ACOUSTO-OPTIC EFFECT IN OPTICAL FIBRE TAPERED STRUCTURES FOR THE DESIGN OF FILTERS

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ABSTRACT

Acousto-optic all-fibre filters are a promising technology for dynamic gain equalisation of optical fibre amplifiers. In this paper we show that a controlled tapering of optical fibres can be regarded as a new degree of freedom for the design of acousto-optic filters. In particular, we investigate the coupling between the fundamental and several cladding modes, studying the evolution of the resonance conditions as the fibres are progressively tapered. Theoretical predictions are in agreement with experimental results for several tapered fibres.

The application of this acousto-optic filter for gain equalisation of optical fibre amplifiers is demonstrated. The design consists of two cascaded multi-tapered fibre lengths driven by only one acoustic frequency. The spectral characteristics are determined by the taper profile. The amplified spontaneous emission of an erbium doped fibre amplifier is flattened to within 1dB over a spectral range of 30nm for different saturation levels of the amplifier. This method results in a simplified implementation of the acousto-optic filter in contrast to other multi-frequency design approaches. Optimum filter designs can be achieved by the combination of both degrees of freedom: taper control and multi-frequency tuning.

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Introduction

The acousto-optic effect in optical fibres has been used in a wide number of applications ranging from optical switches and modulators to tunable filters, frequency shifters and equalisers. These devices rely on the selective coupling among the propagation modes of an optical fibre induced by an acoustic wave. Recently, AO filters that couple light from the fundamental guided mode (LP_{01}) of a single mode optical fibre to several low order cladding modes (LP_{11}, LP_{12}, LP_{13}) through an acoustic flexural wave have been reported [1,2]. As the loss spectrum of these filters can be dynamically controlled, they are suitable for flattening the gain profile of optical fibre amplifiers. The major advantage offered by AO filters with respect to their static counterparts, i.e. long-period gratings [3], is that gain saturation effects caused by power fluctuations of the input signal can be equalised. In order to achieve tunability, these AO filters exploit the dependence that the resonance wavelength has on the frequency of the acoustic wave. Filters with complex loss spectrum have been synthesised by driving the acoustic transducer with several radio frequency (RF) tones of different amplitudes and frequencies. In this paper we investigate the effects that a controlled tapering of the optical fibre has on the coupling between the fundamental and the low order cladding modes of the AO filter previously described. It is recognised that the control of the radius profile along a nonuniformly tapered fibre can be regarded as a new degree of freedom to tailor the spectral characteristics of the filter. One potential advantage of this approach is that the need of several RF synthesisers to drive the acoustic transducer could be avoided, simplifying the implementation of the AO filter.

Principle of operation of the Acousto-Optic filter

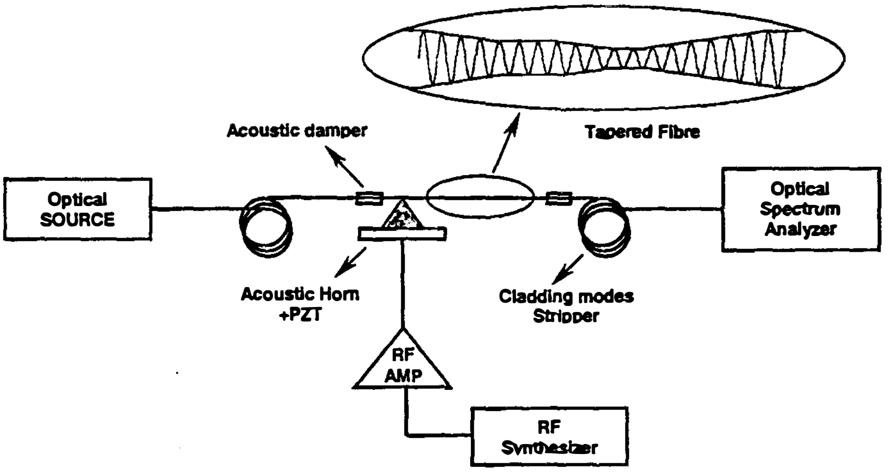

Figure 1 – Principle of operation of the AO filter

The principle of operation of our AO filter is described in Figure 1. A single mode optical fibre is tapered along a certain length to modify its acoustic and optical properties. A flexural acoustic wave is applied to the optical fibre tapered structure through an acoustic horn. The horn is attached to a piezoelectric element driven by an amplified RF signal. As the acoustic wave travels along the tapered section of the single mode optical fibre, it induces coupling between the optical modes supported by the fibre.

A single mode optical fibre has a finite cladding and therefor supports cladding modes that are not guided in the core. These modes have an effective refractive index that lies between the refractive index of air as lower limit and the refractive index of the cladding as upper limit. In the proposed filter, symmetry considerations indicate that the flexural acoustic wave induces coupling between the fundamental mode (LP_{01}) and several low order odd cladding modes LP_{1m} (m=1,2,3) in the tapered region of the fibre. If the taper transition is smooth enough, the modes will evolve adiabatically, maintaining their identity with insignificant losses along their propagation. The difference in propagation constants between each pair of interacting modes (LP_{01} - LP_{1m}) is expressed by the normalised beatlength $L_m = 2\pi a/(\beta_{01}-\beta_{1m})$, where a is the core radius.

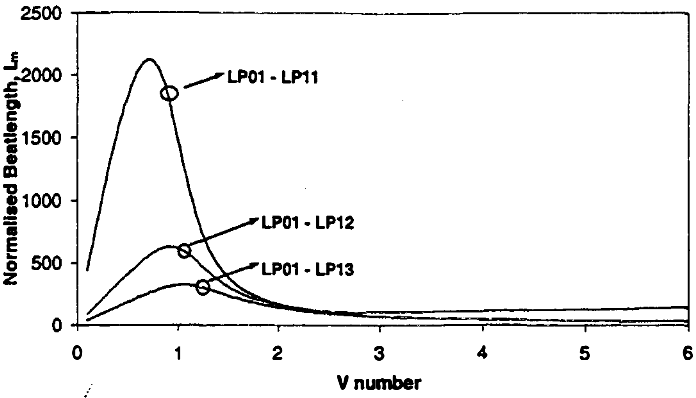

Figure 2 – Dispersion of the effective beatlength L_m as a function of the normalised frequency V.

Figure 2 shows the dispersion of the normalised beatlength L_m for the first three pairs of modes (LP_{11}, LP_{12}, LP_{13}) as a function of the normalised frequency V. The dispersion curves were calculated theoretically with an exact vectorial model. The only assumption in the calculation of the beatlength dispersion is that the ratio between the cladding and core dimensions is 62.5/4.

The AO resonance conditions for effective coupling between two optical modes is obtained by the momentum and energy conservation requirements that can be expressed as:

$$L_m(\lambda_R,b) = \Lambda(b,\Omega) \qquad (1.a)$$
$$\omega_m\text{-}\omega_0 = \pm\Omega \qquad (1.b)$$

Equation (1.a) states that at resonance, the beatlength L_m between two of the optical modes is equal to the acoustic wavelength Λ. Equation (1.b) indicates that the frequency of the cladding mode LP_{1m} is shifted by the acoustic frequency Ω, with respect to the fundamental optical mode LP_{01}. From condition (1.a) the resonance wavelengths (λ_R), were calculated, as a function of the taper radius b for the three AO interactions that we have experimentally detected. The results shown in Figure 3, indicate that the resonance wavelengths are double-branched functions of the taper radius. The short resonance wavelength corresponds to the long V range of beatlengths, where the fundamental mode is well confined to the core. On the other hand, the long resonance wavelength corresponds to the low V range, where the fundamental mode becomes a cladding mode.

The resonance condition is usually tuned by means of the acoustic wave frequency. The effect of tuning the acoustic frequency is opposite for both resonance branches. This behaviour can be observed by Equation (1) and Figure 2. For the short-resonance wavelength branch, an increase of the acoustic frequency gives rise to a decrease of the resonance wavelength. In contrast, the opposite is happening in the long-resonance wavelength.

Experiments

The fibres were tapered using a flame-brush technique [4-6] where a point-like gas burner sweeps back and forth a section of the fibre that is pulled symmetrically from both ends. The fibre used in our experiments was a standard telecommunication single-mode fibre, with a NA of 0.12, a core radius of 4μm, and a cladding radius of 62.5μm.

The tapered fibre is excited by a flexural acoustic wave using an acoustic horn glued to the fibre. The horn has a conical shape in order to concentrate the acoustic power into its apex, where the fibre is glued. A piezoelectric element (PZT) drives the horn by means of an amplified electrical signal with frequency in the 1 - 1.8 MHz range. The electrical power consumption of the fabricated loss filters varies enormously with the taper radius and the length of the devices. The typical power consumption for these devices is of the order of several hundreds of mW for a 30-50μm radius range.

The first experiments aimed to prove the theoretical dispersion relations that relate the resonance wavelength of the AO interaction with the acoustic frequency for several tapered fibre radii and for the three optical modes. A set of fibres was tapered with a uniform waist radius that ranged from 30μm to 50μm. The total waist length was 10cm. The results for the $LP_{01}\leftrightarrow LP_{13}$ and $LP_{01}\leftrightarrow LP_{12}$ interactions can be observed in figures 3(a) and 3(b) respectively. The theoretical fits assume a numerical aperture for the fibre of 0.12, a cladding-core ratio of 62.5/4 and an applied tension of 0.9N.

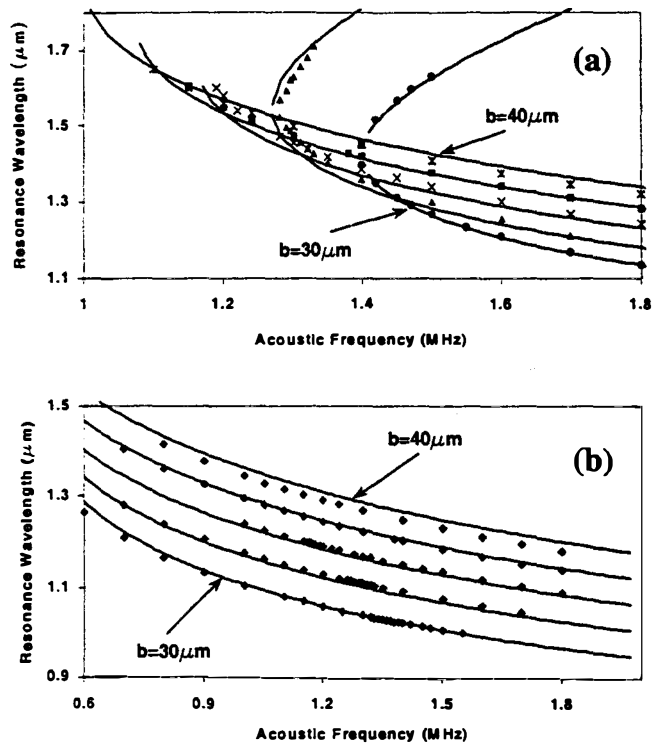

Figure 3 – Dependence of the resonance wavelength with the acoustic wave frequency for different taper radii. The dots refer to experimental values of radius 30, 32.5, 35, 37.5 and 40μm, and the solid curves to the theoretical fittings. (a) $LP_{01} - LP_{13}$ interaction (b) $LP_{01} - LP_{12}$ interaction.

Once the AO interaction was characterised, our objective was to design a dynamic equaliser for the gain profile of an erbium doped fibre amplifier (EDFA). The EDFA gain spectrum extends over a bandwidth of more than 30nm and is characterised by two main amplification lobes centred at 1532nm and 1550nm. In order to compensate gain variations under different saturation conditions, it is convenient to control independently the attenuation in these two spectral regions. Our equaliser consists of two independent AO filters, as shown in Figure 1, which are cascaded and driven by two independent RF synthesisers. Both filters are operated at the same acoustic frequency 1.24MHz and variable power levels, in contrast with other multi-frequency schemes [1,2]. Each of the filters relies only on the $LP_{01}\leftrightarrow LP_{13}$ AO interaction. The first AO filter (AOF#1) is based on a nonuniform taper consisting of three uniform sections. The first section has a length of 10mm and radius of 40.2μm, the second was 20mm long and had a radius of 38.4μm, and the third section was 60mm long and had a radius of 37.2μm. The second AO filter (AOF#2) relies on a two stage taper, with a first section 12mm long and 42μm in radius, and a second section 50mm long with a 41μm radius. The multi-taper designs were adopted to enhance or suppress side-lobes, in order to optimise the filter shape, for the equalisation of the used EDFA. The attenuation spectrum of the designed equaliser for several driving powers is shown in Figure 4.

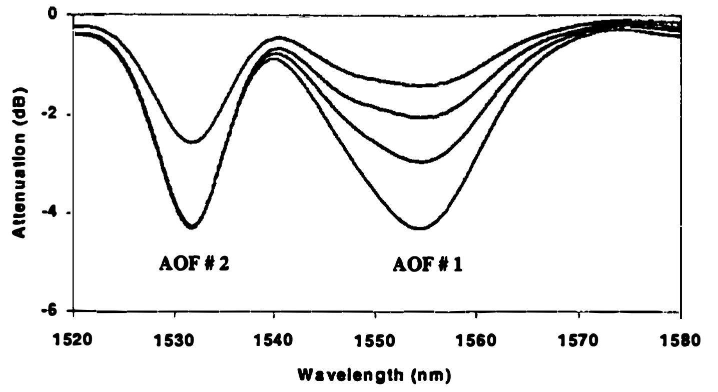

Figure 4 – Characterisation of the two-filter equaliser for different acoustic powers.

The filter was tested by flattening the amplified spontaneous emission (ASE) from an EDFA with aluminium germanosilica as host glass. The filter was placed at the output of the EDFA with an estimated insertion loss of less than 0.5dB. The gain of the EDFA was saturated by an input signal from a DFB laser diode at a wavelength of 1548nm. For several DFB saturation power levels (-26.0dBm, -22.0dBm and -18.4dBm), the ASE was flattened within 1dB in a 30nm bandwidth, as shown in Figure 5. In each case the filter response was re-adjusted by changing the fed acoustic powers.

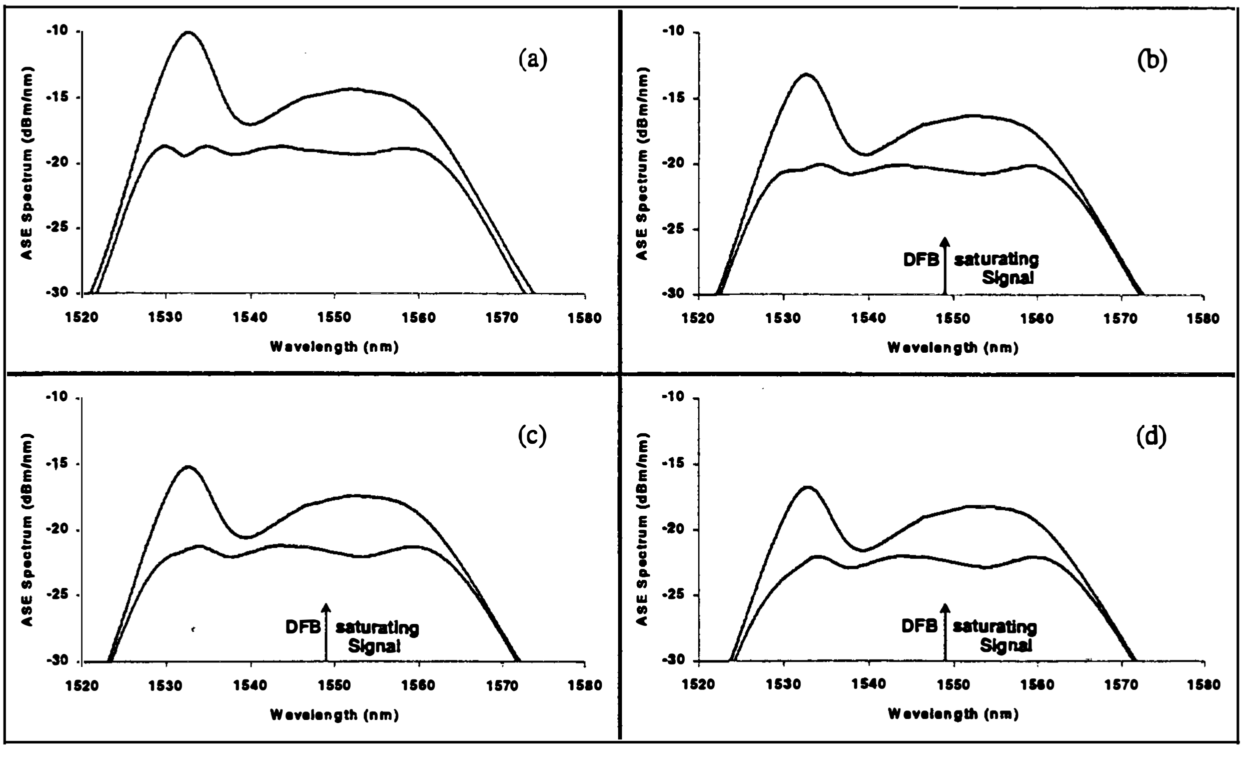

Figure 5 – Flattening of the ASE spectrum of an EDFA (a) No saturation power. (b) Saturation power level of -26.0dBm (c) Saturation power level of -22.0dBm. (d) Saturation power level of -18.4dBm.

Conclusions

In this paper we have demonstrated that the taper profile can be another degree of freedom to tailor the spectral characteristics of an AO filter. The influence of the radius of the taper has been characterised experimentally and theoretically.

The application of this type of filters for dynamic gain control and equalisation of optical amplifiers has been demonstrated. An equaliser consisting of two cascaded AO filters was designed to flatten the gain profile of an EDFA. The equaliser achieved a fluctuation smaller than 1dB for a spectral gain band of 30nm and different saturation conditions. The novelty of the present design with respect to previous approaches is that only one acoustic frequency was used to drive the equaliser, relying on the complex multi-taper profile to spectrally tailor the filter.

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