, there is a relative phase difference between these two beams; thus when they arrive at the second 45°-TFG, the combined beam will generate interference output of linear polarization state. Figure 1(b) shows a 3-stage all-fiber Lyot–Őhman filter, which can be formed by concatenating four 45°-TFGs spaced by three PM fibers with a length ratio 4 : 2 : 1 and all aligned at 45° to the fast axis of the PM fibers that are hosting 45°-TFGs. In this 3-stage Lyot-Őhman filter, only the light at the wavelengths in phase (i.e., the phase difference is a multiple of 2π) will be constructive and pass the filter. The final output spectrum thus consists of a serial of transmission bands. By applying the transfer matrix method, the m-stage Lyot filter can be described as:

$$
\begin{aligned}
M=&\left(\frac{1}{2}\right)^m\times\begin{bmatrix}0&0\\0&1\end{bmatrix}\times\begin{bmatrix}e^{-i\Delta\varphi_1}+1&e^{-i\Delta\varphi_1}-1\\e^{-i\Delta\varphi_1}-1&e^{-i\Delta\varphi_1}+1\end{bmatrix}\\
&\times\begin{bmatrix}0&0\\0&1\end{bmatrix}\cdots\begin{bmatrix}e^{-i\Delta\varphi_m}+1&e^{-i\Delta\varphi_m}-1\\e^{-i\Delta\varphi_m}-1&e^{-i\Delta\varphi_m}+1\end{bmatrix}\times\begin{bmatrix}0&0\\0&1\end{bmatrix}\\
\equiv&\left(\frac{1}{2}\right)^m\begin{bmatrix}0&0\\0&(e^{-i\Delta\varphi_1}+1)(e^{-i\Delta\varphi_2}+1)\cdots(e^{-i\Delta\varphi_m}+1)\end{bmatrix},
\end{aligned}\quad (1)
$$



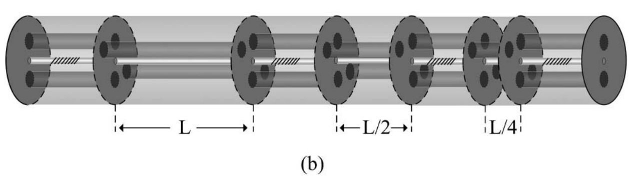


Fig. 1. (a) Configuration of an all-fiber Lyot filter using two 45°-TFGs and a PM fiber cavity. (b) Configuration of an all-fiber 3-stage Lyot–Őhman filter using four 45°-TFGs with three PM fiber cavities at a ratio 4:2:1.

where, for simplifying the calculation, we defined the fast axis of PM fiber that is hosting 45°-TFG as x-axis, and the fast axis of the PM fiber cavity is aligned at 45° with respect to the x-axis. In Eq. (1), $\Delta\varphi_m$ is the relative phase difference induced by the mth section BM. It is defined by:

$$\Delta\varphi_m = 2\pi L_m \Delta n/\lambda \quad m = 1, 2, 3\ldots, \tag{2}$$

where L_m is the length of PM fiber of mth BM; Δn is the birefringence of PM fiber; and λ is the working wavelength.

The normalized transmittance of m-stage Lyot filter is given by [2]

$$T = \cos^2(\Delta\varphi_1/2)\cos^2(\Delta\varphi_2/2)\cdots\cos^2(\Delta\varphi_m/2). \tag{3}$$

Also, the FSR of Lyot filter can be obtained from Eq. (2) [13], as

$$\mathrm{FSR} \cong \lambda^2/(L_m\Delta n). \tag{4}$$

All 45°-TFGs were inscribed in PM1550 fiber (Corning) along the fast axis by using the scanning phase-mask technique and a 244 nm UV source from a CW frequency doubled Ar^+ laser (Coherent Sabre Fred). The phase-mask (Ibsen) has a uniform pitch of 1830 nm and 33.7° tilted angle with respect to the fiber axis. The tilted pitch pattern in the phase-mask glass plate is 50 mm long, thus giving an effective grating length around 49 mm in the fiber core. The PER values of the 45°-TFGs were measured by an Optical Vector Analyzer system (OVA2000). Figure 2 shows the PER distribution of one of the UV-inscribed 45°-TFGs from 1525 nm to 1608 nm. The maximum PER is 33 dB at 1530 nm and dropped to 29 dB at 1608 nm. The polarization distribution figure is shown in Fig. 3, which was measured using the method presented in our previous paper [9,10]. The near-perfect figure 8 shape indicates the 45°-TFG in PM1550 fiber can act as a highly linear polarizer.

We first constructed and evaluated all-fiber single-stage Lyot filters with different cavity lengths. The PM fiber sections of 20, 40, and 80 cm were spliced between the two 45°-TFGs, in turn forming three Lyot filter structures. The two ends of the PM fiber cavity were spliced with its fast axis aligned at 45° to the fast axis of the two 45°-TFGs. Figure 4(a) shows the measured spectra of the three Lyot filters. The output spectra from the 45°-TFG based Lyot filter exhibits comb-like transmission and the bandwidth and FSR are cavity length dependent. The FSRs for 20, 40, and 80 cm PM fiber cavities are 26.6 nm, 14.9 nm, and 6.9 nm, respectively, showing the FSR is inversely proportional to the length of PM fiber cavity. The longer the cavity length is the smaller FSR. All the maximum transmissions occur when the relative phase difference is equal to $2m\pi$, $(m = 0, 1, 2, 3\ldots)$, and in contrast, the minima occur when the phase difference is equal to $(2m + 1)\pi$.

We also experimentally measured the FSR of seven Lyot filters with cavity lengths of 10, 20, 30 40, 60, and 80 cm, and the results are plotted in Fig. 4(b), which are in excellent agreement with the theoretically calculated ones, and the whole curve shows the inversely proportional relationship between the FSR and Lyot filter cavity length. Note, in the calculation the birefringence of the PM fiber was estimated by inscribing a fiber Bragg grating with known period in the PM fiber and the birefringence value of the PM fiber was estimated around 3.27×10^{-4}.

We further experimentally constructed a 2- and 3-stage Lyot-Őhman filter by concatenating three and four 45°-TFGs with PM fiber cavity length ratios of 1:2 (20 and 40 cm) and 1:2:4 (20, 40, and 80 cm), respectively. The transmission spectra of the 2- and 3-stage Lyot-Őhman filters are shown in Fig. 5(a) and 5(b). It can be seen clearly from the figure that the transmission bands of the Lyot-Őhman filters are generated from coupled cavities, i.e., the transmission maxima are only occur at those wavelengths in phase for each individual cavities, and the other nonphase matched wavelengths are suppressed. The simulation results of the 2- and 3-stage Lyot-Őhman filter are also plotted in Fig. 4. It can be seen that the experimental results are in very good agreement with the simulation ones. The strength of each peak is not quite the same for the 3-stage filter, as shown in Fig. 5(b); this is because the length ratio of PM fiber cavity may not be exactly at 1:2:4. We can also find that the bandwidth

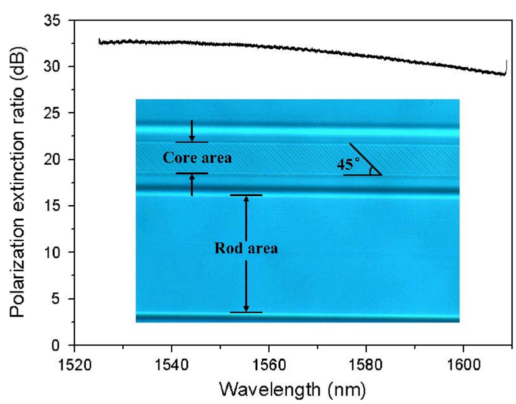


Fig. 2. (Color online) Spectral polarization extinction ratio over wavelength range from 1530 nm to 1608 nm. Inset: microscopic image of 45°-TFG structure in a PM fiber.

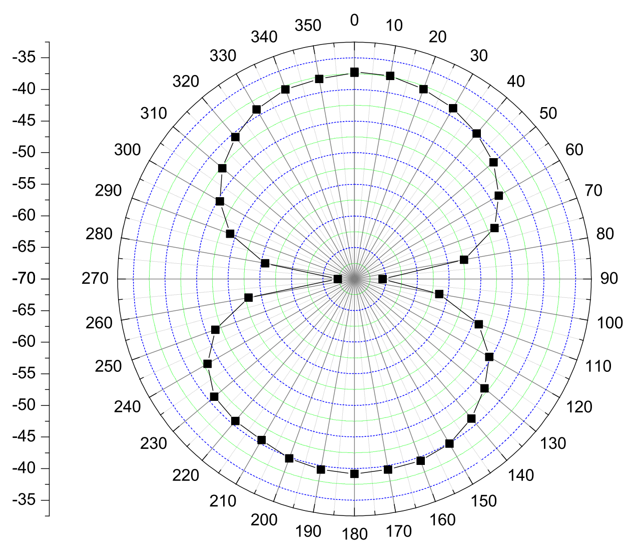
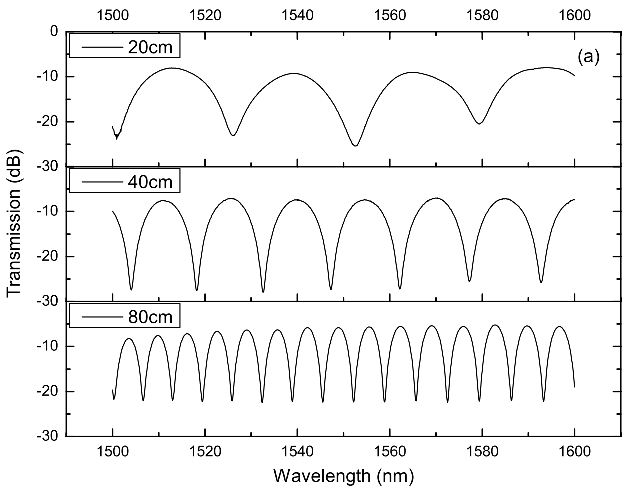


Fig. 3. (Color online) Polarization distribution of one of the 45°-TFGs UV-inscribed in PM fiber.



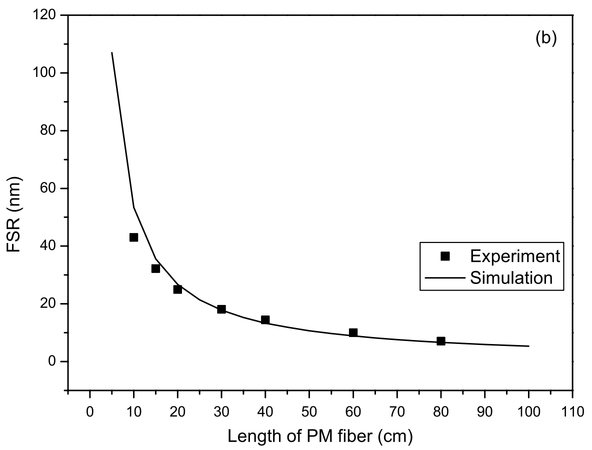
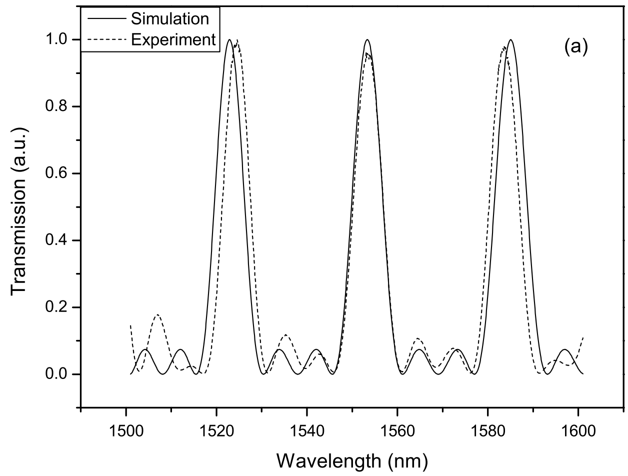


Fig. 4. (a) Measured transmission spectra of three 45°-TFG based all-fiber Lyot filters with 20 cm, 40 cm, and 80 cm cavity length. (b) Experimentally measured and theoretically calculated the relationship between FSR of the filter and the length of PM fiber cavity.



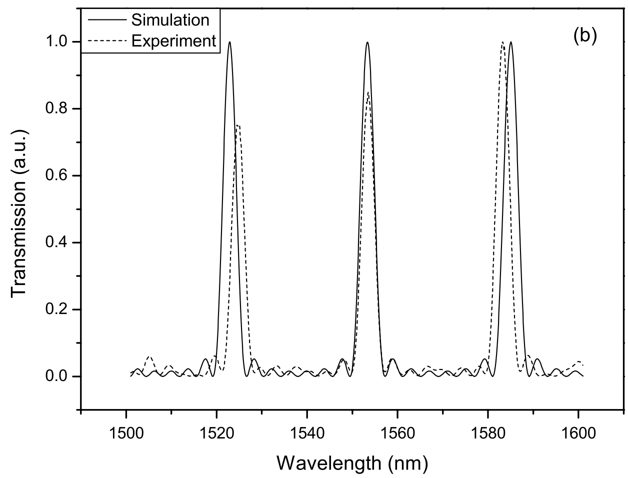


Fig. 5. Simulated (solid) and experimentally measured (dash) comblike transmission spectra of (a) 2-stage Lyot filter with PM fiber cavity length ratio 1:2 (20 cm and 40 cm) and (b) 3-stage Lyot filter with ratio 1:2:4 (20 cm, 40 cm, and 80 cm).

of the multistage Lyot-Őhman is determined by the length of the longest while the FSR is by the shortest cavity in multistage filters.

All-fiber Lyot and Lyot-Őhman filters have been demonstrated by concatenating 45°-TFGs and PM fibers. The 45°-TFGs were UV-inscribed along the fast axis of the PM fiber and then spliced with the PM fiber cavities with designed length ratio and at 45° to their principal axes. Such polarization interference filters generate comblike transmission spectrum, showing the FSR can be easily designed by altering the cavity length. The multistage filters offer another dimension to tailor the comblike transmission spectral response with desirable FSR. The filters all give linearly polarization output, which will make them good in-fiber polarization filters for applications in-fiber laser, spectral imaging, optical communication and sensing measurements and systems.

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