# An All-fiber Tunable Polarization-Dependent Loss Element

**Rong Huang, Fares Alhassen, David Tseng, Ozdal Boyraz, and Henry P. Lee**
*Dept. of Electrical Engineering and Computer Science, Henry Samueli School of Engineering,*
*University of California, Irvine, Irvine, CA 92697 USA Tel (949) 824-4861*
*rongh@uci.edu*

**Abstract:** We describe the implementation of a wavelength-tunable polarization-dependent-loss element on polarization-maintaining fiber using two independently-controlled acoustic gratings. Continuous attenuation in both fast and slow axes at the same wavelength is demonstrated.

**OCIS codes:** (230.1040) Acousto-optical devices; (060.2420) Fibers, polarization maintaining;

## 1. Introduction

Research related to polarization-dependent loss (PDL) has gained considerable interest for high-capacity transmission networks because of PDL-induced transmission impairment. Several PDL elements have been investigated such as two polarization controllers (PCs) [1] and twisted–tilted fiber gratings [2]. Recently, Jung *et al.* [3] reported an all-fiber variable PDL element by applying acousto-optic mode coupling from a single piezoelectric transducer (PZT) on a polarization maintaining fiber (PMF). In their experiment, the vibration direction of the acoustic wave is carefully aligned parallel to the fast axis of the PMF to achieve a high coupling efficiency. Variable attenuation along this axis is attained by varying the amplitude of the acoustic wave. In this paper, we demonstrate a variable PDL element on a PMF whereby the attenuation in both slow and fast axes at the same wavelength can be varied using two orthogonally vibrating acoustic waves launched from a pair of PZTs driven at two different frequencies. By controlling the amplitude and phase of the acoustic wave, polarization can be attenuated in a variable manner. When used in conjunction with a PDL monitor, the device can be used as an all-fiber PDL compensator.

## 2. Theory and Experiment

Fiber acousto-optic tunable filters (AOTFs) can filter light and perform mode conversions with near-zero insertion loss. In a single mode fiber (SMF), an RF frequency flexural wave launched onto a bare fiber can induce mode coupling between the core and an anti-symmetrical cladding modes when the phase-matching condition is satisfied. Since the cladding mode is eventually absorbed by the fiber jacket, a fiber AOTF results in a notch-filter like transmission spectrum in which the depth and resonant wavelength of the notch can be tuned by varying the amplitude and the frequency of the flexural wave.

AOTFs have also been applied to PMFs [3], which are of special interest for polarization-related applications due to their intrinsic birefringence properties. A distinguishing feature of PMFs is that the strain-induced members cause not only birefringence for the core modes but also the lower-order cladding modes [4]. This renders coupling between core and cladding modes to occur only for those having the same polarization. **Fig.1 (a)** illustrates the perturbation profile introduced by two PZTs that are vibrating in the orthogonal directions in a PMF. In addition, the two-fold symmetry of the index profile along the birefringence axes of the PMF localizes the lower-order cladding modes in a region between the stress members as illustrated in **Fig. 1(b)**. Since the degeneracy is removed for core and $LP_{lm}$ cladding modes, the polarization-dependent resonances are separated in wavelength. The magnitude of the separation varies from one type of PMF to another. In **Fig. 1(b)**, the slow and fast axes of the PMF are aligned to x and y axes, respectively. The $PZT_2$ and $PZT_1$ are aligned to x' and y' axes, respectively; and $\theta$ is the angle between y' and y axes.

To show that one can attenuate core mode light in both x (slow axis) and y (fast axis) directions, we first consider an x-polarized core mode light. When two acoustic gratings are present, the overall coupling coefficients $\left(\kappa_{1,x}+\kappa_{2,x}\right)$ is the coherent sum of individual gratings, $\kappa_{1,x}$ and $\kappa_{2,x}$. The overall coupling coefficient is proportional to $A_{y'}\cos\theta+A_{x'}\sin\theta$, where $A_{x'}=|A_{x'}|e^{j\alpha_{x'}}$ and $A_{y'}=|A_{y'}|e^{j\alpha_{y'}}$ are the complex magnitudes of each acoustic wave. If the coupling strengths for each grating are equal, i.e., $|A_{y'}|\cos\theta=|A_{x'}|\sin\theta=A_o$, the intensity of the out-coupled (attenuated) cladding mode, in the weak coupling regime, is proportional to $2A_o^2(1+\cos\alpha)I_x^{co}$ where $\alpha=\alpha_{y'}-\alpha_{x'}$ is the phase difference between the two acoustic waves and $I_x^{co}$ is the intensity of the x-polarized core mode light. Thus by varying the phase between the acoustic waves, we can continuously attenuate x-polarized core mode light. A similar expression can be obtained for y-polarized core mode light. In the dual-transducer scheme, the maximum

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attenuation (dynamic range) for both core modes is set by the amplitude of each acoustic grating which is controlled by the applied voltage to each transducer whereas the attenuation level is adjusted by varying the phase between the two gratings. The advantage of the dual-transducer approach over single-transducer approach in Ref. 3 is two-fold: (1) it removes the need to align a single PZT parallel to a birefringent axis of the PMF and (2), the PDL can be aligned and varied without converting the input core mode light to the loss axis using a separate polarization controller.

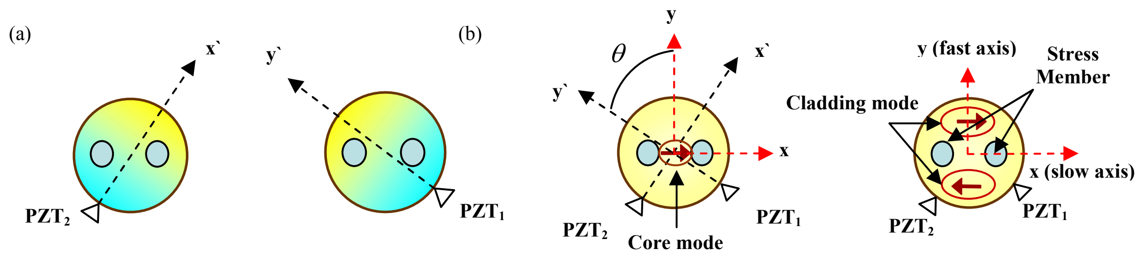


Fig. 1 (a) Illustration of the perturbation profile introduced by two PZTs; (b) Illustration of the vibration directions for a dual-transducer with respect to the birefringence axes of the fiber for x-polarized core and $LP_{1m,s}^{x}$ cladding modes.

**Fig.2** shows the experimental setup of the PDL element. A polarized broadband LED source and an optical spectrum analyzer (OSA) are used to measure the transmission spectra. The input polarization was controlled with a PC. The dual-transducer is constructed from a pair of shear mode PZTs [5]. The PMF we used is a 30-cm of stripped Fujikura PANDA PMF [4]. **Fig. 3** shows the measured transmission spectra for the PMF at a single frequency when the input light is aligned to either x or y axis. The two groups of polarization-dependent resonances are widely tunable over the entire S, C and L bands by varying the acoustic frequency.

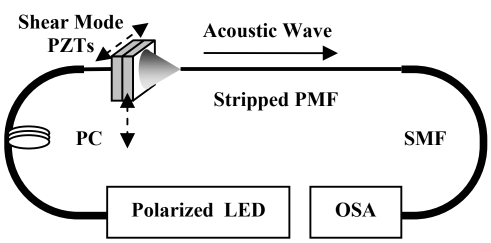


Fig.2 The experimental setup of the variable PDL compensator, consisting of a polarized LED, a PC, a dual-PZT, a segment of stripped PMF and an OSA.

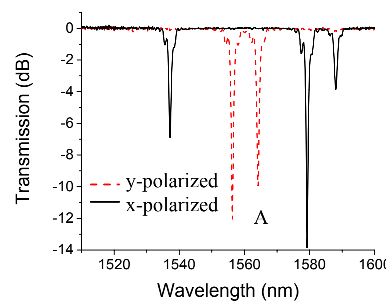


Fig.3 The transmission spectra for x- and y- polarized core modes light at acoustic frequency of 1.765 MHz. The tuning rate (resonant wavelength/RF frequency) is ~0.233 nm/kHz in the C-band.

**3. Results and Discussion**

To implement a variable attenuator for x-polarized light, we first align the input light along the x-axis using the input PC. We then turn on $PZT_1$ (leaving $PZT_2$ off) and adjust the voltage so that the attenuation is less than 1 dB at resonant wavelength as viewed from the OSA. Next, we turn on $PZT_2$ (leaving $PZT_1$ off) and adjust the voltage so that the same attenuation level is achieved as before. At these settings, $|A_{y'}|\cos\theta = |A_{x'}|\sin\theta = A_0$. We then adjust the phase difference ($\alpha$) between the two PZTs while leaving their amplitudes fixed. **Fig. 4(a)** shows the transmission spectra around the notch A in **Fig.3** as $\alpha$ is varied in steps of $20^o$. The peak attenuation at the resonant wavelength 1564.20nm versus $\alpha$ is plotted in **Fig. 4(b)**, exhibiting the sinusoidal variation as predicted theoretically. The slight phase shift of the peak from the origin is attributed to the propagation delay of $PZT_2$ (the back PZT) relative to $PZT_1$ (the front PZT). The results validate the coupling model for PMF we use here. Variable attenuation is also achieved for y-polarized core mode by coupling it to a y-polarized cladding mode.

To demonstrate that we can attenuate both x- and y- components of the core mode at the same wavelength, we applied a second set of RF voltages to the PZTs at a different frequency so that the resonant wavelength for y-polarized coupling coincides with that of the x-polarized coupling as illustrated in Fig. 5(a). The acoustic amplitudes at this new frequency are calibrated so that equal coupling is achieved between the two PZTs for y-polarized coupling. For a resonant wavelength at 1564.20nm, the frequencies $f_1$ and $f_2$ for y and x-polarized core mode light are 1.765 MHz and1.8295 MHz respectively. By tuning the phase between the two RF driving signals at 1.8295 MHz, the x-polarized core mode light can be attenuated continuously from 0 to -19dB. Likewise, by tuning the phase between the two RF signals at 1.765 MHz, the y-polarized core mode light can be attenuated continuously from 0 to -17dB. When both frequencies are applied to the dual-transducer, the total attenuation at the resonant wavelength is an incoherent sum of the attenuated x- and y-polarized core modes. **Fig. 5 (b)** shows the experimental result of attenuation spectra of a polarized broadband light when we apply $f_1$ and $f_2$ separately, and when we apply both $f_1$ and $f_2$. The attenuations at the resonant wavelength (1564.20nm) at $f_1$ and $f_2$ are 36% and 55% for x and y-polarized core mode light respectively. The total attenuation (91%) at the resonant wavelength when both $f_1$ and $f_2$ are applied to the dual-transducer is the incoherent sum of the individual attenuation for x and y polarized core mode light. Since variable attenuation can be achieved for x and y polarized core mode light, this demonstrates attenuation of SOP for the core mode light free of cross-talk.

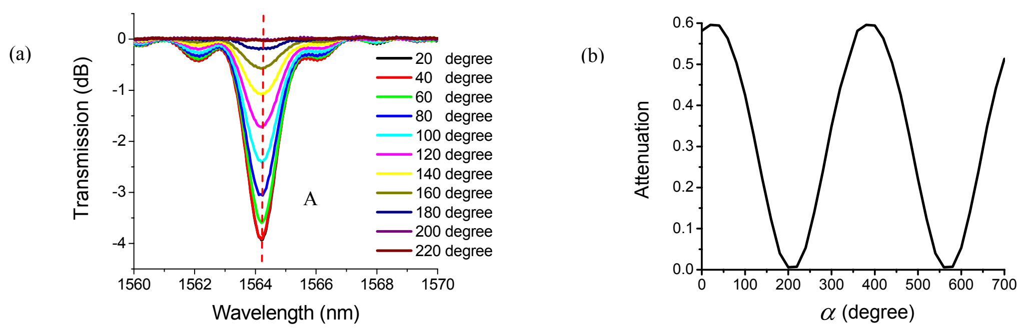


Fig.4 (a) The transmission spectra versus α, the phase difference between the two PZTs; (b) the attenuation in linear scale at the resonant wavelength of 1564.20nm versus α, which changes sinusoidally with α.

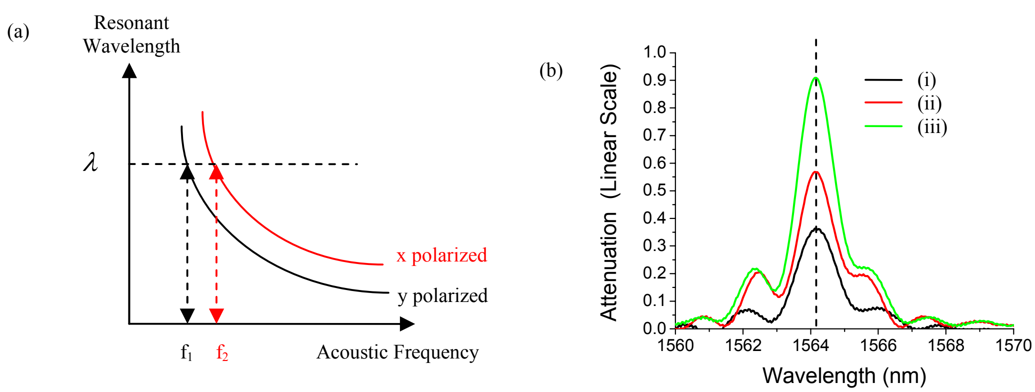


Fig.5 (a) The schematic of the tuning characteristics of the PMF for x and y polarized core mode light; (b) The PDL for a polarized input core mode light when (i) y-polarized core mode is attenuated when only $f_1$ (1.7650 MHz) is applied, (ii) x-polarized core mode is attenuated when only $f_2$ (1.8295MHz) is applied, and (iii) both x- and y-polarized core modes are attenuated when both $f_1$ and $f_2$ are applied.

## 4. Conclusion

An all-fiber PDL element is demonstrated on a 30-cm PANDA PMF. The PDL of the incoming light can be simultaneously and electronically tuned by adjusting the phase between the set of RF signals.

## 5. References

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