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# Acousto-optic in-Fibre Modulator using Acoustic Focusing

**I. Abdulhalim and C.N. Pannell**

**Optoelectronics Research Centre**
**Optical Fibre Group**
**University of Southampton**
**Southampton SO9 5NH UK**

A new efficient in-fibre acousto-optic phase modulator is demonstrated in which the acoustic wave is focused onto the fibre by reflection from a cylindrical surface. The device exhibits a phase modulation of 2.63 radians at the light wavelength of 1550 nm, using an RF frequency of 86 MHz and a power of 1 W.

In-fibre phase modulators are active fibre components with a low insertion loss, high damage threshold and negligible back-reflection[1]. They have applications in optical fibre sensing, and as mode-lockers for fibre lasers. One of the best means for achieving in-fibre phase modulation of the guided light is by coupling an acoustic wave to the fibre core, thus modulating the refractive index through the acousto-optic effect[1]. The change in the refractive index is proportional to $\sqrt{I_a}$ where $I_a$ is the acoustic Poynting vector[2]. Hence when the 1 W of acoustic power available from a planar transducer of width H = 1 mm is focused onto the fibre core of diameter $a \approx 10$ μm, the modulation of the refractive index is higher by a factor of $\sqrt{}(H/a) \approx 10$ than when the fibre is directly pressed on top of the same transducer. One of the means to achieve strong acoustic coupling is to use thin film piezoelectric transducers deposited directly on the curved surface of the fibre[3-6]. The necessary non-planar piezoelectric thin film technology is not very well developed however, and is not used in commercial acousto-optic devices. On the other hand planar piezoelectric transducers made of $LiNbO_3$ are widely used in acousto-optic modulators (AOMs) and can be easily polished or milled[7] down to a thickness of few μm, which corresponds to thickness mode frequencies in the GHz region. In this letter we report on a novel in-fibre AOM which uses a planar $LiNbO_3$ transducer in a special geometry that allows focusing of the acoustic wave onto the fibre. The focusing relies on the fact that the focal length of a cylindrical (or spherical) mirror is equal to half the radius.

A schematic of the focusing AOM is shown in figure 1. An aluminium cylindrical rod of 20 mm diameter and a length of 20 mm was cut along its length parallel to its axis of symmetry such that the maximum thickness was equal to one quarter of the diameter. We refer to this section as the quarter cylindrical rod (QCR). A U-groove was formed along the symmetry axis of the planar side of the QCR by pressing into it a stainless steel wire of 125 μm diameter. A special jig made from an aluminium block and machined to the same dimensions as of the curved cylindrical surface of the QCR was used to assemble the QCR while pressing or polishing, to avoid deformations of the cylindrical surface. The planar side of the QCR was then polished flat. The optical fibre used in the device was aluminium jacketed and single mode at 1550 nm with a 125 μm diameter, and was obtained from Fibreguide Inc. A short section of the aluminium coated fibre and the flat surface of the QCR were nickel plated using electroless sulphate bath process[8] until a nickel layer several μm thick was formed on the aluminium. The fibre was then soldered to the U-groove using an indium based alloy solder leaving two ≈ 50 cm pigtails. The solder acts as a strong metallic thermally stable and acoustically transmitting joint. The planar side of the QCR, together with the embedded fibre, was carefully lapped and polished to a flatness of 0.5 μm. A 250 nm layer of Cr/Au was then evaporated onto it. The piezoelectric transducer, which consisted of a 42 μm thick plate of $LiNbO_3$ (36° rotated Y-cut), corresponding to a nominal resonant frequency of 80 MHz, was indium cold-welded onto the flat polished surface of the QCR. The top electrode was of Cr/Au in the form of two stripes 2 mm x 8 mm, each aligned directly above the soldered fibre (figure 1a). The two stripes were connected electrically in series and the transducer was connected via a matching network which was adjusted so that the device presented a 50 Ω electrical load. The generated acoustic wave travelled through the QCR, and was reflected from its cylindrically curved surface and focused back onto the fibre and the transducer (figure 1b). This gave a standing wave device with a series of resonances around the 80 MHz RF frequency separated by approximately $V_a/2\ell \approx 0.6$ MHz, where $V_a = 6.42$ km/s is the acoustic velocity in aluminium and $\ell \approx 5$ mm is the maximum distance from the transducer to the curved surface, i.e one half the radius R (figure 1b) of the cylinder from which the QCR was cut. It is worth mentioning here that aluminium was selected for the QCR material because its acoustic impedance ($17.3\text{x}10^6$ kg/m$^2$s) is close to that of silica ($13.1\text{x}10^6$ kg/m$^2$s). This yields an acoustic power transmission coefficient[2] on the aluminium/silica interface of 98%. In addition, aluminium is a good thermal conductor which distributes efficiently any generated heat.

To characterise the device, the modulator was spliced into one arm of a fibre Mach-Zehnder interferometer operating at a wavelength of 1550 nm. We used a pigtailed narrow-band light source (HP 8168A) tunable in the range 1500-1565 nm with a power of 400 μW. We measured a visibility of $\approx 0.9$ with this interferometer. A fast photodiode was used to detect the signal from one of the output arms of the interferometer and the resulting photocurrent was fed into an RF spectrum analyzer. Figure 2 is a photograph of the traces from the spectrum analyzer showing both a peak which corresponds to the fundamental frequency (86.864 MHz) and a peak at twice this frequency. Assuming a linear change of the modulated phase, $\phi(t) = \phi_0 + \phi_a \sin\omega t$, with the applied sinusoidal electrical signal, the ratio between the maximum heights of the second-order frequency-shifted peak to the fundamental peak is equal to $J_2(\phi_a)/J_1(\phi_a)$[9]. Here $\phi_0$ is the static phase difference and $J_1$, $J_2$ are Bessel functions of the 1st and 2nd order respectively. We estimated $\phi_a$ by comparing the tabulated values of $J_2(\phi_a)/J_1(\phi_a)$ with the measured ratio between the maximum heights of the 2nd harmonic and the fundamental. In figure 2 the ratio between the two peaks is $\approx 1$ which corresponds to a phase modulation of $\phi_a \approx 2.6$ radians. The variation of the phase modulation with the RF power is shown in figure 3.

In order to determine the extent to which acoustic focusing was occurring in this QCR device, the RF signal applied to the transducer was pulsed at a low repetition rate (1 kHz). The amplitude modulation of the output signal was observed by connecting the photodetector output to a high bandwidth digital oscilloscope. Without pulsing the RF signal we measured a modulation depth of ≈ 50% at $\lambda = 1550.3$ nm and an RF frequency of 85.38 MHz. When the RF signal was pulsed at 1 kHz repetition rate we observed the same amplitude modulation with a time delay between the RF pulse and the optical response of the order of ≈ 1-2 μs. This delay time corresponds to the round trip time, $2\ell/V_a$, for the acoustic wave to travel back and forth between the transducer and the cylindrical reflecting surface. This is a direct experimental evidence for acoustic focusing.

The quality of the acoustic focusing depends strongly on how smooth and cylindrical the curved surface is, on the amount of acoustic mode conversion (compressional to shear) upon reflection, and on the width of the "line focus" coinciding with the fibre. The required smoothness of the curved surface has to be much less than $\Lambda/4$ where $\Lambda$ is the acoustic wavelength in aluminium. At 86 MHz, $\Lambda = 70$ μm, which with the smoothness of few μm of our curved surface, ensures to minimise acoustic wave distortions upon reflection. The width of the acoustic column (i.e the width of the transducer) was only 2 mm and so the working f-number for the acoustic focusing was approximately 2.5. At this small value, spherical aberration of the focused acoustic wave ensures that the line focus is substantially larger than the diameter of the optical fibre core, making alignment easier at the expense of efficiency. Conversion to shear modes is not expected to be large as acoustic rays are all striking the cylindrical aluminium/air interface at close to normal incidence. Improvement of the performance of the QCR-AOM is possible by complete optimisation of the above parameters. The acoustic beam "line focus" in the vicinity of the fibre can be made thinner by using high acoustic frequencies, in order to shorten the acoustic wavelength and minimise acoustic diffraction effects. The dimension of the QCR can be made smaller in the direction of travel of the acoustic wave (smaller $\ell$) and longer in the direction of the fibre (longer d). Smaller $\ell$ will minimise losses due to attenuation and divergence of the acoustic wave while the larger d increases the interaction length with the optical beam, thus increasing the phase modulation. The acoustic attenuation coefficient in aluminium[2] at 86 MHz is $\alpha = 6.36\ \mathrm{m}^{-1}$, so the acoustic intensity decays by 12% due to absorption each round trip through the QCR.

In order to quantify how "good" the acoustic focusing in our device is, we estimate the acoustic Poynting vector in the fibre core from the measured phase modulation. The acoustic Poynting vector[2] is given by $I_a = \rho V^3 S_e^2/2$ where $\rho$ is the density, V is the acoustic velocity and $S_e$ is the effective strain. The change in the refractive index in response to the effective strain $S_e$ is $\Delta n = -n^3 P_e S_e/2$ or $\Delta n = -n^3 P_e (I_a/2\rho V^3)^{1/2}$ where $P_e$ is the effective photoelastic constant, and the phase modulation is then $\phi_a = 2\pi d \Delta n/\lambda$. For the silica fibre n = 1.46, $\rho = 2.2\mathrm{x}10^3\ \mathrm{kg/m^3}$, V = 5950 m/s and $P_e \approx 0.2$, so we get $\Delta n \approx 2 \times 10^{-8}\sqrt{I_a}$ [MKS]. Using $\phi_a = 2.63$ radians at $\lambda = 1550$ nm and d = 16 mm we get $I_a \approx 4 \times 10^6\ \mathrm{W/m^2s}$. On the other hand the incident Poynting vector from the 16 x 2 $\mathrm{mm}^2$ transducer giving 1 W power is $I_a \approx 3 \times 10^4\ \mathrm{W/m^2s}$. Hence the phase modulation due to the focused acoustic wave is larger by a factor of $\approx$12 than that due to a direct contact between the fibre and the transducer. This is close to the ideal value ($\approx$ 15) which can be obtained if all of the acoustic intensity available from the transducer was focused onto the fibre core with a diameter of 9.5 μm.

In conclusion, a novel highly efficient in-fibre acousto-optic phase modulator has been demonstrated. The high efficiency was achieved by using a special geometry which allows focusing of the acoustic beam onto the fibre core. This modulator is of use for example in mode locking of fibre lasers and for high frequency signal processing in fibre-optic sensors.

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## Figure Captions

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.

Figure 2. A photograph of the traces from the spectrum analyzer showing both a peak which corresponds to the fundamental frequency of 86.864 MHz and a peak at twice this frequency. The centre of the graticule is at 130 MHz and the scale is 10 MHz/division. The RF power is 1 W and the light wavelength is 1550.3 nm.

Figure 3. The variation of the measured phase modulation with the applied RF power. The RF frequency is 86.864 MHz and the wavelength is 1550.3 nm.

**References**

[1] R. H. Stolen, R. P. DePaula, "Single mode fibre components", Proceedings of the IEEE, Vol. 75, pp. 1498-1511, 1987.

[2] G. S. Kino, Acoustic Waves : Devices, Imaging and Analog Signal Processing, (Prentice-Hall, Inc., New Jersey, 1987), Chapters 1 & 2.

[3] B. L. Heffner, G. S. Kino, "Switchable fiber-optic tap using acoustic transducers deposited upon the fiber surface", Optics. Lett., Vol. 12, pp.208-210, 1987.

[4] A. Odajima, M. Imai, "Piezoelectric ferroelectric polymer jacketed optical fibers for optical phase modulation", Ferroelectrics, Vol. 92, PP.41-46, 1989.

[5] D. B. Patterson, A. A. Godil, G. S. Kino, B. T. Khuri-Yakub, "Acousto-optic modulators for optical fibers using Hertzian contact with a grooved transducer substrate", in Proc. IEEE Ultrasonic Symp., pp. 413-416, 1988.

[6] F. S. Hickernell, "The characteristics of Coaxial ZnO thin film BAW transducers on optical fibers", in Proc. IEEE Ultrasonic Symp., pp. 417-420, 1988.

[7] J. Rosenbaum, M. G. Price, R. Bonney, O. G. Zehl, "Fabrication of wideband Bragg cells using thermocompression bonding and ion beam milling", IEEE Trans.Sonics and Ultrasonics, Vol. SU-32, PP.49-55, 1985.

[8] A. Brenner, "Electroless plating", in "Modern electroplating", Editor F.A. Lowenheim, 2nd edition, (John Wiley & Sons, Inc., New York 1974), Chapter 33.

[9] D. A. Jackson, A. Dandridge, S. K. Sheem, "Measurement of small phase shifts using a single-mode optical fiber interferometer", Optics Let., Vol. 5, pp. 139-141, 1980.

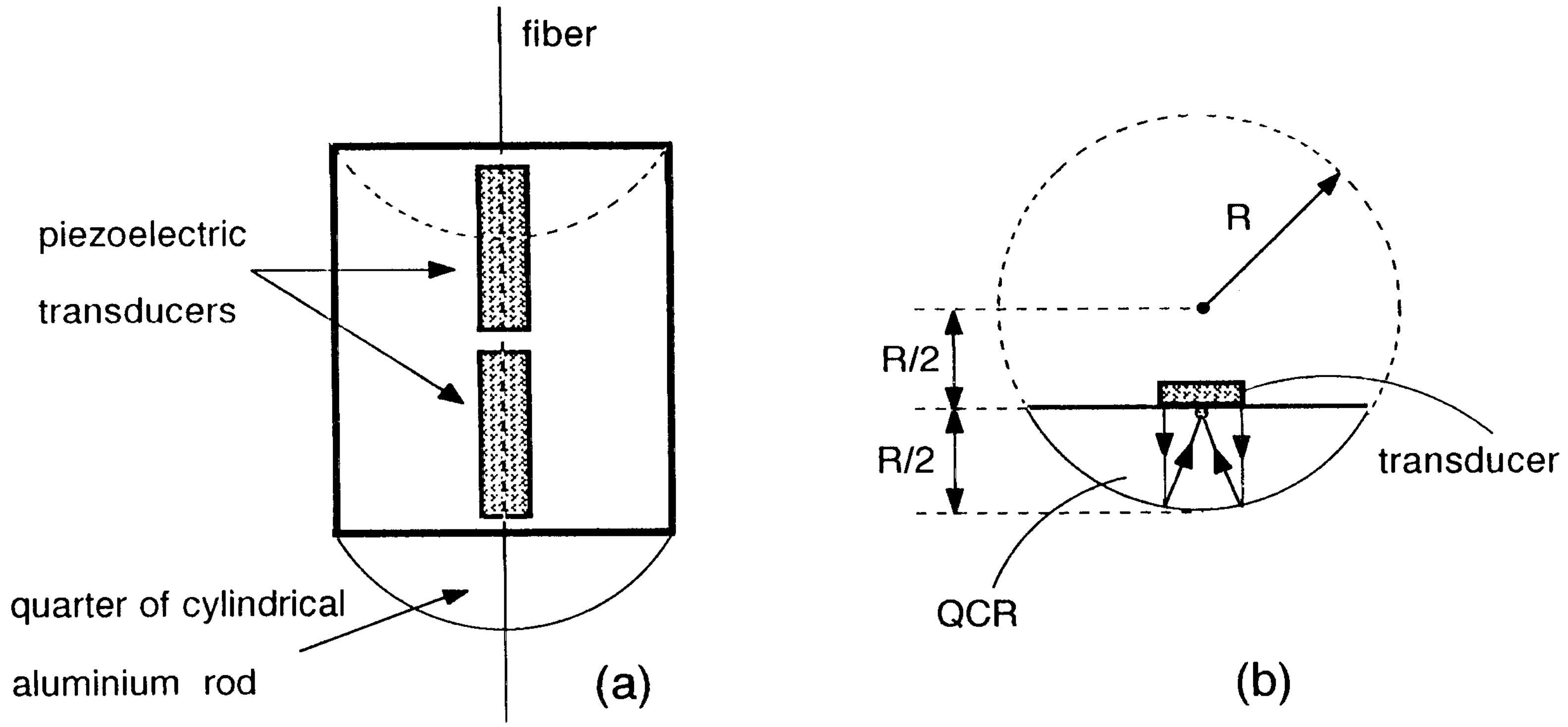
fiber
piezoelectric
transducers
quarter of cylindrical
aluminium rod
(a)
R
R/2
R/2
transducer
QCR
(b)

Fig. 1

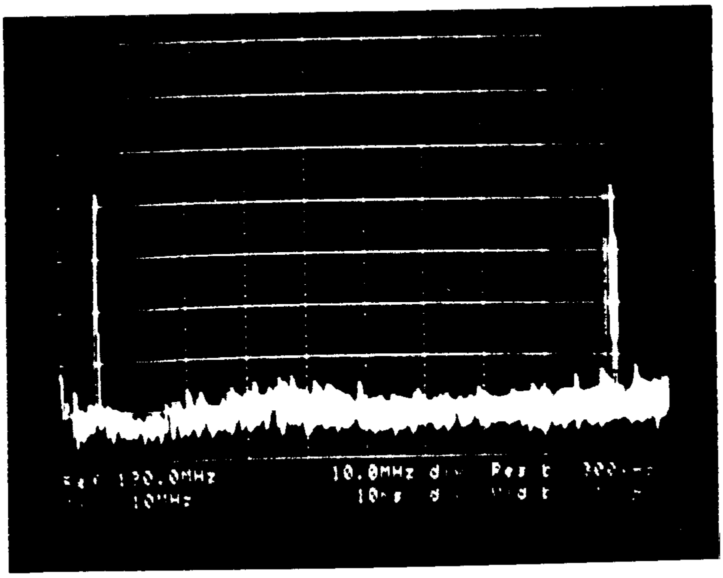

fig. 2

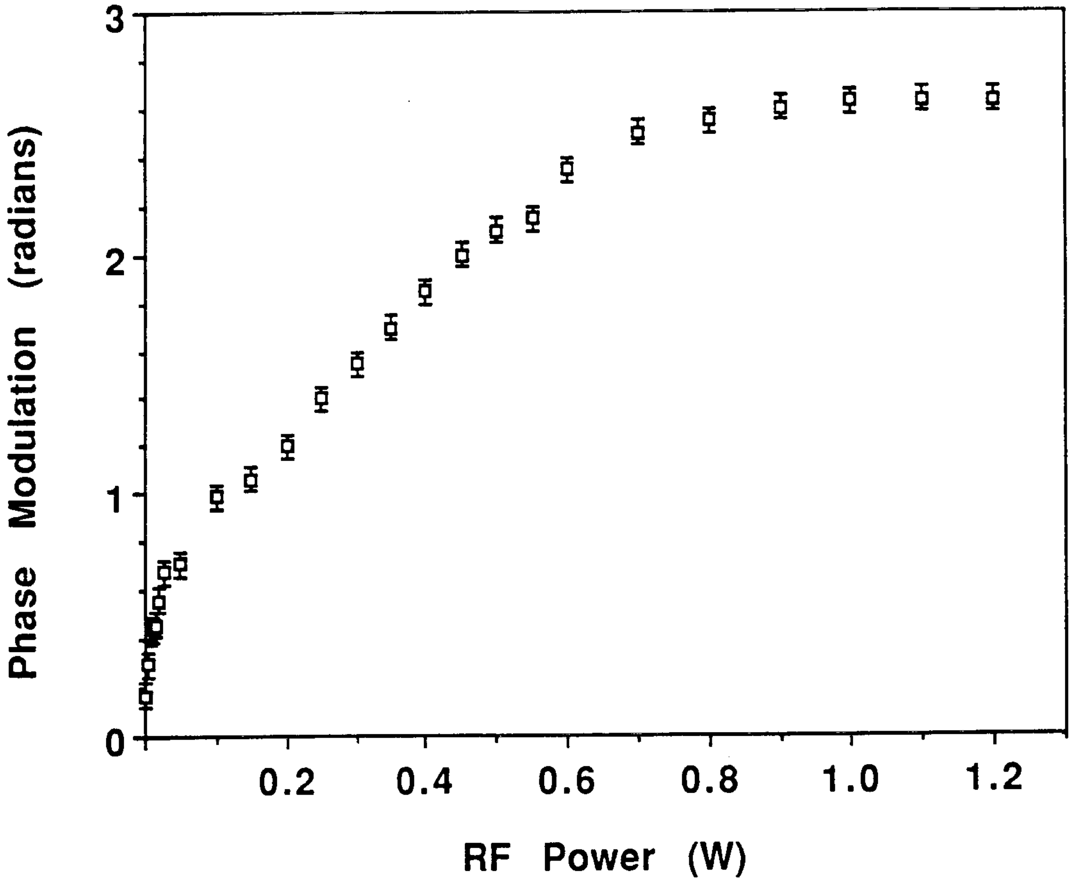

fig.3