Highly efficient all-fiber tunable polarization filter using torsional acoustic wave

Kwang Jo Lee*, Hyun Chul Park, Hee Su Park, and Byoung Yoon Kim
Department of Physics, Korea Advanced Institute of Science and Technology
373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Korea
* kjl@kaist.ac.kr
http://fiber.kaist.ac.kr

Abstract: We demonstrate an all-fiber tunable polarization filter with high coupling efficiency based on acousto-optic coupling between two optical polarization modes of the LP_{01} mode propagating in a highly birefringent single mode optical fiber. An over-coupling between the two polarization modes is realized over the wavelength range from 1530 nm to 1610 nm using traveling torsional acoustic wave. The measured 3-dB optical bandwidth of the filter was 4.8 nm at the wavelength around 1550 nm. The details of the filter transmission and the coupling characteristics are discussed.

©2007 Optical Society of America

OCIS codes: (060.2310) Fiber optics; (230.1040) Acousto-optical devices.

References and links


1. Introduction
Tunable optical filters are key components in optical communication networks and optical sensor systems. In particular, all-fiber acousto-optic tunable filters (AOTFs) have attracted considerable interest because of their advantages such as wide and fast wavelength tuning and variable attenuation with simple electronic control [1]. Practical AOTFs with a simple structure for various applications such as optical switches and wavelength tuning devices have been realized as notch type [2] or bandpass type [3]. Most of reported all-fiber acousto-optic
(AO) devices are based on wavelength selective AO coupling between several spatial modes of light propagating in an optical fibers using traveling flexural acoustic wave. On the other hand, it has also been known that AO coupling between two optical polarization modes in a highly birefringent (HB) optical fiber can be realized using traveling torsional acoustic wave, which is one of the three acoustic modes propagating in a cylindrical optical fiber without cutoff when the acoustic wavelength is much longer than the dimension of the fiber core [4, 5]. Several researchers have investigated the potential of the polarization mode coupling by torsional acoustic wave theoretically [6] and experimentally [7, 8]. However, the optical coupling efficiency between two polarization modes demonstrated so far were only 6% and 12% [7, 8], which is too small for practical applications and therefore it has not been seriously pursued.

In this paper, we demonstrate, for the first time to our knowledge, that a full coupling can be achieved in an all-fiber acousto-optic tunable polarization filter (AOTPF) using the lowest torsional acoustic mode traveling in a HB single mode optical fiber. The complete optical power transfer between two polarization modes is realized over the wavelength range from 1530 nm to 1610 nm by employing a newly designed transducer that efficiently generates torsional acoustic wave in the fiber. The fabricated AOTPF can operate as the notch type or the bandpass type according to the polarization direction of the output polarizer. The coupling characteristics between two optical polarization modes by the lowest torsional acoustic mode and the transmission characteristics of the fabricated filter are discussed in detail.

2. Principles of operation

A cylindrical optical fiber, whose diameter is smaller than acoustic wavelengths, can support longitudinal, flexural and torsional acoustic fundamental modes traveling along the fiber without cut-off [4, 5]. Among them, the torsional acoustic mode having only the circumferential angular displacement component in the cross-section of the fiber can efficiently produce AO coupling between two optical polarization eigenmodes in a HB optical fiber [6]. The periodic twists of the optical polarization eigenaxes in the HB fiber induced by the torsional acoustic wave perturb the incident polarization eigenstate of the LP01 mode and cause the energy to be transferred efficiently between two polarization eigenmodes. The torsional acoustic modes can exist in the optical fiber with the various radial orders which are defined as the number of nodes of the acoustic energy distribution in the radial direction [4]. The lowest torsional acoustic mode propagates for all frequencies and wave numbers with a constant velocity equal to the shear-wave velocity, while the torsional acoustic modes of higher radial orders are dispersive only above their cutoff frequencies of a few hundreds MHz [6]. For the acoustic frequencies of a few MHz of our interest that provide phase matching condition for efficient polarization coupling, only the lowest torsional acoustic mode can propagate along the fiber. Coupling between the two polarization eigenmodes caused by the periodic twists of the HB optical fiber can be described by the coupled mode equations [6], and the coupling coefficient $\kappa$ can be expressed as following,

$$\kappa = \frac{2\pi}{L_B} \left( \frac{1}{2} n^2 p_{44} \right).$$  (1)

Here, $\Phi$ denotes the angular displacement in the cross-section of the fiber and $L_B$ is the optical beatlength between two polarization eigenmodes. The refractive index of $n$ and the photo-elastic tensor element of $p_{44}$ are 1.46 and -0.075 for fused silica, respectively. The first term of the Eq. (1) corresponds to the perturbation between two polarization eigenstates of the incident LP01 mode caused by the birefringence effect due to the periodic angular deviation of the polarization eigenaxes in the HB optical fiber. The second term, $(1/2)n^2 p_{44}$, accounts for the refractive index changes caused by the photo-elastic effect due to the induced strain in the periodically twisted fiber, which has the numerical value of -0.08 and hence tends to reduce the mode coupling [9]. Therefore, the main contribution of AO coupling by the lowest
torsional acoustic mode is from the geometrical twist effect which is reduced by 8% due to the elasto-optic effect. As is well known, the most efficient coupling is achieved when phase matching condition is satisfied where the acoustic wavelength is the same as $L_B$.

3. Experiment and analysis

Figure 1 shows the schematic of a proposed AOTPF. The device is composed of a torsional acoustic transducer, two polarizers, and a HB single mode optical fiber ($L_B = 2.8$ mm @ 1550 nm, the stress induced birefringence produced by an elliptical stress member in the cladding, 3M$^{TM}$). The input polarization state of the LP$_{01}$ mode was aligned to one of the polarization eigenstate using the in-line fiber polarizer. The torsional acoustic wave was generated by the combination of two shear mode lead zirconate titanate (PZT) plates attached to the end of an acoustic horn with epoxy adhesive, as shown in Fig. 2. The two PZT plates were arranged so that they oscillate 180 degree out of phase. The torsional acoustic wave generated by the acoustic transducer was coupled to a bare section of the fiber bonded to the central hole in the acoustic horn, and was absorbed by an acoustic damper at the end of the interaction region.

The incident eigen polarization of the LP$_{01}$ core mode is converted to the other eigen polarization of the same core mode at resonant wavelength satisfying the phase matching condition, as the following:
\[ |\beta_{01,x} - \beta_{01,y}| = \frac{2\pi}{L_B}, \quad (2) \]

where, \(L_B\) is the beatlength and each \(\beta\) denotes the wave number for two eigen polarizations of LP\(_{01}\) mode, respectively. When the phase matching condition is satisfied, the acoustic wavelength is the same as beatlength between two polarization eigenmodes. As can be seen in Eq. (2), the beatlength is a function of wavelength and, for a given acoustic frequency, a specific wavelength component will be filtered in the device. The resonant wavelength and the transmitted power of the filter can be tuned by adjusting the frequency and the magnitude of the applied electric signal, respectively. Since the converted polarization mode can be selected or removed by adjusting the polarization direction of the output polarizer, the fabricated filter can be operated as the notch type or the bandpass type as illustrated in Fig.1. For instance, when the polarization directions of the input and the output polarizers are oriented parallel to each other, the AOTPF operates as a notch filter. On the other hand, when the polarization direction of the output polarizer is perpendicular to that of the input polarizer, the AOTPF operates as a bandpass filter.

Figure 3 shows the measured transmission spectra of the polarization filters operating as the notch type (Fig. 3(a)) and as the bandpass type (Fig. 3(b)) at the applied acoustic frequency of 1.337 MHz. The measured 3-dB optical bandwidth for a 60-cm-long AO interaction region was 4.80 nm at the wavelength around 1550 nm, which agrees well with the theoretical value of 4.85 nm calculated with the equation in [10]. The variation of 3-dB bandwidth was only about 0.5 nm for optical wavelength range from 1530 to 1610 nm.

Figure 4 shows the dependence of the optical coupling efficiency between two polarization eigenmodes to the magnitude of the applied voltage. The coupling strength increased with the increase of applied voltage and then decreased after complete optical power transfer between two polarization modes because of an over-coupling between the two eigenmodes. The achieved maximum coupling efficiency was 100% at the wavelength around 1550 nm. The angular displacement of the torsional wave, \(\Phi\) can be calculated from the coupling length \(L_c = \pi/(2\kappa)\) for a 100% coupling as;

\[ \Phi = \frac{1}{4} \frac{L_c}{L} \left(1 + \frac{1}{2} n^2 p_{44} \right)^{-1}. \quad (3) \]

For a 60 cm-long coupling length used in this experiment, \(\Phi\) is estimated to be 0.073° for a complete coupling. This corresponds to 11.3 mW of average acoustic power propagating along the fiber and that is 5.65% of the electrical power applied to the transducer in our experiment. The values are comparable to the reported efficiency of acoustic transducer for all-fiber AOTF using flexural acoustic wave [11]. The device can be reduced in length by...
using the HB fiber of smaller diameter because the coupling coefficient $\kappa$ is inversely proportional to the square of the fiber radius [6] and the AO interaction length $L_c$ can be expressed as $L_c = \frac{\pi}{2\kappa}$ with the coupling coefficient $\kappa$. Figure 5 shows the center wavelength change of the AOTPF as a function of the acoustic wavelength showing an almost linear relationship.

Fig. 4. Optical coupling efficiency between two polarization eigenmodes versus the magnitude of the applied voltage.

Fig. 5. Center wavelength of the all-fiber AOTPF as a function of the acoustic wavelength.
In order to investigate the influence of fiber tension to the filter performance, we induced tension to the AO interaction length of the device and measured the transmission spectra of the filter. Preliminary experiment results show 0.15 nm shift of the center wavelength for 0.1% strain and the detailed study is underway.

4. Conclusion

In conclusion, we have demonstrated a practical all-fiber tunable polarization filter based on AO coupling between two polarization eigenmodes of the LP_{01} mode in a HB single mode optical fiber using traveling torsional acoustic wave. The fabricated filter was operated as the notch type or the bandpass type according to the polarization direction of the output polarizer. Complete coupling between two polarization eigenmodes was achieved and the measured 3-dB bandwidth was 4.8 nm at the wavelength around 1550 nm. The center wavelength could be tuned continuously and almost linearly by tuning the acoustic frequency over the whole tuning range of 1530 - 1610 nm limited by the light source. The transmission characteristics of the filter and the coupling characteristics between two optical polarization modes by the lowest torsional acoustic mode were investigated in detail. Many new active polarization controlling devices would be possible for applications in optical communications and sensing.