Acoustic-induced switching of the reflection wavelength in a fiber Bragg grating

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Coupling between copropagating core and cladding modes was implemented by acoustic generation of lateral vibration of an etched fiber. When these coupling processes were combined with counterpropagating coupling of a core mode and a cladding mode and the Bragg reflection of a fiber grating, switching of reflection wavelength between the Bragg wavelength and cladding-mode coupling wavelengths was achieved. We report the implementation of such acoustically induced switching behaviors and explain their operation principles. The implemented results can be used for wavelength-division multiplexed add–drop filtering. © 2000 Optical Society of America

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Acoustics-induced fiber vibration has been used to control the optical characteristics of bare fiber, fiber couplers, and fiber Bragg gratings. All-fiber frequency shifting based on the coupling of two-mode fibers with a traveling flexural acoustic wave has been demonstrated.1,2 Acousto-optic attenuation filters based on tapered optical fiber were implemented by Feed et al. to flatten amplified spontaneous emission in an Er-doped fiber amplifier.3 An acoustic wave was used to excite the transverse vibration of a four-port taper fiber coupler for shifting of the coupling frequency.4 An acoustic wave was also used to achieve tunable filtering in a two-mode fiber coupler.5 Meanwhile, acoustic waves were employed to excite the longitudinal vibration of a fiber Bragg grating for generation of sidebands of the reflection window.6 The spectral location and intensity of the sidebands were controlled by the acoustic frequency and intensity, respectively. Recently, Huang et al. acoustically generated lateral vibration of a fiber Bragg grating to control its reflectivity level after it was written.7

In this Letter we report, for the first time to our knowledge, switching of the reflection window of a fiber Bragg grating through the application of an acoustic wave to the fiber grating. The acoustic wave induced lateral vibration and hence microbending of the fiber grating. The microbending served as a long-period grating for coupling the core and cladding modes.8 With this coupling mechanism, the reflection window of the fiber grating can be switched between the Bragg wavelength and the cladding-mode coupling wavelengths. Such a switching function can be applied to wavelength-division multiplexed add–drop operations in fiber communications.

Figure 1 shows the setup of the acoustics-modulated device. A fiber Bragg grating was spliced to a 3-dB fiber coupler for measurements. Between the grating section and the coupler, the fiber was laterally glued to the tip of a solid metal (aluminum) horn, whose base was attached to a piezotransducer (PZT). The PZT was driven by a voltage source for generation of an acoustic wave. The acoustic wave translated onto the fiber and produced transverse vibration. The vibration propagated to the grating section to form microbending. To enhance microbending effects and control the cladding-mode characteristics we etched the grating section of the fiber with hydrofluoric acid solution to reduce the cladding diameter from 125 to 40 μm. The grating was 1.7 cm in length, with a slant angle of 2°. The Bragg wavelength was 1541.5 nm, with a Bragg reflectivity of ~63%. The uniform part of the etched section had a length of 3.5 cm, with the center coincident with the grating

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Fig. 1. Device setup for acoustically induced reflection wavelength variation. Etching a section of the fiber near the slanted Bragg grating reduced the cladding diameter to 40 μm. Close to the edge of the etched section, the fiber was laterally glued to the tip of a metal horn, which was used to translate acoustic vibration from a PZT to the fiber.
center. A LED and a spectrum analyzer were used to measure the reflection and transmission spectra.

Figure 2 demonstrates the transmission spectra of the fiber grating for various applied voltages. The spectra were normalized with respect to the transmission power at 1550 nm with zero applied voltage. In the solid curve, i.e., in the case of zero voltage, two major dips can be observed. The one at 1541.5 nm corresponds to the Bragg wavelength, \( \lambda_B \). The next one, near 1539.7 nm (\( \lambda_S \)), corresponds to the first (strongest) cladding-mode coupling feature. This dip originates from the coupling between the forward-propagating core mode [with the propagation constant \( \beta_{01}(\lambda_B) \)] and a backward-propagating cladding mode [with the propagation constant \( \beta_{1m}(\lambda_S) \)]. Therefore the input signal at \( \lambda_S \) is coupled out of the core [see Fig. 5(b), below]. Next we turned on a cw voltage source with a frequency at 1.3 MHz and measured the reflection spectra. Figure 3 shows the variation of the spectrum at various applied voltages. One can see that the reflectivity of the \( \lambda_B \) signal decreases from 63% almost to 20% as the voltage increases to 15 V. Meanwhile, the reflectivity of the \( \lambda_S \) signal increases from the noise level to almost 60%. Besides, when the applied voltage is higher than 10 V, the reflectivity of the second cladding mode emerges. Figure 4 summarizes the variations of reflectivity of the signals at the two wavelengths.

In the figure, one can see that switching occurs at \( \sim 10 \) V of applied voltage, with the crossing reflectivity at \( \sim 47\% \). Also, one can observe that the reflectivity variation from 10\% to 50\% for either wavelength is more sensitive to voltage change, implying a possible saturation effect in the reflectivity variation when it approaches the value of the unperturbed grating.

Figure 2 shows the transmission spectra when the applied voltages were 10 and 15 V. One can see that, because of microbending loss, transverse vibration resulted in global reduction of the transmission spectral intensity. However, the relative levels at \( \lambda_B \) and \( \lambda_S \) were not significantly changed. The results shown in Fig. 4 can be used for add–drop operations in wavelength-division multiplexed fiber communications. The maximum switching speed is of the order of tens of kilohertz. It depends on the acoustic speed and the distance between the acoustic source and the grating.\(^9\)

The observed phenomena can be interpreted by reference to Fig. 5, in which couplings between various core and cladding modes with their phase-matching mechanisms are shown. For the signal \( \lambda_B \), forward-propagating core mode \( \beta_{01}^s(\lambda_B) \) is coupled with backward-propagating core mode \( \beta_{01}^b(\lambda_B) \) through grating phase matching. When the acoustic wave is applied, forward-propagating (backward-propagating) core mode \( \beta_{01}^s(\lambda_B) [\beta_{01}^b(\lambda_B)] \) is coupled with forward-propagating (backward-propagating) cladding mode \( \beta_{1m}^s(\lambda_B) [\beta_{1m}^b(\lambda_B)] \) through microbending phase matching. Although part of the signal power at this wavelength can be coupled back to the core modes after it is coupled into the cladding modes, most of it radiates through the propagation of cladding modes. Such a coupling process in either propagation direction leads to the reduction of reflectivity at this wavelength. On the other hand, without acoustic waves, for the signal at \( \lambda_S \), grating phase matching results in coupling between forward-propagating core mode \( \beta_{01}^s(\lambda_S) \) and backward-propagating cladding mode \( \beta_{1m}^b(\lambda_S) \). When microbending is produced, the coupling between backward-propagating cladding mode \( \beta_{1m}^s(\lambda_S) \) and backward-propagating core mode \( \beta_{01}^b(\lambda_S) \) is phase matched. Hence the outcoupled power at this wavelength can be coupled back into the core mode and reflectivity can be observed. This reflectivity increases with increasing microbending effect or strength of the applied acoustic wave. The couplings between copropagating core and cladding

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**Fig. 2.** Transmission spectra of the fiber Bragg grating for three applied voltages (rms values). The dips at 1541.5 and 1539.7 nm correspond to the Bragg wavelength and the strongest cladding-mode coupling wavelength, respectively.

**Fig. 3.** Variation of reflection spectrum of the device when the voltages applied to the PZT is (a) 0, (b) 1.8, (c) 10, (d) 15 V.

**Fig. 4.** Variation of reflectivity at the two wavelengths, \( \lambda_B \) and \( \lambda_S \), as functions of applied voltage. The results show switching behavior.
modes at both $\lambda_B$ and $\lambda_S$ can be phase matched by the acoustics-induced microbending because its phase-matching bandwidth is larger than a Bragg window.$^8$

In summary, we have implemented coupling between the core and cladding modes near a fiber Bragg grating by acoustically generating microbending of the fiber. The microbending phase matching together with the grating phase matching resulted in a reflectivity decrease at the Bragg wavelength and an increase at the cladding-mode coupling wavelengths. The decrease and increase are determined by the acoustic intensity. The cladding-mode coupling wavelength can be controlled by the etched cladding diameter and the acoustic frequency. Such reflectivity switching behaviors can be used for wavelength-division multiplexed add–drop operations. Finally, the length and diameter of the etched section and its relative position with respect to the Bragg grating will be appropriately designed for optimized operation of the device.$^{10}$ Meanwhile, the tilted angle may play an important role in optimizing the device operation.$^{11}$

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