# Tunable Polarization-Dependent Loss Element Based on Acoustooptic Mode Coupling in a Polarization-Maintaining Fiber

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***Abstract*—We demonstrate a tunable polarization-dependent loss (PDL) element based on the polarization-dependent coupling of the fundamental core mode to the cladding mode by the flexural acoustic wave in a polarization-maintaining fiber with an elliptical stress member. The resonant wavelength of PDL is tunable by adjusting the frequency of radio-frequency (RF) signal applied to the acoustic transducer, while the magnitude of PDL is variable by the voltage of the same RF signal. Over the wavelength from 1530 to 1570 nm, the variable ranges of PDL for two linear orthogonal polarizations are 16 and 17 dB, respectively.**

***Index Terms*—Acoustooptic mode coupling, fiber polarizer, polarization-dependent loss (PDL), polarization-maintaining (PM) fiber, wavelength-tunable.**

## I. INTRODUCTION

THE CONTROL and compensation of polarization-dependent loss (PDL) have attracted much interest in high-capacity transmission networks, because the PDL degrades the system performance. In the presence of polarization-mode dispersion (PMD), PDL not only increases the system penalty, but also limits the compensation of PMD [1], [2]. Several tunable elements for PDL compensation have been fabricated by using a tiltable planar lens [3], two polarization controllers [4], long-period fiber gratings [5], and twisted–tilted fiber gratings [6]. Recently, Lin *et al.* reported the transmission spectra of the PANDA polarization-maintaining (PM) fiber by acoustooptic mode coupling [7]. However, adjacent PDL peaks were still present in their work due to the misalignment between the bending direction of the PM fiber and the birefringent axes. The misalignment may result in the decrease of mode coupling efficiency and the neighboring resonant loss peaks may induce unwanted PDL at different resonant wavelengths for the multi channel transmission system.

In this letter, we demonstrate a tunable PDL element based on the polarization-dependent coupling of the fundamental core mode to the cladding mode by the flexural acoustic wave in a PM fiber with an elliptical stress member. The cladding mode coupled from the fundamental core mode is experimentally identified and the variation of PDL is measured with a commercial PDL meter. We could generate large variation in PDL by adjusting the voltage applied to the acoustic transducer. Though PDL peaks have a narrow bandwidth, its resonant wavelength is easily adjusted by changing the frequency of radio-frequency (RF) signal. Thus, the PDL spectrum of the multichannel transmission system may be compensated by cascading the proposed elements. The spectral range of PDL may be determined by the 37-nm polarization splitting of coupling to the $\mathrm{LP}_{11}$ cladding mode, which is wide enough to cover the optical $C$-band (1530–1565 nm). Therefore, the polarity of PDL can be selected within the optical $C$-band by changing the frequency of RF signal. The unwanted resonant loss peaks are suppressed by aligning the birefringent axes with the direction of the acoustic vibration and by using an elliptically stressed PM fiber. Since only one of two linearly polarized core modes may be suppressed, the insertion loss at a given wavelength is intrinsically smaller than that of the element using the twisted–tilted fiber gratings [6].

## II. PRINCIPLE OF OPERATION

The operation of the proposed device is based on the codirectional coupling between the fundamental core mode and the antisymmetrical cladding modes (i.e., $\mathrm{LP}_{1n}$ modes, $n = 1, 2, 3, \ldots$) in a PM fiber. The mode coupling occurs if the acoustic wavelength $\Lambda$ of the flexural acoustic wave satisfies the following phase-matching condition:

$$\beta_c(\lambda) - \beta_n(\lambda) = \frac{2\pi}{\Lambda}$$

where $\beta_c$ and $\beta_n$ are the propagation constants of the fundamental core mode and the $\mathrm{LP}_{1n}$ cladding mode, respectively. The acoustic wavelength is variable by changing the frequency of RF signal applied to the acoustic transducer. Since the stress-induced birefringence makes the propagation constants of the PM fiber different for two linear orthogonal polarizations, the mode coupling occurs at different wavelengths. Therefore, each of two linearly polarized core modes in the PM fiber is coupled at a given wavelength. By adjusting the frequency and the voltage of RF signal, we may select the wavelength of the resonant loss peaks and control the magnitude of PDL easily.

## III. EXPERIMENT AND DISCUSSION

To measure the transmission spectra of the PM fiber with acoustooptic mode coupling, the flexural acoustic wave is launched by the glass horn along the PM fiber. It couples

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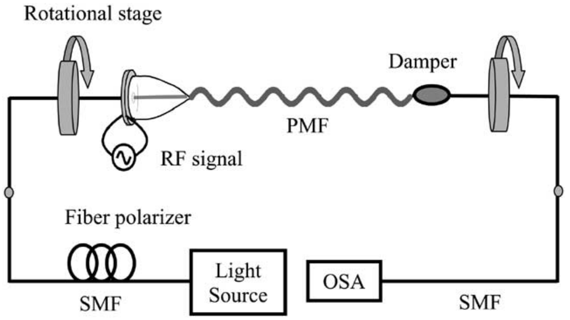
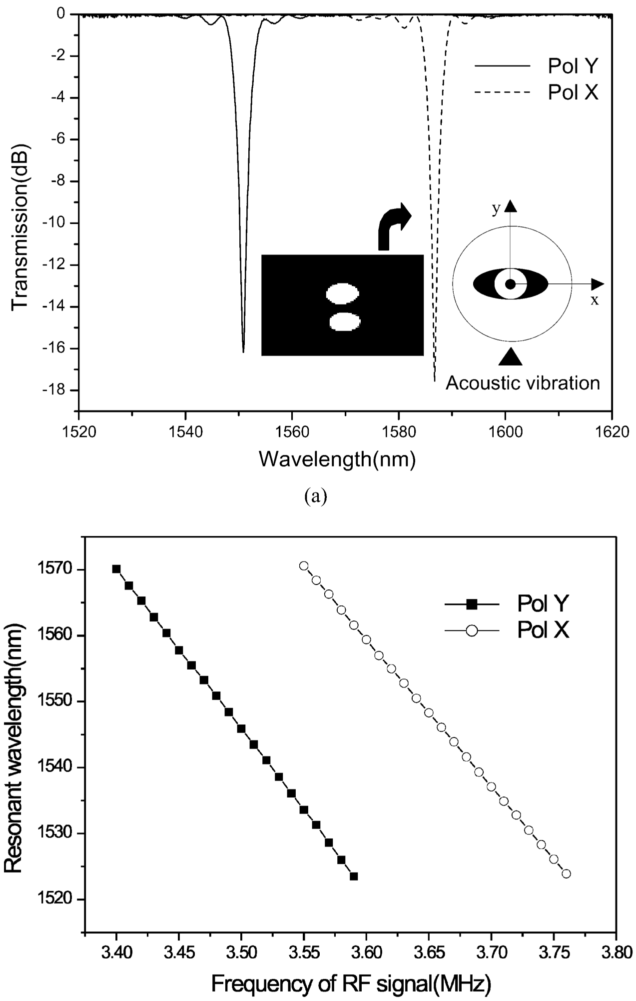


Fig. 1. Experimental setup (PMF: PM fiber. SMF: single-mode fiber. OSA: optical spectrum analyzer).

the fundamental core mode to the cladding modes in the 20-cm-long interaction region, and then it is absorbed by an acoustic damper. The experimental setup is shown in Fig. 1. The PM fiber used in this experiment is a 3M fiber (FS-PM 7621). It is composed of a concentrically circular core (a dark dot) with an inner silica cladding, an elliptical stress member, and a circular silica support layer with the diameter of 125 $\mu$m, as shown in Fig. 2(a). The beat length between two linearly polarized core modes, which is measured at the wavelength of 1550 nm by the pinch roller method [8], is 2.7 mm (birefringence of $5.7 \times 10^{-4}$).

To get a coupling of the core mode to either the even or the odd $\mathrm{LP}_{1n}$ cladding mode, we have to align one of the birefringent axes to the direction of the acoustic vibration. By rotating the PM fiber, one of the birefringent axes is aligned with the direction of acoustic vibration that is fixed in a certain direction. The alignment is confirmed by analyzing the reflection spectra of the coherent light source incident on the PM fiber [8]. To make it possible, the PM fiber is softly bonded to the acoustic transducer. After alignment, we adjust the polarization of the propagating light source by using a linear fiber polarizer. The polarization of the light source is confirmed by using a polarizer at the end of the PM fiber. The transmission spectrum is measured by using a broad-band unpolarized erbium-doped fiber amplifier light source and an optical spectrum analyzer. The identification of the cladding mode coupled from the fundamental core mode is made by observing the far field image that is formed by a tunable laser diode at the resonant wavelength.

The transmission spectrum of PM fiber with the RF signal of the acoustic transducer at 3.48 MHz is shown for two linear orthogonal polarizations in Fig. 2(a). The fast axis of the PM fiber is oriented in the $y$ direction. The dashed line represents the transmission spectrum of $x$ polarization (i.e., the polarization of the input source is parallel to the $x$ axis), while the solid line represents that of $y$ polarization. The resonant wavelengths of $y$-polarized and $x$-polarized light are 1550.8 and 1586.8 nm, respectively. The wavelength difference between them is 36 nm. For each linear polarization, the wavelength separation between the first PDL peak and the nearest loss peak is larger than 120 nm. Thus, it is wide enough not to affect the polarization splitting. While the mode coupling does not occur at a certain rotation angle of the PANDA fiber [7], the mode coupling always occurs during a rotation of the 3M fiber. The 3-dB bandwidths for the $y$-polarized and the $x$-polarized light in Fig. 2(a) are about 3.8 and 3.4 nm, respectively. The measured image of the $\mathrm{LP}_{11}$ cladding mode for the $x$-polarized light is shown in Fig. 2(a). The polarization mode splitting [7] of the $\mathrm{LP}_{11}$ cladding mode in the 3M PM fiber is $5.1 \times 10^{-4}$ at the wavelength of 1550 nm.For the $x$-polarized and the $y$-polarized light, wavelengths of the resonant loss peak as a function of frequency of RF signal are shown in Fig. 2(b). With the RF signal at 3.56 MHz, the resonant loss peaks of two linear polarizations are located at 1528.6 and 1566.3 nm, respectively, and their difference is about 37 nm. It will be the spectral range of the proposed PDL element. If the frequency of RF signal is below 3.56 MHz, only the $y$-polarized light is coupled within the optical $C$-band. If it is above 3.58 MHz, only the $x$-polarized light is coupled. Here, we can select the polarity of PDL within the optical $C$-band because one of two PDL peaks can be suppressed by adjusting the frequency of RF signal. Applying the RF signal at 3.486 MHz, we plot in Fig. 3 the PDL of the $y$-polarized light with respect to the applied voltage. It is characterized by the commercial PDL meter (Fiberpro, PL2000) after the PM fiber is permanently glued to the glass horn. Although the magnitude of PDL for each linear polarization can be enhanced up to 16 and 17 dB, respectively,



(a)

(b)

Fig. 2. Transmission spectra of 3M PM fiber. (a) Transmission spectrum (Frequency was 3.48 MHz. Pol X and Pol Y mean the polarizations of the input source are parallel to the $x$ axis and the $y$ axis, respectively. A far field image on the screen is given for the $x$-polarized light). (b) Wavelength of the resonant loss peak as a function of frequency of RF signal.

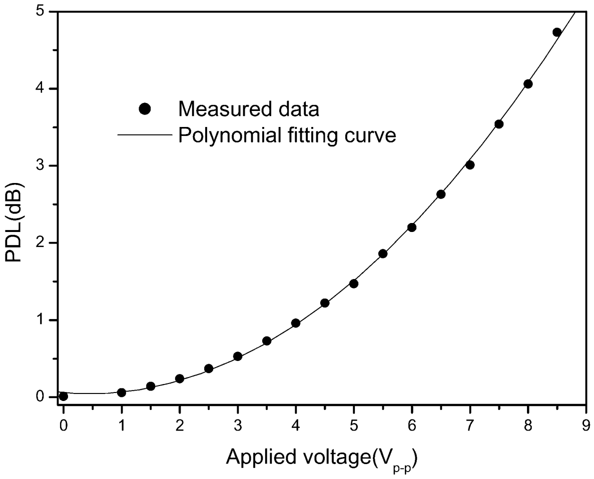


Fig. 3. Variation of PDL as a function of applied voltage of RF signal.

it is measured only up to 5 dB due to the measurement limitation of the PDL meter. The magnitude of PDL is proportional to the square of the applied voltage. The initial insertion loss and the PDL are 0.5 and 0.01 dB, respectively. They are mainly caused by the splicing between the single-mode fiber and the PM fiber. The proposed device may be used as a wavelength-tunable fiber polarizer if its extinction ratio is improved [9]. In addition, it may be used as a PDL emulator or a PDL compensator along with a polarization controller. The fast PDL adaptation by acoustooptic mode coupling may be used for the dynamic equalization of PDL that is accumulated from many optical components in a fiber-optic link [4].

## IV. CONCLUSION

We have demonstrated a tunable PDL element. It utilizes the acoustooptic mode coupling in the PM fiber with an elliptical stress member. The proposed device can generate large variation in PDL and tune the resonant wavelength of PDL by adjusting the voltage and the frequency of RF signal applied to the acoustic transducer.

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