All-Fiber Wavelength-Tunable Acoustooptic Switches Based on Intermodal Coupling in Fibers

Hee Su Park, Kwang Yong Song, Seok Hyun Yun, and Byoung Yoon Kim, *Fellow, IEEE*

***Abstract*—In this paper, we demonstrate a novel all-fiber wavelength-tunable acoustooptic switch utilizing intermodal coupling in a two-mode fiber (TMF). Its all-fiber configuration consisting of a fiber acoustooptic tunable filter and a mode-selective coupler results in the low loss ($<$ 2 dB) operation. The operating bandwidth $>$ 50 nm, the switching time of 40 μsec, and the crosstalk of 20 dB were achieved. By controlling the design parameters of the two-mode fiber, the 3-dB bandwidth of the switched signal was varied from 2.5 nm to $>$ 35 nm. A novel all-fiber dynamic optical add-drop multiplexer is also demonstrated using two acoustooptic switches in series.**

***Index Terms*—Acoustooptic devices, acoustooptic switches, optical fiber devices, optical fiber switches, wavelength division multiplexing (WDM).**

I. Introduction

The optical switch/router with wavelength selectivity is a key component in optical networks [1]. As the fields of optical telecommunication systems expand from long haul point-to-point transmission to metropolitan systems and optical access networks, there is increasing need for the flexible manipulation of the many wavelength channels. The technology of wavelength-tunable optical switches is important because they are building blocks of advanced network elements such as dynamic optical add-drop multiplexers and optical crossconnencts. Among various switching technologies demonstrated over the years, an integrated-optic (IO) switch based on acoustooptic (AO) interaction in $LiNbO_3$ waveguides has shown several advantages including wide tuning range, multi wavelength filtering capability, and fast switching speed ($<$ 100 μs) [2]. The IO AO switch is also advantageous in that it is not limited to a specific set of wavelength channels unlike the devices comprising conventional optical switches and passive wavelength filters such as fiber Bragg gratings, thin film filters, and arrayed waveguide gratings.

Moreover, it has been also shown that the AO interaction is strong enough to control the light inside optical fibers [3]–[8]. In this paper, we introduce this AO interaction to all-fiber structures to control the coupling between spatial modes by applying a flexural acoustic wave along a fiber. A novel all-fiber wavelength-tunable AO switch is proposed and demonstrated comprising a fiber acoustooptic tunable filter (AOTF) and a fused-type mode-selective coupler (MSC) [9]. A distinct point is that the all-fiber AO switch routes the switched signal and the unswitched signal through the MSC while the IO switch needs a polarization beam splitter. The all-fiber AO switch shares the same advantages as the IO device. But it is particularly attractive in that it is relatively easy to achieve low insertion loss and low cost that is more important when a large number of optical switches are employed in complicated optical networks. Design parameters for the fiber and the components are presented and the fabricated devices are characterized. In addition, a novel all-fiber dynamic optical add-drop multiplexer (OADM) is demonstrated based on the AO switches.

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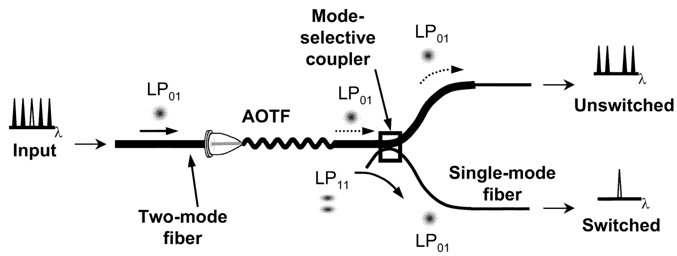

Fig. 1. Schematic of the AO switch. AOTF: acoustooptic tunable filter.

II. Device Principle

The proposed AO switch consists of an in-line acoustic generator in a two-mode fiber (TMF) [3] followed by an MSC as explained in Fig. 1. The TMF is a fiber designed to guide two spatial modes, the LP_{01} mode (the fundamental mode) and the LP_{11} mode (the second order mode). The acoustic generator, driven by an RF electric signal, makes a flexural acoustic wave along the TMF to induce periodic microbends. The MSC is a fiber directional coupler made of an SMF and a TMF, in which strong mode coupling takes place between the LP_{01} mode of the SMF and the LP_{11} mode of the TMF. However, little coupling occurs between the LP_{01} modes of the two fibers in the MSC. The operating principle of the AO switch is as follows. When the wavelength-multiplexed optical signals enter the input as the LP_{01} mode, a particular wavelength channel is converted to the LP_{11} mode by the acoustically generated microbends. The converted LP_{11} mode is then funneled to the "switched" port after passing through the MSC. And the LP_{01} mode passes through the MSC without coupling and reaches the "unswitched" port. The switching wavelength is tunable by varying the RF frequency. And the frequency of the "switched" light is shifted by the amount equal to the RF frequency. Although this device has the same physical topology with another previous all-fiber AO switch [5], one can achieve more homogeneous AO interaction since the AO interaction takes place in a regular fiber section rather

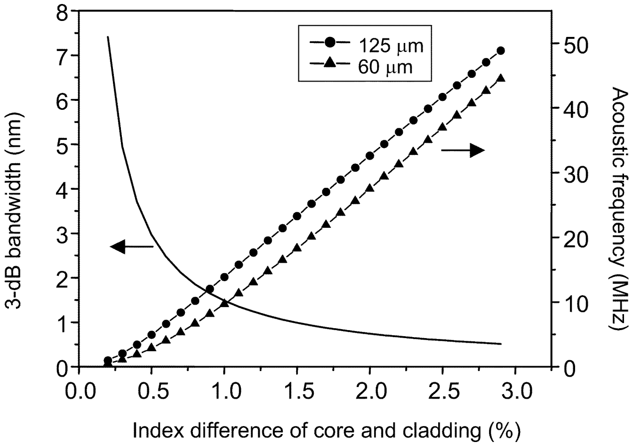

Fig. 2. Calculated optical bandwidths and acoustic frequencies of fiber AOTFs using TMFs near the LP_{11} mode cut off. The fibers have step-index, circular core, and cladding diameters of 125 μm and 60 μm. The interaction length is set to 10 cm.

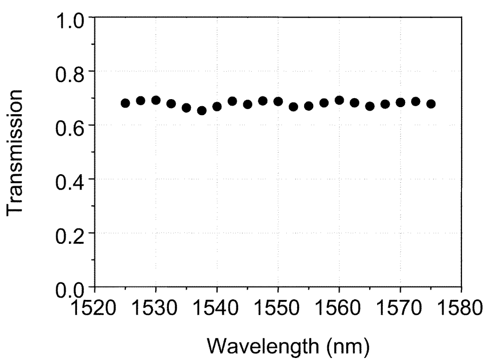

Fig. 3. Coupling efficiency of the fused-type mode-selective coupler.

than in a tapered fiber coupler. The more homogeneous AO interaction results in the smaller sidelobes in the filter spectra.

The spectral characteristics of the AO switch are mainly determined by the AOTF because the MSC generally has a relatively broad operating wavelength band [9]. The FWHM bandwidth of the AOTF can be expressed as a function of the mode propagation characteristics in the TMF as

$$\Delta\lambda_{3dB} \cong \frac{0.8}{L_c}\left[\frac{dL_B}{d\lambda}\right]^{-1}$$
$$L_B^2 = 0.8\left(\frac{\lambda^2}{L_c}\right)\left(\frac{1}{\Delta(n_g)}\right), \quad \Delta n_g \neq 0$$

where L_c is the coupling length of the AOTF, L_B is the optical beat length, and $\Delta(n_g)$ is the group index difference between two coupling modes [10]. From the equation, one can easily verify that a TMF having large group index difference is needed in order to make a narrow bandwidth AOTF that would be useful for WDM optical communication. However, as shown in [3], the efficiency of the AOTF decreases with the beat length L_B. Therefore, it is optimal to design the TMF near the LP_{11} mode cutoff for an efficient narrow bandwidth AOTF because the group index difference is largest while the beat length is fixed. Fig. 2 summarizes the bandwidths and the required acoustic frequencies of AOTFs near the LP_{11} mode cut-off

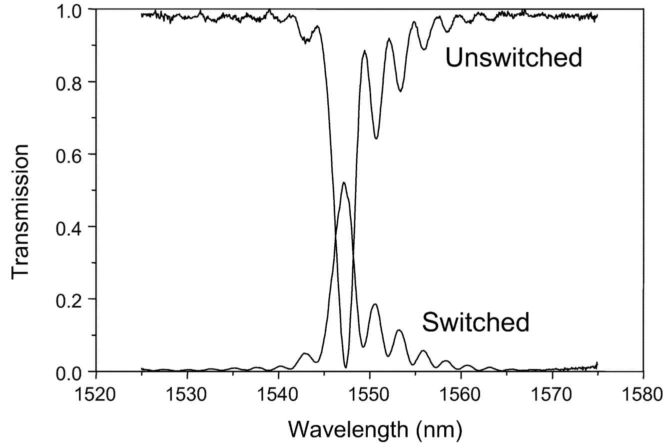

Fig. 4. Transmission spectra of the narrow bandwidth AO switch.

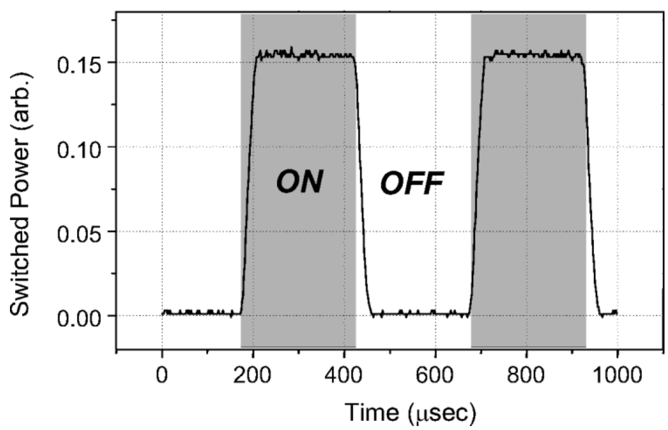

Fig. 5. The modulation of the "switched" signal using the amplitude modulated RF signal applied to the AO switch.

using step-index and circular core TMFs. The interaction length is set to 10 cm in the calculation. When the properties of the fiber core are kept constant, the reduction of the cladding diameter lowers the required modulation frequency as shown in Fig. 2, and increases the coupling efficiency noticeably [11]. The bandwidth is practically limited to $1 \sim 2$ nm with step-index TMFs because of the poor AO coupling efficiency of the RF signal at high frequency.

The TMFs generally have a particular wavelength where the two spatial modes have the same group index [12]. The bandwidth of the AOTF working in this wavelength should be expressed as follows:

$$\Delta\lambda_{3dB} \cong \left[1.6\left(\frac{\lambda}{L_c}\right)\left(\frac{1}{\frac{\partial^2\Delta n}{\partial\lambda^2}}\right)\right]^{1/2}, \quad \Delta n_g = 0$$

where Δn is the phase index difference. If one designs a fiber with this mode configuration, a broadband device of > 50 nm bandwidth can be fabricated [7]. In our experiment, elliptic core fibers, instead of conventional circular core fibers, are used because the orientation of the LP_{11} mode should be maintained over a long distance inside the TMF [13]. In order to estimate the bandwidth of the e-core TMF AOTFs for the fiber design, the approximate empirical formula relating an elliptic core TMF to an equivalent circular core TMF is used [14].

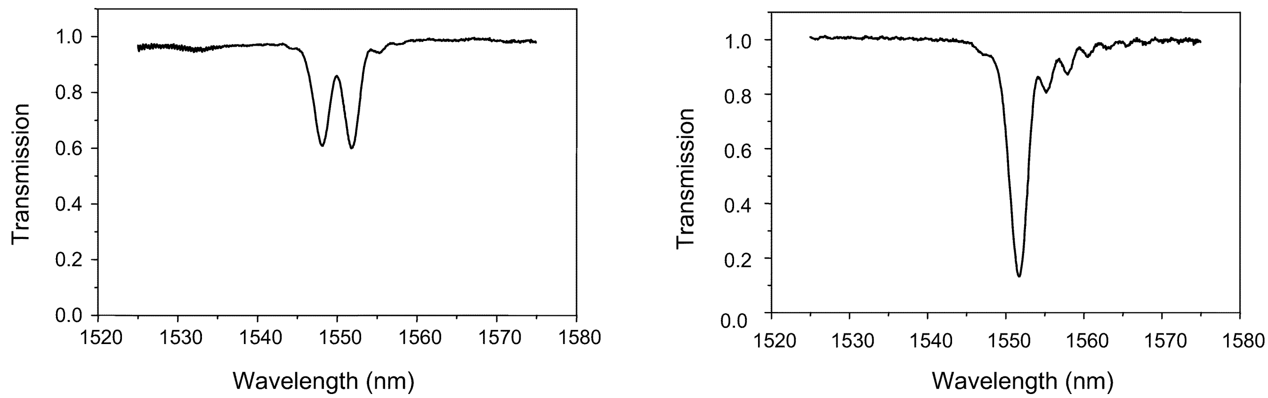

Fig. 6. Transmission spectra of the AOTF with unpolarized input light (a) using the original TMF, (b) using the TMF after the flame brushing.

III. Experimental Results

An elliptic core TMF near the LP_{11} mode cut-off is designed and used for narrow band application. (NA 0.20, core diameter 8 μm$\times$ 5 μm and cladding diameter 88 μm) In the MSC and the AOTF used for the experiment, only the even LP_{11} mode with the intensity lobe along the major axis of the core is excited. Note that the odd LP_{11} mode is cut off (not guided) in the fiber core in order to minimize unwanted loss due to coupling to the odd LP_{11} mode. In addition, we fabricate a new fused-type MSC that is compact and environmentally stable as compared to polished-type MSCs [9]. The coupling efficiency of the fused MSC is shown in Fig. 3. For the test, a broadband light source is launched to the SMF arm and the optical power coupled to the TMF is measured. The maximum transmission is 69% and remains over 62% in the wavelength range of $1525 \sim 1575$ nm. The polarization dependent loss in the transmission is 0.25 dB. It turned out that less than -25 dB of the light coupled to the TMF is the LP_{01} mode. The optical loss includes the insertion loss ($\sim$ 3/4) and the loss due to the finite coupling ratio ($\sim 1/4$). Both of them contribute to only the insertion loss of the AO switch.

The acoustic transducer is attached to the unjacketed fiber section of 13 cm in the strand of the TMF arm of the MSC. The fiber in the AOTF is etched to the diameter of 58 μm from the original 88 μm so as to increase the coupling efficiency [11]. The performance of the fabricated AO switch is shown in Fig. 4. Broadband light is launched to the input port and the output spectra both at the switched port and the unswitched port are measured. The RF signal of 6.8 MHz is applied for the measurement and the center wavelength is tuned at a rate of -0.11 nm/kHz by changing the RF frequency. The background insertion loss is 0.15 dB, the extinction of the unswitched signal is 20 dB, and the loss of the switched signal is 1.9 dB. The 3-dB optical bandwidth of the main peak is 2.5 nm. The large asymmetric sidebands are attributed to the nonuniformity of the fiber diameter as $\sim 0.7\%$ introduced during the etching of the TMF in the AOTF [15]. The sidebands are easily lowered if the fiber is initially drawn with the smaller cladding diameter. When the AOTF is turned off, the coupled power to the switched port, the crosstalk, is less than -20 dB.

The switching time is measured to be 40 μsec by applying the amplitude-modulated RF signal to the AOTF, as shown in

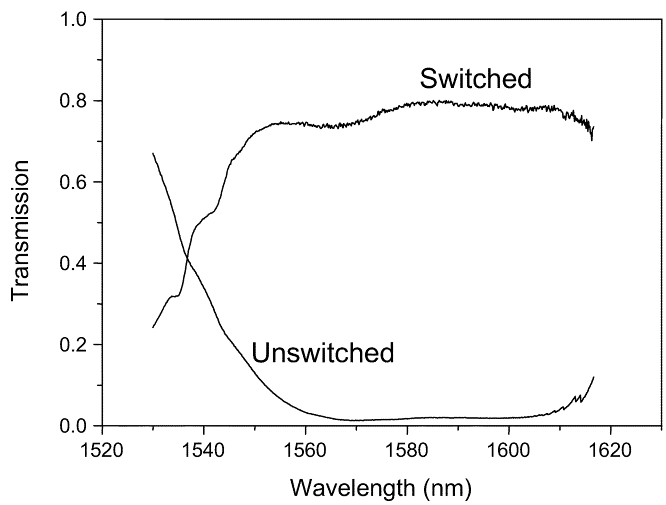

Fig. 7. Transmission spectra of the broad bandwidth AO switch.

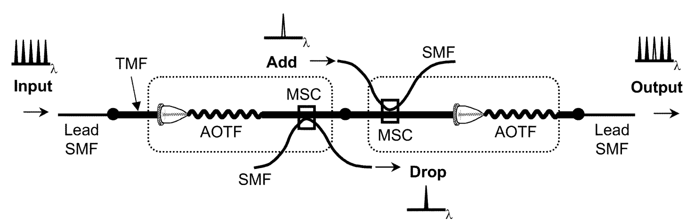

Fig. 8. Dynamic optical add-drop multiplexer based on the proposed AO switch.

Fig. 5. The switching time is close the calculated traveling time of the acoustic wave through the fiber section of the AOTF. The group velocity of the flexural acoustic wave is calculated to be 2880 m/s based on the acoustic frequency and the fiber outer diameter [11].

In the e-core TMF, each of the two spatial modes has two distinct polarization modes that are linearly polarized along the direction of the major axis and the minor axis, respectively [13]. The beat lengths between the spatial modes are slightly different for two polarizations. As a result, the polarization-dependent center wavelength variation as large as 5 nm is observed in the AOTF when we use the original TMF. However, the polarization dependence can be suppressed if the fiber geometry and the internal stress of the fiber are properly controlled [16]. To relieve

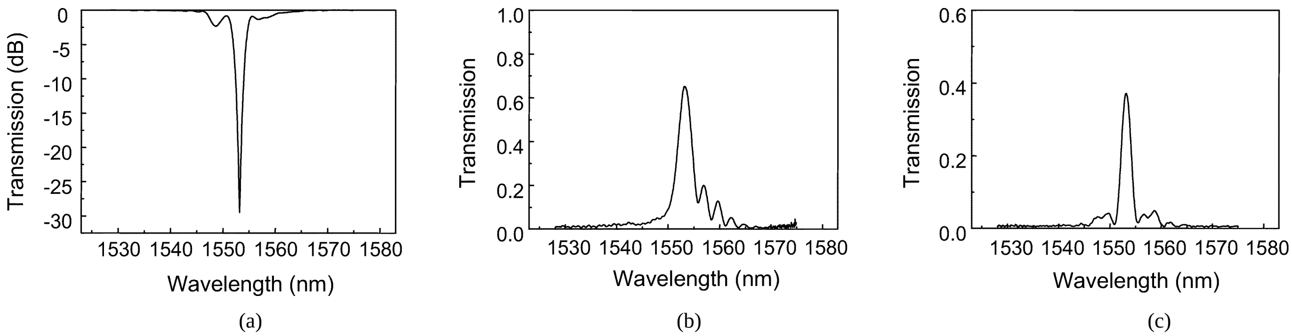

Fig. 9. Transmission spectra of the optical add-drop multiplexer. (a) From the input to the output. (b) From the input to the drop. (c) From the add to the output.

the internal stress, the flame brushing technique [17] is applied to the TMF with a propane torch during the fabrication of the AO switch. The resultant polarization-dependent wavelength variation is reduced to 1 nm as shown in Fig. 6. However, the effect of the flame brushing on the internal stress of the fiber is not clearly analyzed at present.

Using a different e-core TMF (NA of 0.16, core diameter of 11 μm$\times$ 7 μm, and cladding diameter of 100 μm) that is designed for a broadband filter, another AO switch was made for comparison. In this fiber, the LP_{01} mode and the even LP_{11} mode have the same group index at the wavelength of 1585 nm and the odd LP_{11} mode is also cut off in the measured wavelength band. The coupling efficiency of the fused-type MSC fabricated with this TMF is more than 79% in the wavelength range of $1515 \sim 1600$ nm. The TMF section in the AOTF is 13 cm long and not etched. The applied RF frequency is 3.675 MHz. Typical output spectra of the fabricated AO switch are shown in Fig. 7. The extinction ratio of the unswitched light is maintained at less than -17 dB over the wide operation range of $1565 \sim 1600$ nm with the polarization dependence of less than 1 dB. If a TMF of the smaller NA is used, the broader operation range (> 70 nm) and the smaller polarization dependence should be achievable [7].

IV. Dynamic Optical Add-Drop Multiplexer

A novel all-fiber dynamic OADM is also proposed and demonstrated by combining two AO switches in series as shown in Fig. 8. The drop process is just the same as the "switch" operation of the optical switch. To "add" a channel, the signal is firstly converted to the LP_{11} mode of the TMF by the second MSC. Then the signal is converted again to the LP_{01} mode by the second AOTF and directed to the output port. Here the uncoupled leakage signals from the first AOTF are coupled to the higher order mode again in the second AOTF and are greatly attenuated afterwards. Therefore, this device shows the higher extinction ratio than the single AOTF. In order to minimize the influence of uncoupled leakage signals in the MSCs and the splice points, the LP_{11} mode strippers are placed on both sides of the splice point. As shown in the transmission from the input to the output (Fig. 9(a)), the leakage level at the center wavelength is -30 dB with proper input polarization control. The transmission from the input to the drop (Fig. 9(b)) is identical to that of the switched light in Fig. 3 and the "add" efficiency (Fig. 9(c)) was 37% because of the lower efficiency of the second MSC. The out-of-band loss is 1 dB that comes mainly from splice losses between the TMF and the lead SMFs.

The current device could be applicable to very coarse WDM systems because of the linewidth and the sidelobes. One should optimally design the fiber and the AOTF structure for practical implementations. The major fraction of the insertion loss of the OADM comes from the incomplete efficiency of the MSCs. The research to improve the performances of the MSC is currently under way [9]. The polarization dependences of the device can be suppressed with the aforementioned proper control of the fiber internal stresses or with the polarization diversity configurations.

V. Conclusion

A novel all-fiber AO switch having 2 dB loss (0.2 dB out-of-band loss), -20 dB crosstalk, and 40 μs switching time has been successfully demonstrated comprising a fiber AO tunable filter and a mode selective coupler. The fabricated optical switch has broad operation wavelength range of > 50 nm thanks to the broad bandwidth of the mode selective coupler. The wavelength bandwidth of the switched signal could be varied from 2.5 nm to $>$ 35 nm by controlling the design parameters of the TMF. In addition, a novel all-fiber optical add-drop multiplexer is demonstrated by connecting two AO switches in series.

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