All-Fiber Acousto-Optic Filters and Modulators

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Abstract: The principles and implementation of all-fiber acousto-optic devices are presented including frequency shifter, tunable filter, modal coupler, polarization coupler and intensity modulator. Potential applications to optical communications and sensors including space division multiplexing will be discussed.  
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1. Introduction

Optical fibers made with silica glass are almost ideal optical transmission media with their low loss and high stability against external perturbations. This property also makes it difficult to realize optical modulators and therefore, other active components made with different material have to be spliced to optical fibers for active control of light in the fiber. This leads to excess losses and added complexity in fiber optic circuits. On the other hand, it is well known that the silica glass is low loss acoustic medium and acousto-optic effect is an efficient means for light modulation in the medium. An all-fiber acousto-optic modulator introduced a few decades ago [1], uses the optical fiber as an acoustic waveguide with high acoustic energy confinement leading to an efficient modulator. The co-linear device keeps the optical signal inside the fiber and the insertion loss is essentially zero. Therefore several modulators can be easily cascaded without introducing optical loss making it possible flexible designs of optical functionalities. Both flexural and torsional acoustic waves have been utilized for the devices. The all-fiber acousto-optic modulator was first demonstrated as a frequency shifter built with a two-mode fiber. Thereafter many different device forms have been demonstrated including tunable filters [2], dynamic gain flattening filter for fiber amplifiers [3], mode control [4,5], polarization switches [6], heterodyne interferometer [7], wavelength selective optical switches [8] etc. Utilizing many unique fiber properties, interesting functions could be achieved that are otherwise could not be easily realized. In this presentation, operating principles of basic acousto-optic modulators will be described along with many variations of devices for interesting functionalities including some of the recent research results.

2. Operating Principles

The basic structure of the all-fiber acousto-optic modulator is shown in Figure 1. Acoustic wave, either flexural or torsional, is generated by an acoustic transducer that is attached to the bottom of a horn structure that launches the acoustic wave onto a fiber bonded to the horn. The co-linear configuration where a bare section of the fiber passes through the horn at the center makes the device mechanically solid. For a flexural wave, the piezoelectric transducer with a hole in its center is operating in shear mode. For torsional wave, two pieces of shear transducers are driven with 180 degrees phase difference. The bare section of fiber, typically a few tens of centimeters guides both acoustic wave and optical wave both without measurable loss. The acoustic wave is terminated by the polymer coating on the fiber at the end of the bare fiber section. The acoustic amplitude of the flexural wave is typically tens of nanometers. For the typical diameter of optical fibers and the acoustic wavelengths of our interest which is greater than the fiber diameter, the only acoustic waves that can propagate along the fiber are the fundamental modes of flexural, torsional and longitudinal modes. For the conventional optical fibers, the longitudinal acoustic wave does not produce efficient acousto-optic mode coupling and will not be discussed.
An acoustic flexural wave creates traveling microbends with the period of its acoustic wavelength as depicted in Figure 1-a. The velocity of light propagating in the fiber is much faster than that of the acoustic wave and the optical wave practically experiences almost static periodic perturbation points that can couple symmetric guided optical modes to anti-symmetric ones. For example, it can efficiently couple the \( \text{LP}_{01} \) mode of the fiber to \( \text{LP}_{11} \) mode in the core (for a two mode fiber) or in the cladding (for a single mode fiber). Because the coupling is periodic, only the wavelength components that satisfy the phase matching condition can be efficiently coupled. In other words, inter-modal coupling takes place at the wavelength where the modal beatlength is the same as the acoustic wavelength. One thing to note is that the coupled optical signal experiences frequency shift by the amount of acoustic frequency. The sign of the frequency shift is determined by the relative propagation direction of acoustic and optical waves as well as the starting and ending optical modes in the fiber. If the coupled wave is tapped for further use, it becomes a bandpass filter or a frequency shifter. If the uncoupled wave is utilized, the device is operated as a notch filter. In both cases, the center wavelength of the filter is tunable by adjusting the acoustic frequency.

For the flexural wave, the acoustic wave creates a traveling periodic twist action that couples between two orthogonal linear polarization modes in a birefringent optical fiber. As in the case of the flexural wave, the periodic nature of the coupling points produces an efficient coupling only at the wavelength that has the same polarization beatlength as the acoustic wavelength. If one selects the coupled polarization using a polarizer at the output, the device functions as a bandpass filter. If the uncoupled component is used, the device becomes a notch filter as in the case of the flexural wave device. One interesting feature of the torsional wave operation is that the torsional acoustic wave is insensitive to mechanical perturbations such as contact with other structure and also to fiber bend. It makes it possible to realize a compact packaging of the device. Also the acoustic velocity of the flexural wave is independent of the fiber diameter that makes it possible to modify fiber outer geometry within the acousto-optic interaction region to incorporate other functions.

3. Applications

Many applications of the all-fiber acousto-optic modulator have been demonstrated. A few of the examples will be discussed here. Figure 2 show the schematic of a frequency shifter. Two mode fiber along with a mode selective coupler and flexural acoustic wave was used to produce frequency shift of a few megahertz. Figure 3 shows the performance of a tunable notch filter built with a conventional single mode fiber that uses coupling between the core mode and cladding modes that will be eliminated. Several of the tunable notch filter can be configure to produce arbitrary filter shape that had been used as dynamic gain flattening filter for fiber optic amplifiers. Figure 4 shows a structure of a reconfigurable optical add/drop multiplexer built with wavelength selective optical switches. Several other applications will also be discussed in the presentation.
Figure 3. Mode coupling and wavelength tunings properties of acousto-optic tunable filter (AOTF) using single mode fiber.

Figure 4. Schematic of a reconfigurable optical add/drop multiplexer built with two acousto-optic tunable filters (AOTF) and mode selective couplers (MSC) a using two mode optical fiber.

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4. References


