All-fiber acousto-optic tunable notch filter with electronically controllable spectral profile

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We demonstrate a novel all-fiber acousto-optic tunable notch filter based on coupling to cladding modes in a single-mode fiber. The device has the advantage of low loss (<0.1 dB) and low polarization dependence. By coupling input light to multiple cladding modes by use of multiple acoustic waves, we achieved an electronically controllable variable spectral profile without a significant coherent cross-talk problem. © 1997 Optical Society of America

The wavelength-dependent gain profile of erbium-doped fibers (EDF's) limits the usable bandwidth of wavelength-division-multiplexed (WDM) optical transmission systems, and the gain flattening of erbium-doped fiber amplifiers (EDFA's) is essential for increasing the number of the WDM transmission channels.[1] There have been significant efforts to obtain gain-flattened EDFA's, and one approach is to make EDF's with inherently wider gain bandwidth by controlling the glass host and (or) the codoping material.[2,3] A hybrid EDF configuration that consists of two or more EDF's having different gain spectra is another approach to good gain flatness.[4] The use of gain-equalizing passive optical filters such as long-period gratings[5,6] is also gaining popularity because of their simplicity.

However, passive components for gain control cannot cope with the often encountered dynamic gain variations owing to varying input optical power in individual WDM channels. Although dynamic equalization of spectral gain in EDFA's and WDM signal power has been demonstrated by use of a $LiNbO_3$ integrated acousto-optic tunable filter (AOTF), this approach has serious limitations because of a coherent cross-talk problem and excessive insertion loss.[7–9]

In this Letter we demonstrate a novel all-fiber AOTF with an electronically controllable spectral profile that can be used for dynamic control of spectral gain in EDFA's. The AOTF is based on the acousto-optic coupling of light from the input fundamental mode to cladding modes and has the advantages of low insertion loss, negligible backreflection, and low polarization dependence. The device is free from the detrimental coherent cross-talk problems,[8,9] making it a practical AOTF.

Figure 1 shows a schematic of the all-fiber AOTF. A flexural acoustic wave generated by a coaxial acoustic transducer[10] propagates along a bare section of a conventional single-mode fiber. The acoustic wave creates antisymmetric microbends that travel along the fiber, introducing a periodic refractive-index perturbation along the fiber. The perturbation produces coupling of an input symmetric fundamental mode to an antisymmetric cladding mode when the phase-matching condition is satisfied in that the acoustic wavelength is the same as the beat length between the two modes.[11] The coupled light in the cladding mode is attenuated in the polymer jacket of the lead fiber. For a given acoustic frequency, the coupling between the fundamental mode and one of the cladding modes takes place for a particular optical wavelength, because the beat length has considerable wavelength dispersion. Therefore the device can be operated as an optical notch filter, as described for passive long-period gratings.[5] In the active AOTF described here, the center wavelength and the rejection efficiency are tunable by adjustment of the frequency and the voltage of rf signal applied to the acoustic transducer, respectively.

Figure 2(a) shows the typical transmission spectrum of an AOTF with a 15.5-cm-long interaction length for a broadband unpolarized input light from a LED. We used a conventional communication fiber with a nominal core diameter of 8.5 μm, a cladding diameter of 125 μm, and a normalized index difference of 0.37%. The frequency of the applied rf signal was 2.33 MHz, and the corresponding acoustic wavelength was estimated to be ~ 650 μm.[12] The three notches shown in Fig. 2(a) are from the coupling to three different cladding modes with the same beat length at the corresponding wavelengths. The coupled cladding modes were the $LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$ modes, which was confirmed from far-field radiation patterns. We could tune the center of each coupling wavelength over >100 nm by tuning the acoustic frequency. Figure 2(b) shows the measured and the calculated center wavelengths of the notches as a function of acoustic frequency. The fiber parameters used in the calculation for best fit with the experimental results are a core diameter of 8.82 μm, a cladding diameter of 125 μm, and a normalized index difference of 0.324%, in reasonable agreement with the experimental fiber parameters. The re-

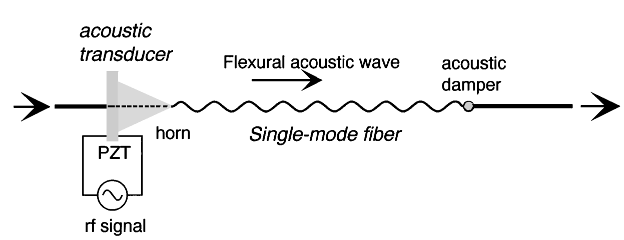

Fig. 1. Schematic of a novel all-fiber acousto-optic tunable filter. PZT, piezoelectric transducer.

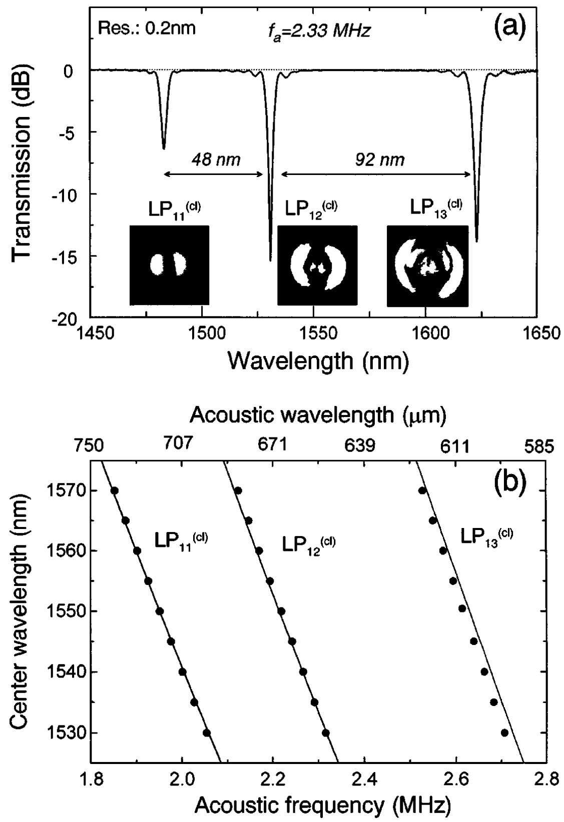

Fig. 2. (a) Transmission spectrum for a unpolarized broadband source, showing coupling to three different cladding modes [$LP_{11}^{(cl)}$, $LP_{12}^{(cl)}$, and $LP_{13}^{(cl)}$] at an acoustic frequency of 2.33 MHz. Insets, far-field radiation patterns of the cladding modes. (b) Measured (•) and calculated (—) center wavelengths of notches as a function of acoustic frequency for couplings to three different cladding modes. Res., resolution.

lationship between the center wavelength and the acoustic frequency was almost linear in the wavelength range of 1500–1600 nm, and the proportionality constants were −0.199 nm/kHz, −0.208 nm/kHz, and −0.223 nm/kHz for coupling to the $LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$ modes, respectively. The filter exhibited very low background loss of less than 0.1 dB. The maximum rejection efficiency for the unpolarized source was ∼−25 dB and was limited mainly by polarization splitting, and the 3-dB bandwidth was ∼3.7 nm.

We investigated the polarization dependence of the filter with a polarized source (a distributed-feedback laser diode, $\lambda = 1.530$ nm). Figure 3 shows the experimental results of transmission as a function of the acoustic frequency. The separation of the phase-matching frequencies for two orthogonal input polarization states was ∼700 Hz, which implies that the splitting in the center wavelengths of notches would be ∼0.15 nm when the filter operates at a given acoustic frequency. The maximum rejection efficiency reached as much as −34 dB. We attributed the splitting mainly to the birefringence induced by thermal residual stress in the core/cladding boundary of the fiber.[13] However, we note that it is negligible compared with that of AOTF's based on $LiNbO_3$ (Ref. 7) or tapered fiber.[14]

One of the important potential advantages of AOTF's over other types of tunable filter is that various spectral profiles can be produced by multiple acoustic waves. However, in the case of conventional AOTF's built with $LiNbO_3$ waveguides or two-mode fibers that use only two polarization or spatial modes, a significant amount of coherent cross talk limits the use of the device in WDM systems.[8] The origin of the coherent cross talk comes from the fact that the frequencies of multiple acoustic waves are closely spaced to control the filter profile over the optical bandwidth of EDF's. In this case the light coupled by one acoustic wave can be coupled back to the input mode by another acoustic wave at a different acoustic frequency, resulting in a net frequency shift in the recoupled light that in turn interferes with uncoupled input light to produce coherent cross talk.[8,9]

On the contrary, the AOTF demonstrated here is free from significant cross talk because multiple cladding modes are used for the coupling of different wavelength components. As can be seen in Fig. 2, coupling light of a given wavelength from the fundamental mode to different cladding modes requires acoustic frequencies that are separated from each other by a few hundred kilohertz. This separation is large enough to provide a wide wavelength-tuning range of almost 50 nm for each coupling mode pair without significant overlap with each other, thereby practically eliminating the coherent cross talk that is present in conventional counterparts. The tuning range is sufficient to cover the bandwidth of typical EDFA's. Therefore the AOTF can be considered a combination of independent tunable notch filters built into one device, and the number of involved cladding modes corresponds to the number of filters. The multifrequency acoustic signals can be generated by a single transducer, and the spectral profile of the filter is determined by the frequencies and amplitudes of the multiple acoustic signals.

To compare the behavior of coherent cross talk in our AOTF operating with multiple cladding modes with that in the conventional filter, we performed the following experiments. As an attempt to simulate a conventional two-mode approach, we applied two rf

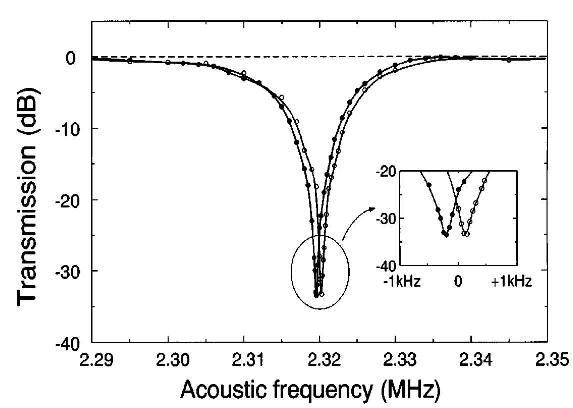

Fig. 3. Measured transmission for two eigenpolarization states of input light at $\lambda = 1530$ nm as a function of acoustic frequency.

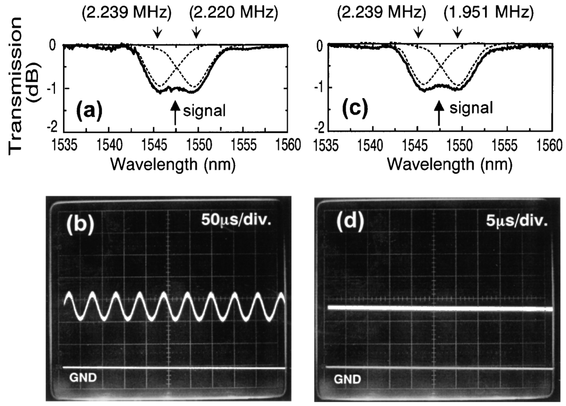

Fig. 4. Performance comparison of the conventional method using only two modes [(a) filter profile and (b) output signal] with our novel multifrequency operation using multiple modes [(c) filter profile and (d) output signal]. GND, electrical ground.

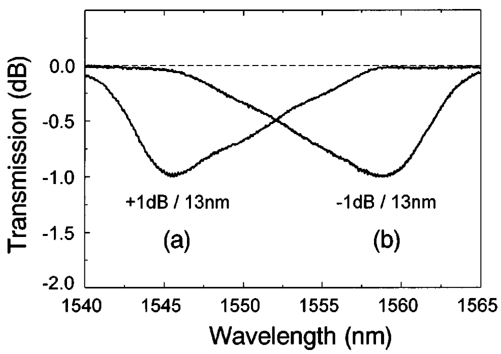

Fig. 5. Variable spectral profile of the AOTF: two examples are demonstrated with different spectral tilt coefficients.

frequencies of 2.239 and 2.220 MHz, both of which provided coupling between the fundamental and the $LP_{12}^{(cl)}$ mode, and the centers of the notches were at 1545.5 nm and 1549.5 nm, respectively. Figure 4(a) shows the transmission spectrum observed by an optical spectrum analyzer. We measured the output signal intensity with a narrow-line input source (a distributed-feedback laser diode; $\lambda = 1547.4$ nm). The photodetector output signal as a function of time exhibited a large beating at 19 kHz, as shown in Fig. 4(b), and the power ratio of ac to dc level of the output electric signal was -17 dB. Figure 4(b) clearly shows the coherent cross talk that prohibits the successful application of the device. In the second experiment the signal at 2.220 MHz was replaced with one at 1.951 MHz, which provided coupling to the cladding $LP_{11}^{(cl)}$ mode at the probe wavelength of 1547.4 nm. Figures 4(c) and 4(d) show the spectral profiles of the filter and the photodetector output signal for a narrow-band source, respectively. The measured ratio of ac to dc electrical power was reduced to ~ -46 dB, and the overall spectral profile remained essentially the same as the one in Fig. 4(a). We think that the cross-talk level of -46 dB came from the slowly decaying sinc function-type sidelobe.

Figure 5 shows two examples of the configurable spectral profiles with spectral tilt, which can be used to recover the gain flatness in an EDFA with a gain tilt caused by signal saturation. In this experiment we used three cladding modes [$LP_{11}^{(cl)}$, $LP_{12}^{(cl)}$, and $LP_{13}^{(cl)}$] and therefore simultaneously applied three rf signals with different voltages and frequencies adjusted for the particular profile. The 3-dB bandwidth of the individual notch was ~6 nm with a 10-cm-long interaction length. As another example, we used the device for spectral control of a broadband amplified spontaneous emission source from an EDFA. The amplified spontaneous emission spectrum could be actively stabilized against the effect of pump power change to confine the spectral power fluctuation from 2 to <0.3 dB over a wavelength range of 14 nm.

In conclusion, we have demonstrated an all-fiber acousto-optic tunable filter that has an electronically controllable spectral profile. The detrimental coherent cross-talk problem has been eliminated. The low-loss polarization-insensitive device can be used for adaptive gain equalization of EDFA in WDM optical communication systems. Although the demonstration was performed with three acoustic frequencies, one can use more frequencies for finer spectral control. Since the loss is negligible, one can also cascade several AOTF's without much difficulty and achieve great flexibility of device performance.

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