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In-fibre and fibre-compatible acousto-optic components

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Abstract

Fibre-optic and fibre-compatible versions of some bulk acousto-optic components, together with general design rules are discussed. We illustrate by describing some recent work at the Optoelectronics Research Centre.

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Abstract

Acousto-optics has been shown to be a powerful and versatile means of controlling and modulating laser radiation in bulk components. We discuss the fibre-optic and fibre-compatible versions of components such as the Bragg cell, together with general design rules for such components and illustrate by describing some recent work at the Optoelectronics Research Centre.

1. Introduction

While the technology of passive in-fibre and fibre-compatible components is well advanced, that of active components such as amplitude/phase modulators and frequency shifters is relatively undeveloped. Thus we have commercially available directional couplers and fibre isolators but few fibre-compatible active components of the type referred to above have as yet appeared. The elasto-optic interaction (the dependence of refractive index on strain) is present in all materials to a greater or lesser extent and it provides a natural and general way of building such devices. We discuss general principles and limitations of acousto-optic component design and describe some of the ongoing work and recent results obtained by the acousto-optics group at the Optoelectronics Research Centre. In particular we will discuss the relative merits and desirability of in-fibre as opposed to simply "fibre-compatible" devices and will illustrate by presenting examples. Before this, however, it is worth considering what is meant by a "fibre-compatible" component. We mean a component which is effectively a black box with fibres attached; the box contains the modulator which must be capable of doing its job without excessive back-reflections or insertion loss and must not limit the optical power handling capacity of the system. Of course, depending on the application not all these conditions may need to be applied. If we are considering a fibre-optic phase modulator to be used to mode-lock a fibre laser, because it will be used intra-cavity the absence of back reflections and the power handling capacity are of prime importance. A fibre frequency shifter to be used in a laser Doppler velocimetry (LDV) system may have to handle large CW optical powers, but the same component used to generate a local carrier in an intrinsic fibre sensor will not, and may not require large conversion efficiency either, if the power budget is not a tight one.

It is important to consider the aspects of long-term stability and robustness of the components. For example, early demonstrations[1] of the fibre-optic frequency shifter frequently employed bare fibres in contact with silica and aluminium blocks on which Rayleigh waves were propagating, and such devices were potentially fragile due to the large masses in contact with the fibres and therefore the large forces imparted to the fibres on movement of the device, due to inertia of the blocks. Long term stability was poor due to the requirement for the application of a critical amount of static biasing force on the fibre, and most of the acoustic energy missed the fibre altogether necessitating the use of unrealistically high RF drive powers. Later devices such as the two-mode fibre frequency shifter reported by Kim et al[2] used the freely suspended fibre itself as an acoustic waveguide, concentrating the acoustic power near to the fibre core and raising the conversion efficiency. Acoustic flexure waves travelling along the fibre having a wavelength corresponding to the beatlength between the fundamental and second guided modes caused the appearance of frequency shifted light in the second mode. The four-port fibre frequency shifter reported by Birks et al[3] uses flexure wave propagation along a tapered section of a (null) fibre coupler. The last two devices might first appear to be too fragile to be practicable until one considers the obvious success of the fused fibre-optic coupler. Thin or tapered fibres mean low inertia and hence resistance to shock and vibration; the problem is one of cleanliness and packaging rather than inherent fragility.

2.1 In-fibre versus fibre-compatible devices

The question of whether one should be trying to make an in-fibre acousto-optic component of a given type, as opposed to a fibre-compatible component is an interesting one. As the in-fibre component neatly sidesteps the problems of back reflection and insertion loss, it has an inherent appeal. However, established passive fibre-compatible components such as the Faraday isolator have demonstrated impressive performance with respect to insertion loss and back reflections due to their "monolithic" method of construction and near axial symmetry, which simplifies the task of getting light in and out of the fibre with low loss. The very inertness of silica that makes it suitable for a long distance transmission medium results in its having both a low Verdet constant and poor acousto-optic performance. Diffractive acousto-optic components simply do not work well in silica. The high efficiency fibre frequency shifters of references 2 and 3 work because of mode coupling induced by a geometric (i.e. strain-optic) effect, not because of the elasto-optic effect. The perturbation needed to couple a symmetrical optical mode (01 in the LP mode nomenclature) to an antisymmetric (11) mode must clearly be itself antisymmetric. The antisymmetry is provided by the lengthening and shortening of the optical paths either side of the neutral axis at the bends in response to the passage of the acoustic wave[4], and this should properly be referred to as a strain-optic effect. The elasto-optic effect also contributes by changing the refractive index but interestingly enough it opposes the geometric effect in silica and actually subtracts approximately 22% from the geometrical contribution. Thus flexure-wave frequency shifters in silica fibres work because of the strain-optic effect and in spite of the elasto-optic effect, a situation unparalleled in bulk acousto-optics!

2.2 The influence of the fibre material

In order to see why silica fibres make poor diffractive components, consider equation 1 which shows the efficiency of diffraction into the first order of a plane optical wave by a plane acoustic wave, at the Bragg angle,

$$\frac{I_{diff}}{I_{in}} = \eta = \sin^2\left[\frac{\pi L}{\lambda\sqrt{2}}\sqrt{M_2 I_{ac}}\right] \tag{1}$$

Here L is the length of the interaction region (effectively the length of the acoustic transducer in small angle Bragg scattering which is being considered here), λ is the optical wavelength and I_{ac} is the acoustic intensity. The quantity M_2 is the so-called second acoustic figure of merit[5] which is given in terms of the refractive index n, the relevant Pockels coefficient p, the acoustic velocity v and the density by

$$M_2 = \frac{n^6 p^2}{\rho V^3} \quad . \quad \text{For silica,} \quad M_2 = 1.5\times10^{-15}\, m^2/W \quad .$$

A realistic acoustic intensity in a bulk device would be 10^6 Wm^{-2} (1 W into a transducer 1 mm square) giving an efficiency of only 1.8%. To raise the efficiency to 50% would require an RF drive power of 34 W, which would cause heating problems if nothing else. Certain materials have values of M_2 which are hundreds of times higher than silica. Examples include the low phonon energy glasses currently being developed at the ORC and elsewhere for the 1.3 μm fibre amplifier and for long wavelength fibre lasers having lidar and gas sensing applications. We have tested two of these materials in our acousto-optic devices, a gallium lanthanum sulphide (GLS) glass[6] and a chlorotellurite glass[7], with very encouraging results. There is a definite correlation between low phonon energy and high M_2, and apart from a paper by Pinnow et al[8] little literature exists on the interesting connection between microscopic structure and M_2. There is little doubt, however, that when single mode fibre lasers constructed from these materials become available, in-fibre acousto-optics will be the method of choice for manipulating the radiation they produce.

With silica fibres, diffractive components are best realised in fibre-compatible form. Before discussing this technique, consider the in-fibre phase modulator. Such a component has important applications, for example as a mode-locker for a fibre laser. It works by producing a periodic change in optical path length (OPL) given by $\Delta(OPL) = n^3 pSL/2$ where S is the strain and L is the length of the interaction region. Note that p, S and quantities like n (which is derived from the impermeability tensor) are meant to denote representative values derived from the actual tensor components or linear combinations of tensor components which are selected once the directions of propagation and polarisation have been defined. For an acoustic plane wave, the relation between strain and acoustic intensity is given by the equation $S = (2I_{ac}/\rho V^3)^{½}$. Again we can see that a low density and acoustic velocity are desirable, but because of the square root sign the effect of changing materials is weaker than in the diffractive case. This, coupled with the fact that phase shifts of the order of a radian are easily obtained and are enough to comfortably mode-lock a laser, means that silica in-fibre phase modulators are viable.

3. An in-fibre phase modulator

Figure 1 shows such an in-fibre phase modulator which we manufactured and which uses an aluminium focusing element[9]. An aluminium jacketed single mode fibre was soldered into a "U" groove pressed into a suitably shaped aluminum "quarter cylinder" and lapped flat prior to indium cold-welding a $LiNbO_3$ 80 MHz transducer onto it. A line focus of acoustic energy occurs at the surface of the cylinder, at the position of the fibre core.

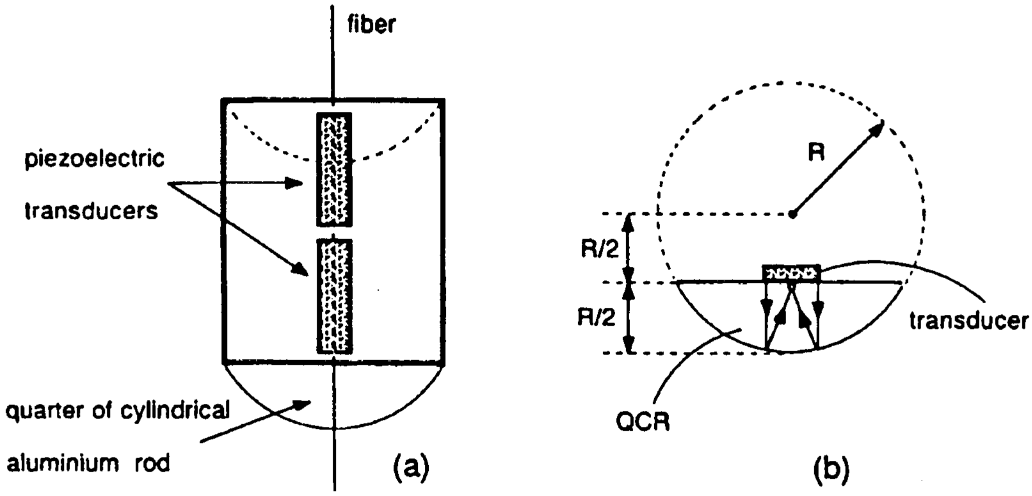

Figure 1 : Schematic of the acoustic-focusing in-fibre modulator showing the main parts of the device. (a) top view and (b) side view showing also two rays of the acoustic beam propagating from the transducer to the curved cylindrical surface, then reflected and focused onto the fibre.

Aluminium was chosen as it has a similar specific acoustic impedance to that of silica and low acoustic absorption. A phase modulation of approximately 2.6 radians was obtained at 86 MHz with this device at a wavelength of 1.5 μm and it was used to mode-lock a fibre laser and to stabilize the pulse-stream from a passively mode-locked soliton laser.

4. Fibre-compatible Bragg cells and frequency shifters

We have recently successfully produced an in-fibre flexural wave frequency shifter/acousto-optic tunable filter based on a special type of fused directional coupler[3]. This device was over 99% efficient with an RF drive power of approximately 1 mW and operated at 1.85 MHz. This in-fibre component is the subject of another presentation so will not be discussed further here, but will doubtless find application in interferometric sensor and LDV systems.

Another approach we are investigating is the use of gradient-index (GRIN) materials as the acousto-optic interaction medium[10]. This in principle solves the problem of fibre compatibility as the lens serves as an expanded beam connector between two fibres. An acoustic transducer deposited on the curved outer surface of the lens focuses energy directly onto the region in which the optical beam is propagating. This allows a larger transducer while ensuring that the acoustic energy is directed towards the small beam waist, allowing efficient operation and fast rise times to be simultaneously obtained. We have so far produced a device having a planar acoustic transducer bonded to a quarter-pitch lens, Figure 2. As yet we have obtained only 4% diffraction efficiency typical of borosilicate materials but a fast rise time of 14 ns. We are currently investigating improvements including the use of zinc oxide non-planar transducers in the hundreds of MHz region and the use of gradient index material having high M_2.

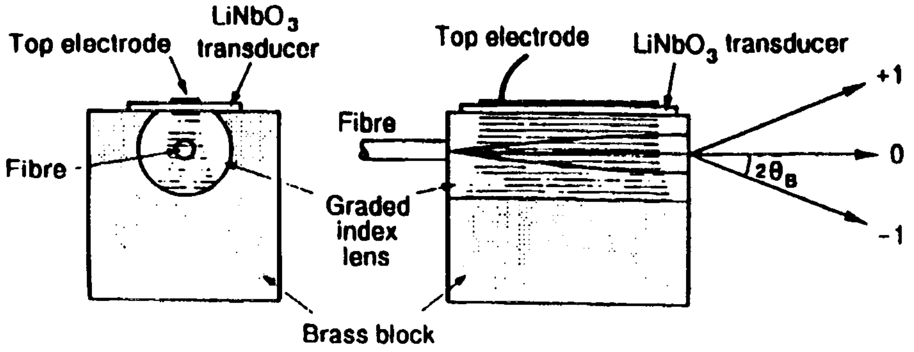

Figure 2 : Schematic drawing of the graded index AOM. The left hand side shows one of the faces of the lens inside a brass block. The right hand diagram shows a side view of the AOM along the length of the lens, with zero, and first order diffracted rays shown schematically.

5. Summary and Conclusions

Fibre acousto-optics is capable of delivering high performance in-fibre and fibre-compatible components for the control of laser radiation and for use in sensor systems. Components that can be realised include frequency shifters, switches, phase modulators and tunable optical filters. Much can be achieved with silica fibres in spite of their inherently poor M_2, and the low phonon energy glasses being developed for long wavelength fibre lasers offer acoustic performance (measured by M_2) hundreds of times better than silica. Diffractive components based on gradient-index media present great possibilities for advanced fibre-compatible Bragg cells. The non-planar high-frequency acoustic transducer technology which is essential to the progression of much of bulk and fibre acousto-optics alike is poorly developed and much advantage would be gained by bringing it to the point where it was commercially exploitable.

6. Acknowledgements

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