Invited Paper

OPTICAL FIBRE ELECTRETS AND ELECTRO-ACOUSTO-OPTIC TRANSDUCTION

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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. Most of the electric field sensors reported so far are hybrid devices, employing an extrinsic active component constructed from a piezoelectric or electrooptic 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 electrooptic coefficient was very small (of the order of 10^{-3} pm/V) and unstable[1]. A recent break-through is the recent observation of high second-order nonlinearities of the order of 1 pm/V in glasses[2-5] and 0.2 pm/V in optical fibres[6-7] using a variety of different techniques: thermal poling, corona poling, and electron implantation. Based on these results it is possible to expect a value of electrooptic coefficient in poled fibre of the same order as in crystalline quartz (1 pm/V). This value is high enough to construct an all fibre-optic electrooptic field sensor. In this paper 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 50 V.

Thermally poled fibre

The fibre used in the experiments was thermally poled in vacuum. The core was Ge-doped (diameter 16 μm, numerical aperture 0.09, fibre outer diameter 125 μm). The OH concentrations were 80 ppm and 150 ppm respectively in the core and in the cladding (formed from Herasil-1). Regions ~8 mm long were side-polished to within 1 μm of the core using a simple wheel polishing technique.

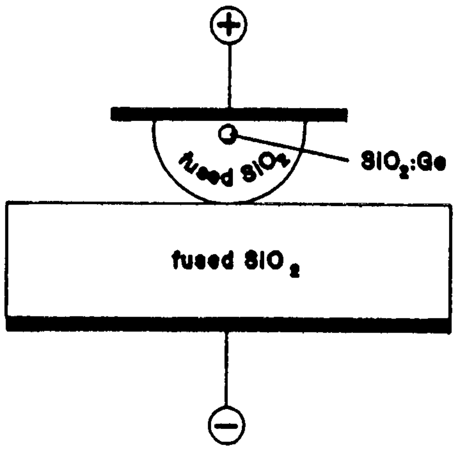

Figure 1: Thermal poling arrangement for the fibre

The side-polished fibres were placed on top of 2 mm thick silica substrates, manufactured by the same method as the starting tubes (Herasil-1), and the final assembly was sandwiched between two electrodes with the anode on top of the polished fibre surface (Fig.1). Thermal poling was carried out at 4.3 kV and 280°C for 15 min

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in evacuated chamber at 1.2 × 10^{-5} mbar. Effective second-order nonlinearities ($\chi^{(2)}_{eff} = \chi^{(2)}\eta$, where η is the overlap factor between the nonlinearity and the modal field) as high as 0.2 pm/V were measured in the poled fibre by second harmonic generation of 1064 nm pump. Present evidence indicates that the thickness of the nonlinear layer is approximately 7 μm, and the overlap factor for our fibre is $\eta = 0.4$, which yields the value of $\chi^{(2)} = 0.5$ pm/V.

Estimation of the phase shift in poled fibre due to Pockels effect

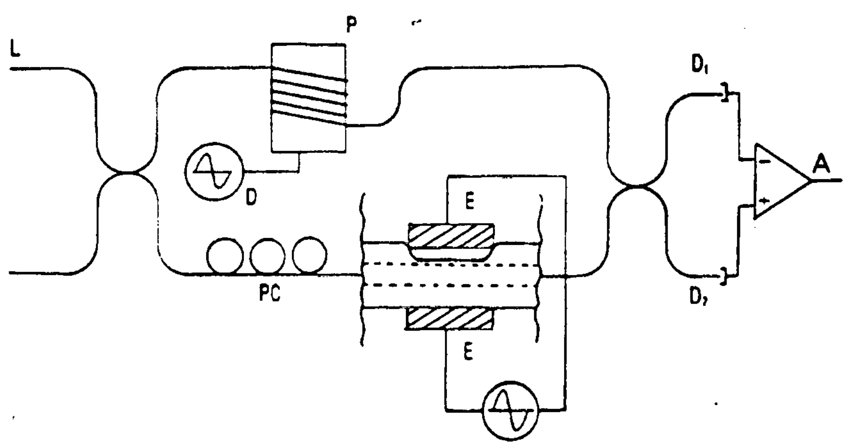
A phase shift due to linear electrooptic effect is given by:

$$\Delta\phi = \frac{\pi n^3 r V L}{\lambda D} \qquad (1)$$

where r is the electrooptic coefficient, V the applied voltage, D the gap between electrodes and L the interaction length. This phase shift $\Delta\varphi$ is estimated to be of about 12 mrad at $r = 0.2$ pm/V, $V = 50$ V, $D = 100$ μm, $L = 8$ mm and $\lambda = 0.63$ μm.

Mach-Zehnder interferometer with poled fibre

A piece of fibre about 40 cm long with an 8 mm long poled region in the middle was fusion-spliced into one arm of a Mach-Zehnder interferometer made from fibres single mode at 633 nm (Fig.2). A He-Ne laser operating at 633 nm was used as the light source. A PZT phase modulator in the arm of the interferometer was used to calibrate the performance of interferometer. Polarization controllers placed before poled fibre were used to adjust the polarization state in the poled fibre. The poled fibre was fixed to a supporting plastic plate with one electrode underneath the poled region and a second electrode 10 mm 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 0-1.5 kHz and amplitude 0-125 V was applied to the electrodes. The difference signal from the output of two silicon detectors was monitored using an oscilloscope and an RF spectrum analyzer.



Key:

P - Piezoelectric tube
PC - Polarisation controller
D - Dither waveform
$D_{1,2}$ - Detectors
A - Difference amplifier
L - Laser
E - Electrodes

Figure 2: Schematic of interferometer with poled fibre

Poled fibre in electrical field: experimental results

We were surprised to observe a much larger phase modulation than expected by (1), together with several resonant frequencies (Fig.3). The output of the RF spectrum analyzer shows a picture typical of phase modulation (Fig.4). The largest phase shifts (~2 rad at 100 V peak-to-peak voltage) were measured at frequencies of 210 Hz and 950 Hz. The output signal of the interferometer was purely sinusoidal, phase-shifted relative to the applied signal: this phase shift was about $\pi/2$ at 210 Hz and about $\pi/4$ at 950 Hz (Fig.5). In between the resonances it was still possible to observe phase modulation, some 20 times smaller. The existence 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.

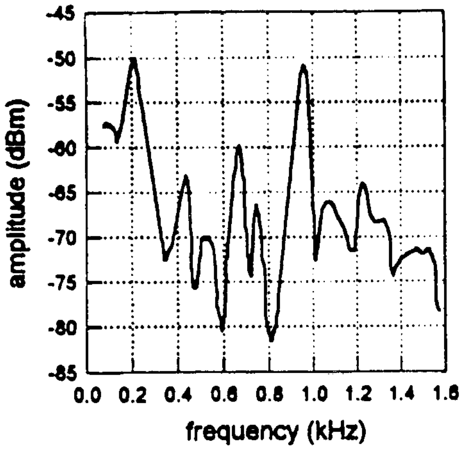


Figure 3: Frequency dependence of interferometer output

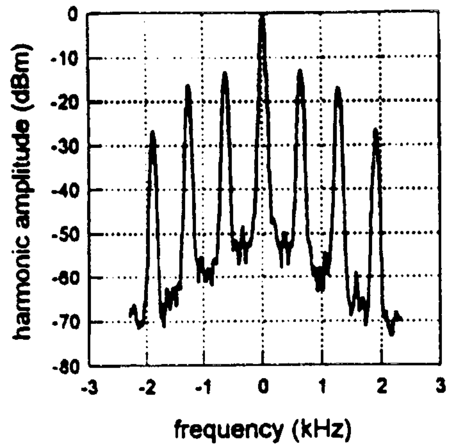


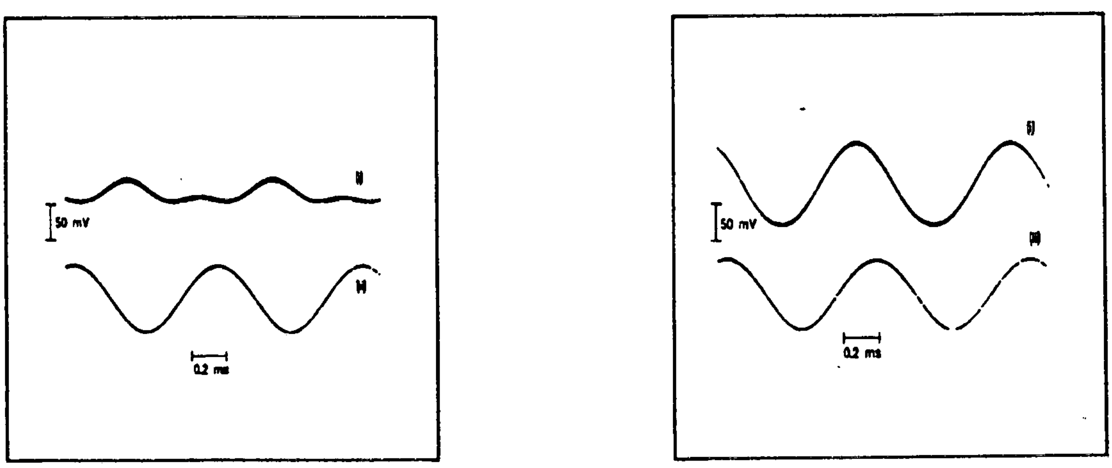
Figure 4: Signal from interferometer output monitored on RF spectrum analyzer at applied signal amplitude 75 V and frequency 0.7 kHz

Poled fibre in electrical field: possible explanation of experimental results

To estimate the electrostatic forces which act on the poled fibre, let us consider first of all 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 (of radius a), α the angle between the electrical field and the dipole, d the distance between the charged layers, $q = 2E_{dp}\epsilon_o\epsilon_r La$ the charge, where $E_{dp} = \chi^{(2)}/3\chi^{(3)}$ is the space charge field in the poled layer (E_{dp} = 1.5 kV/μm, assuming $\chi^{(2)}$ = 0.5 pm/V and $\chi^{(3)} = 10^{-22}$ m^2/V^2). Finally, the expression for the torque is as follows:

$$T = 2\epsilon_o\epsilon_r E_{dp} L a d \frac{V}{D} \sin\alpha \qquad (2)$$

and the value of torque can be estimated as about 1.7×10^{-7} Nm assuming V = 50 V, d = 7 μm, a = 62.5 μm, ϵ_r = 3.7, D = 100 μm, L = 8 mm and α = 90°. Such a torque is equivalent to a force of about 140 mg 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[8]), electrostatic forces of the same order as those estimated above will excite transverse vibrations of the fibre.



(a) (b)

Figure 5: Output light signal (i) and applied ac voltage (ii) at different constant phase shifts in interferometer: approaching 0 (a) and about $\pi/2$ (b)

This is analogous to the behaviour of electroacoustic transducers such as those found in electret microphones and loudspeakers, 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 changes 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 electrooptic effect in the poled fibres are in progress.

Acknowledgments

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