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Acoustics in Optical Fiber

Abhilash Mandloi and Vivekanand Mishra

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1. Introduction

Optical filters are the heart of optical networks; without the wavelength selective device wavelength division multiplexing and dense wavelength division multiplexing network will not exist. As the networks are progressing towards closer wavelength spacing, performance requirement for filters are becoming more demanding. Currently, the popular filters include gratings, thin-film filters, and Fabry-Perot filters and acousto-optic tunable filters (AOTFs).

Acousto-optic (AO) effect in fibers has been studied to produce tunable filters, gain flatteners, modulators, frequency shifters, and optical switches reported. Most AO devices work on coupling from the fundamental mode (LP_{11}) of light to a higher order asymmetrical (LP_{11} , LP_{12} LP_{1n}) modes. Acousto-optics is defined as the discipline devoted to the interactions between the acoustic waves and the light waves in a material medium. Acoustic (vibrational) waves can be made to modulate, deflect and focus light waves by causing a variation in the refractive index. Acousto-optic tunable filters are a promising technology for dynamic gain equalization of optical fiber amplifiers [1]. By launching an acoustic wave directly on the fiber, the device combines the merits of fiber and AOTF devices namely the low insertion loss, low polarization dependence loss, wide tunability, fast tuning speed and ease of packaging. When a flexural acoustic wave is applied to a tapered single mode fiber, coupling takes place between the core mode and the cladding mode. The coupled energy in the cladding mode is essentially absorbed by the fiber jacket as reported so that the device is a notch filter. It means the centre frequency and the rejection efficiency can be tuned by adjustment of the frequency and voltage being applied. Varying the amplitudes and frequency of a RF generator can change the spectral profile of these filters.

To improve the rejection efficiency of the filters, the thickness of the fiber can be reduced. This is achieved through the heating and the acid-etching method. In the heating method, the ratio of cladding to core size is maintained while in the acid etching-method, the ratio between the cladding and core can be changed.

2. Acousto-optic tunable filter

2.1. Device design

The fiber used in our experiment is a Corning SMF-28, standard telecommunication single mode fiber. A region of SMF is etched by dipping the fiber in a hydrofluoric acid solution, which has a concentration of 40%. Etching rate controls the thickness of the SMF and the diameter reduction is observed using a CCD camera.

When the optical signal enters the fiber and interacts with the acoustic energy in a jacket stripped segment of the fiber, the core mode of the light is converted to a higher order cladding mode producing a notch filter like characteristics in the transmission spectrum. Core mode converting to various cladding modes will produce a few notch filters, with each having its peak notch at a separate wavelength [2-4]. A vibrating PZT transducer driven by a RF generator produces the acoustic energy as stated by Yun, Hwang and Kim, (1996). The acoustic energy is further amplified and concentrated to the fiber by a machined aluminium horn.

Figure 1. The setup to study AO interaction inside a fiber.

2.2. Horn design

An acoustic horn functions to transfer and amplify the surface acoustic wave to the fiber. All horns made were conical in shape, where the tip is narrow and the base is broad as described by Lee, Kim Hwang and Yun, (2003). All the horns fabricated for the AOTF experiment have a ratio of length to outer diameter ratio of 2. Length is defined as the length from the tip of the horn to the base of the horn. Horns taken are 1cm in length. Outer diameter of the horn is defined at the diameter at the base. The inside of the horns are made hollow. When the horn is made considerably small, the frequency dependence on the acoustic generator is low. In the experiments done, no transduction is observed when the fiber is not etched. Potential problems can be attributed to the size of the transducer and the adhesive used to bond the tip of the horn to the fiber. Solder acts as a strong, metallic, thermally stable, and acoustically transmitting joint. In these experiments however glue was chosen as the bonding agent. Of particular interest will be the horn tip size. Acoustic impedance at the horn tip is given by:

$$Z_r = c_a v_a A_r \quad (1)$$

where c_a is the longitudinal velocity inside aluminium, v_a is the density aluminium and A_r is the cross section of the horn tip. Acoustic impedance at the bond junction along the fiber is given by:

$$Z_s = 2c_s v_s A_s \quad (2)$$

where c_s is the longitudinal velocity inside silica, v_s is the density silica and A_s is the cross section of fiber. Acoustic impedance inside the fiber is counted twice because of bidirectional acoustic movement along the fiber. Optimum transduction occurs when $Z_r = Z_s$ and since acoustic impedance of silica is almost matching that of aluminium, according to engan et. al maximum acoustic wave transfer occurs when horn tip diameter is almost matching that of the fiber.

2.3. Tuning of peak wavelength

By driving a piezoelectric (PZT) device at an ultrasonic frequency the periodic perturbations can be created inside the fiber. In a phase-matched condition, where the momentum and energy conservation requirement ($L_B = \Lambda$) are met, the resonant frequency of an acoustic wave according to Birks, Russel and Culverhouse (1992) is given by

$$f = \frac{\pi b C_{ext}}{L_B^2} = \frac{\pi b C_{ext}}{\Lambda^2} \quad (3)$$

where b is the radius of the fiber, C_{ext} is the speed of fundamental acoustic mode, which for silica is 5760 ms^{-1} , Λ is the period of the microbend¹.

Assuming a phase-matched condition, the frequency needed to transfer the modes from core to cladding mode for various thickness of the fiber is given in Fig 2 and Fig 3. As the fiber diameter is reduced, the values of $df/d\lambda$ get smaller. For unetched fibres, the frequencies used to create the micro bends and thus, convert the modes are from 1.75 MHz to 2.25 MHz. For thin diameter fibers (20 μm , 30 μm , 40 μm), the frequencies are from 800 kHz to 1.1 MHz.

Figure 2. Calculated RF frequency to convert the LP01 mode to LP11 mode plotted against wavelength (for various thickness of fibre diameter).

¹ A microbend is the physical deformation of fiber achieved mechanically or chemically done to perturbing the optical modes to study mode coupling between core and cladding mode.

Figure 3. Calculated RF frequency to convert the LP0l mode to LP12 mode plotted against wavelength (for various thickness of fibre diameter).

Frequency from the RF generator can be used to control the peak wavelength tuning of the notch filters (Fig.4). The fiber used in the experiment has a diameter of 30 μm , and length of 17 cm. Higher frequencies of the RF generator will blue shift the peak wavelength of the filter [3-7]. The tuning range of the filter is slightly less than 300 nm. From Eq.1.3, we deduce that, micro bend's period is inversely proportional to the frequency of the RF generator. For a larger value of period, the filter's peak is red shifted. Thin fibers have lower period values, thus etching the fibres will blue shift the peak wavelength of the notch filters. Frequency used to tune the peak wavelength as in for thin fibres is from 800 kHz to 1.1 MHz, which is in excellent agreement with the theory as in Fig.3 and Fig.4.

Figure 4. Measured peak wavelength tuning of the filter by changing the RF frequency. Frequency used is from 970 kHz to 1045 kHz. The fiber used has a thickness of 30 μm and length of 17 cm.

a)

b)

c)

Figure 13. The effect of moving the tuneable acoustic absorber on the Amplified Stimulated Emission spectrum at various gain levels: a) low gain single peak at 1560 nm b) and c) high gain two peaks at 1532 nm and 1550 nm.

Fig. 14 shows the flattened gain of ASE spectrum at various gain levels using this technique. For the lowest gain, at -30 dBm, which is achieved with a pump power of 96 mA, a broad filter is needed at 1545 nm; to obtain this; the tuneable acoustic absorber is positioned 14 cm after the AOTF device. The required resonant frequency to produce the coupling will be 990 kHz. A deeper notch is needed at 1532 nm; which is produced through the second frequency generator that is set at 993 kHz. The flattened gain is less than 0.8 dB. For gain at -25 dBm, which is achieved with a pump power of 150 mA, a filter is needed at 1556 nm; and a narrow deep notch is needed at 1532 nm; the required resonant frequency to produce the coupling respectively will be 986 kHz and 993 kHz. To obtain this, the tuneable acoustic absorber is positioned 16 cm after the AOTF device. The flattened gain is less than 0.9 dB.

Similarly for gain at -22 dBm, which is achieved with a pump power of 220 mA, a very deep filter is needed at 1532 nm and a small filter at 1545 nm. The resonant frequencies corresponding to these wavelengths are 990 kHz and 993 kHz respectively. To obtain the narrow filter, the tuneable acoustic absorber was set 17 cm after the AOTF device. And the measured flattened gain is less than 0.9 dB. Fig. 5 represents the notch filters obtained to flatten the gain of the Amplified Stimulated Emission (ASE) spectrum.

a)

b)

c)

Figure 14. Gain profiles of the ASE spectrum and the flattened gain at various pump powers: a) 96 mA which has a gain of -30 dBm b) 150 mA which has a gain of -25 dBm and c) 220 mA which has a gain of -22 dBm.

Figure 15. Corresponding filter spectrum to the flattened gain of various gain levels in Fig. 16.

7. Conclusion

The presence of acoustics inside the fiber will create a sequence of bends periodic in nature along the direction of its propagation. Core mode's energy is transferred to a cladding mode's, when it passes through the sequence of bends. The fiber jacket absorbs the coupled energy and this produces a notch filter observed using an optical spectrum analyzer.

Acoustic horn functions to transfer the acoustic wave of the transducer to the fiber. Aluminium horn is preferred over silica horn because it can be easily reproduced. Furthermore, its acoustic impedance almost matches that of silica's. To allow optimum transmission of acoustics to the fiber, the tip of the horn is made small, with its diameter matching that of silica's.

No resonance peaks were observed when the fiber is unetched. First peaks are observed when the thickness of fiber is approximately $40\text{ }\mu\text{m}$. Overlap integral between the modes is not high in thicker fiber, meaning the transfer of acoustic wave to the fiber is not optimized. Thickness reductions in fibers are observed using a CCD camera. The characteristics of the resonance peaks can be controlled electrically using a RF generator. Voltage of the generator can be used to tune the attenuation depth of the resonance peaks. Frequency of the generator can be used to tune the peak wavelength. Frequency is inversely related to period of bends, thus higher frequencies will shift the peak to lower wavelengths. The 3-dB bandwidth of the resonance peaks can be adjusted by limiting the acoustic bend produced inside the fiber. Introducing a tunable acoustic absorber along the fiber can do this. Frequency used in all experiments was from 800 kHz to 1.1 MHz. All the coupled energy to produce the resonance peaks were to LP₁₁ modes, mode conversion observed using a beam profiler.

The power fed to cause resonance peaks can be reduced by reducing the thickness of the fiber to a value close to $20\ \mu\text{m}$. Allowing light to pass through the acoustic bend region twice, as proposed in the double pass configuration, can increase the attenuation peaks. However, a frequency shift of 13 nm is observed because the light is passing through the bend in opposite directions.

As a spectral shaping tool, the attenuator is efficient as a gain flattening filter for an erbium doped amplifier. The peak of an amplified spontaneous emission at 1531 nm can be reduced to flat levels for various gains of the EDF A pump power. Insertion loss is less than 0.2 dB and polarization dependence loss is less than 0.4 dB.

Author details

Abhilash Mandloi and Vivekanand Mishra
*Department of Electronics Engineering, S.V. National
 Institute of Technology, Surat 395007, Gujarat, India*

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