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Optical fibre electrets: observation of electro-acousto-optic transduction

P.G. Kazansky, P.St.J. Russel and C.N. Pannell

Indexing terms: Optical fibres, Acoustoelectric transducers, Acousto-optical devices

The authors report the first observation of strong electro-acousto-optic transduction in thermally poled optical fibre. Phase shifts at resonance as high as 1 rad have been obtained at applied fields of 0.5 V/μm.

Introduction: Optical fibres have been used to sense many different physical quantities (magnetic fields, vibrations, temperature, rotation etc.). There is however, one important exception: optical fibres are insensitive to electrical fields due to the inversion symmetry of the glass matrix, which ensures that the Pockels coefficients are zero. For this reason most of the electric field sensors reported so far are hybrid devices, employing an extrinsic active component constructed from a piezoelectric or electro-optic crystal. Only one report exists of the observation of a Pockels effect in optical fibre poled with high electric fields, but the value of the induced electro-optic coefficient was very small (of the order of 10^{-3}pm/V) [1]. A recent breakthrough is the observation of high second-order nonlinearities of the order of 1pm/V in glasses [2] and 0.2pm/V in optical fibres [3]. Based on these results it is possible to expect a value of electro-optic coefficient in poled planar silica waveguide [4] and in poled silica fibre of the same order as in crystalline quartz (1pm/V). In this Letter we report the observation of a strong response of thermally poled fibre to an electric field. Phase shifts as high as 1 rad have been obtained at applied voltages of 50V.

Thermally poled fibre: Side polished regions about 8mm long of Ge-doped fibre (core diameter 16μm, numerical aperture 0.09, fibre outer diameter 125μm) were thermally poled at 4.3kV and 280°C for 15min as described in [3]. The expected phase shift $\Delta\varphi$ due to the Pockels effect ($\Delta\varphi = \pi n^3 r V L \lambda^{-1} D^{-1}$, r is the electro-optic coefficient, V the applied voltage, D the gap between electrodes and L the interaction length) in the poled fibre is estimated to be ~12mrad at $r = 0.2$pm/V, $V = 50$ V, $D = 100$μm, $L = 8$mm and $\lambda = 0.63$μm.

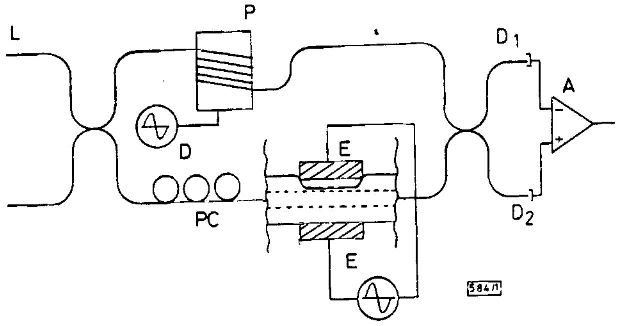

Fig. 1 *Mach-Zehnder fibre-optic interferometer with poled fibre*

P: piezoelectric tube, PC: polarisation controller, D: dither waveform, $D_{1,2}$: detectors, A: difference amplifier, L: laser, E: electrodes

Mach-Zehnder interferometer with poled fibre: A piece of fibre about 40cm long with an 8mm long poled region in the middle was fusion-spliced into one arm of a Mach-Zehnder interferometer made from fibres singlemoded at 633nm (Fig. 1). An He-Ne laser operating at 633nm wavelength was used as the light source. A PZT phase modulator in the arm of the interferometer was used to calibrate the performance of the interferometer. Polarisation controllers placed before the poled fibre were used to adjust the polarisation state. The poled fibre was fixed to a supporting plastic plate with one electrode underneath the poled region and a second electrode 10mm long gently pressed to the ends of the polished region without touching the side-polished region. A signal from an AC voltage generator with frequency 0–1.5kHz and amplitude 0–125V was applied to the electrodes. The difference signal from the output of two silicon detectors was monitored using an oscilloscope and an RF spectrum analyser.

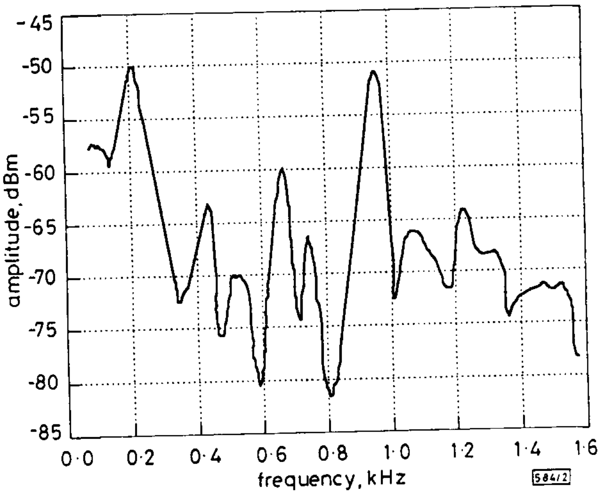

Fig. 2 *Frequency dependence of interferometer output*

Experimental results: We were surprised to observe a much larger phase modulation than expected by the Pockels effect, together with several resonance frequencies (Fig. 2). The output of the RF spectrum analyser shows a picture typical of phase modulation (Fig. 3). The largest phase shifts (~2 rad at 100V peak-to-peak voltage) were measured at frequencies of 210Hz and 950Hz. The output signal of the interferometer (at constant quiescent phase shift between two arms of the interferometer of ~π/2) was purely sinusoidal, phase-shifted relative to the applied signal: this phase shift was ~π/2 at 210Hz and ~π/4 at 950Hz (Fig. 2). In between the resonances it was still possible to observe phase modulation, some 20 times smaller. The existence of these low-frequency resonances suggests that acoustic vibrations are being excited in the system. To test this we changed the pressure of the upper electrode on the fibre and observed that the strength and position of the resonances changed. Moreover, we observed that when the upper electrode was disconnected from the voltage source the picture of phase modulation remained unchanged. This observation led us to the idea that some form of electroacoustic transduction is taking place.

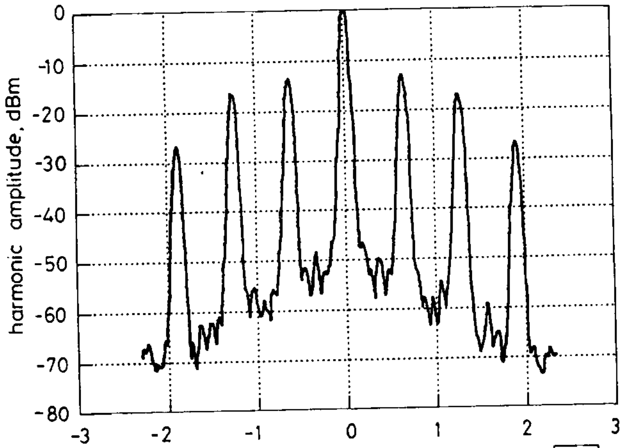

Fig. 3 *Signal from interferometer output monitored on RF spectrum analyser at applied signal amplitude 75 V and frequency 0.7kHz*

Possible explanation of experimental results: To estimate the electrostatic forces which act on the poled fibre, we first consider the most probable situation, when the fibre is electrically neutral. According to our model, the thermally poled fibre has two space-charge layers of equal and opposite sign. Under these conditions, a torque $T = qdE\sin\alpha$ acts on the fibre, where E is the applied electric field inside the fibre, α the angle between the electrical field and the dipole, d the distance between the charged layers, $q = 2E_{dip}\epsilon_0\epsilon_r La$ the charge, where $E_{dip} = \chi^{(2)}/3\chi^{(3)}$ is the space charge field in the poled layer ($E_{dip} = 1.5$kV/μm, assuming $\chi^{(2)} = 0.5$pm/V [3] and $\chi^{(3)} = 10^{-22}$m^{-2}/V^2). Finally, the expression for the torque is as follows: $T = 2\epsilon_0\epsilon_r E_{dip} LadVD^{-1}\sin\alpha$ and the value of torque can be estimated to be ~1.7×10^{-7} Nm assuming $V = 50$V, $d = 7\mu$m, $a = 62.5\mu$m, $\epsilon_r = 3.7$, $D = 100\mu$m, $L = 8$mm and $\alpha = 90°$. Such a torque is equivalent to a force of ~140mg acting on each side of the fibre, and is sufficient to excite resonant vibrations. If the poled fibre is not electrically neutral (this can be controlled by the poling conditions), electrostatic forces of the same order as those estimated above will excite transverse vibrations of the fibre. This is analogous to the behaviour of electroacoustic transducers such as those found in electret microphones and loud speakers, and indeed the poled fibre contains an electret, a dielectric with one or more layers of space charge. In the fibre, mechanical deformations caused by electroacoustic forces produce (via the photoelastic effect) various types of isotropic and anisotropic refractive index change in the fibre. The observed phase shift of the detected light signal relative to the applied voltage is a signature of a driven resonance.

Conclusions: In conclusion, large phase shifts are observed in poled fibres under an applied AC electric field. These can be explained by electro-acousto-optic transduction, and may have important practical applications for fibre optic electric field sensors at low frequencies (such as those on electricity supply lines). Measurements of the intrinsic linear electro-optic effect in the poled fibres are in progress.

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Two-mode fibre spatial-mode converter using periodic core deformation

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Indexing terms: Optical fibre polarisation, Optical fibres

Efficient conversion between the LP_{01} and LP_{11} modes in a two-mode fibre is achieved by periodically ablating the fibre surface with a CO_2 laser and then annealing the fibre with an electric arc. The resulting periodic core deformation produces 99% mode conversion over a 37nm bandwidth around 1540nm and 0.38dB insertion loss.

Introduction: The ability to efficiently convert energy from one spatial mode to another in optical fibres has potential applications in fibre-based devices such as wavelength filters, sensors, and dispersion compensators [1–3]. A variety of grating-based mode converters have been demonstrated using periodic stress [4], microbending [5, 6], and photoinduced index changes [7]. The first two of these techniques have the potential for high conversion efficiency and low insertion loss but suffer from poor long-term reliability. Mode converters based on photoinduced index gratings promise both high reliability and performance, and thus have been the focus of research in recent years.

In this Letter we demonstrate an alternative to photoinduced gratings that uses periodic deformation of the fibre core. This technique can achieve highly efficient and reliable gratings, and also has the advantage that extremely large bandwidth gratings can be obtained. This is because the effective index changes that are produced by deforming the core ($\Delta n \simeq 0.1$) are approximately an order of magnitude greater than the largest permanent index changes achieved in photoinduced gratings [8]. This feature is important for applications requiring mode conversion over a large wavelength region.

Experiment: LP_{01} to LP_{11} mode converters were produced in a step-index, germania-doped fibre having an effective index step of ~1% and cutoff wavelength for the LP_{11} mode of 1720nm. Periodic deformation of the core was achieved in a two-step process illustrated in Fig. 1.

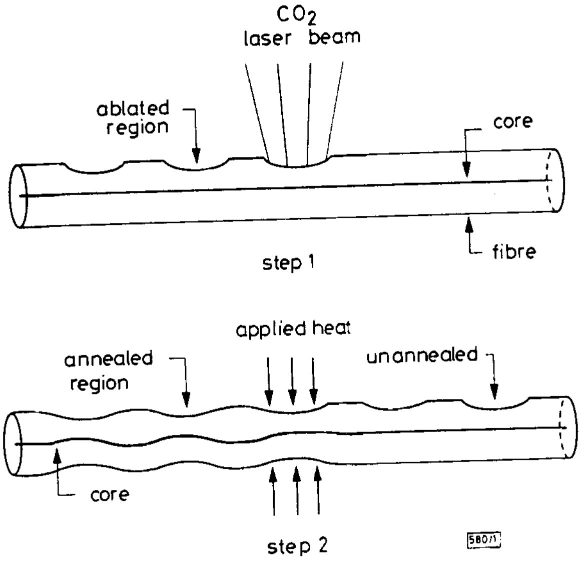

Fig. 1 *Two-step process for creating periodic deformation of the core*

In the first step, periodic cuts are made in the surface of the glass fibre using a focused CO_2 laser beam. The cuts are made in a short section of the fibre where the jacket has been removed. Each cut is made with a single laser pulse.

After completing a cut, the fibre is translated a distance equal to the intermodal beat length for the LP_{01} and LP_{11} modes (265μm in this case) and the process repeated to obtain a corrugated pattern on the surface of the fibre. At this point no mode conversion is obtained because the perturbation created on the surface of the fibre does not extend into the core region.

The next step in the process involves annealing the fibre. In this step, the fibre is locally heated to the melting point for a short time using the arc in a fusion splicer. The arc is applied individually to each cut. The purpose of the annealing process is to use the surface tension of the molten glass to transform the corrugation on the fibre surface into a sinusoidal deformation of the core as illustrated in Fig. 1. Mode conversion is monitored in real time as the grating is being annealed by measuring transmission through the grating with LP_{11} mode strippers placed at the input and output sides. Coupling from the LP_{01} to the LP_{11} mode shows up as a decrease in transmitted power in this configuration because all of the LP_{11} mode power is stripped away by the output mode stripper.

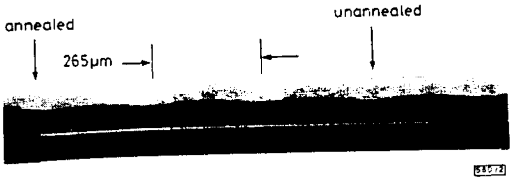

Fig. 2 *Two-mode fibre mode converter: Grating before and after annealing*