PERMANENTLY-INDUCED LINEAR ELECTRO-OPTIC EFFECT IN SILICA OPTICAL FIBRES

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Abstract

Permanent electric-field-induced linear electro-optic effects have been observed in fused-silica optical fibres subjected to strong electric fields by means of internal electrodes. This electric-field-poling phenomenon can be used to construct a Pockels modulator and other electro-optic devices.

Introduction

Fibre switches and modulators are desirable because they exhibit low losses and are fully compatible with fibre systems. Unfortunately, fused silica possesses a centre of symmetry which precludes a linear electro-optic (Pockels) effect, leaving only the small quadratic electro-optic (Kerr) effect as a candidate. Electro-optic modulators are therefore difficult to construct. The linear electro-optic effect is found only in materials which possess a second-order non-linearity and is responsible for phenomena such as second-harmonic generation, sum-frequency generation and parametric amplification and oscillation. Despite this, photo-induced permanent second-harmonic generation in silica fibres has been recently observed[1-5] by several authors, implying the existence of a second-order non-linearity and non centro-symmetry.

In this paper we report the production of a permanent second-order non-linearity in silica fibres by application of an intense electric field to pole the fibre. An electric field of more than 4MV/cm can be applied by using a special fibre with integral metal electrodes disposed on either side of the core.

Measured values of the quadratic and field-induced linear electro-optic coefficients were 2.2×10^{-16} m/V^2 and 2.1×10^{-15} m/V for GeO_2/P_2O_5-doped fibres, respectively. Experimental techniques and basic electric-field-poling phenomenon are described.

Internal-Electrode Fibres

Fibres with integral electrodes are similar to conventional telecommunications-type fibre, but containing one or more longitudinal holes filled with metallic material to act as electrodes. We have found that liquid metals and alloys make better electrodes and permit higher voltages to be applied because they are smooth and provide better surface contact. Gallium was used in the experiment, even though it has a melting temperature of 29.6°C, since it remained liquid at room temperature due to its super-cooling property. Figure 1 shows the cross-sections of two typical fibre structures with integral electrodes. Fibre (a) possesses two metal sections and offers a well-defined electrode separation while Fibre (b) has only one electrode, the other being an external flat metal plate placed against the fibre section. The electrode separations are chosen to be as close as possible consistent with avoiding excessive absorption effects resulting from the proximity of the metal to the core. Electrical signals were applied using fine gold wires which were inserted into the holes to make contact with the electrodes. In this way an electric-field as high as 4000 kV/cm has been achieved over the core region without dielectric breakdown.

Birefringence can be introduced into the fibre by allowing the core to deform from circular to elliptical using higher fibre drawing temperatures. The resulting birefringent axis of the fibre is always aligned with the electrodes and a birefringence of 1.06×10^{-4} has been obtained. This intrinsic birefringence is useful for preserving polarisation in the fibres, which is important for the investigation of electro-optic effects in fibres when long interaction lengths are involved.

Quadratic Electro-Optic Effects

The quadratic electro-optic Kerr coefficients were first measured in the as-drawn Ge/P-doped (7 mol.% GeO_2 & 0.5 mol.% P_2O_5) fibres. The fibre preform was fabricated by the standard MCVD technique, after which holes were drilled on either side of the core. After drawing, the fibre holes were filled with gallium. The electrodes had a separation of 15 μm and a length of 65 cm.

A linearly-polarised He-Ne laser beam (λ = 633nm) was launched into the fibre at 45° with respect to the x-polarisation axis. An ac electric field E_{ac} of up to 140 kV/cm was applied to the fibre core through the internal electrodes (i.e. along the x-axis). The linear birefringence ($n_x - n_y \approx 1.06 \times 10^{-4}$) of the fibre plus the birefringence caused by the electric field E_{ac} produced a phase difference $\Delta\psi$ between x- and y-polarised components of the transmitted optical signal. A Soleil-Babinet compensator following the fibre was adjusted so that $\Delta\psi = \pi/2$ when $E_{ac} = 0$, in which case the intensity, transmitted through the second polariser at 45° with respect to the x-axis, was half of its maximum value. With the applied field E_{ac} on, the intensity of the beam transmitted through the analyser is given by

$$\Delta\psi = \pi K L E_{ac}^2 [1+\cos(2wt)] \qquad (1)$$

where K is the Kerr coefficient, L is the interaction length and w is the modulation frequency. Figure 2(a) shows the modulated optical signal. Note that the frequency is twice the applied electrical frequency as predicted in (1). The modulated optical signal is 180° out of phase when the analyser is at -45° with respect to the x-axis.

Figure 3 shows the variation of a.c. phase retardation in rads/m with applied a.c. field and, as expected, show a square-law form consistent with the existence of a quadratic electro-optic effect. The experimental results agree well with the theoretical calculations (dotted line), using a value of K for silica of 2.2×10^{-16} m/V^2. The experiments showed no detectable linear electro-optic effects in any of the as-drawn fibres and this has been confirmed by using a spectrum analyser to identify any fundamental component of the applied optical field in the optical output.

Note that the integral metal-electrode structure allows the construction of a 6m-long fibre Kerr modulator with a $\pi/2$ voltage of about 200V. This is an extraordinarily low voltage for an electro-optic modulator based on fused silica.

Electric-Field-Induced Linear Electro-Optic Effects

Permanently-induced linear electro-optic effects were observed after the application and removal of a dc electric-field of higher than 50 kV/cm transverse to the fibre core, implying the creation of a second-order non-linearity. Poling-field intensities up to 4000 kV/cm were applied and each poling time was approximately 10 mins, after which further changes were small. The fibres were then tested by applying an ac electric-field of 10 kHz using the same experimental setup described earlier. Figure 2(b) shows the modulated optical waveforms where the modulation phases depend on the analyser orientation. Note that the optical signal has the same frequency as that of the applied electric field. For the fibre poled at 4MV/cm a linear relationship was found between the optical phase retardation ψ and the applied electric-field as shown in Figure 3. The corresponding induced linear electro-optic coefficient γ is 2.1×10^{-15} m/V, calculated by using the conventional definition:

$$\psi = 2\pi n^3 \gamma EL/\lambda \qquad (2)$$

where n is the refractive index of the fibre core and λ is the wavelength of the light. The magnitude of the induced linear electro-optic coefficient as a function of poling-field intensity, for a poling time of approximately 10 mins, is shown in Figure 4. The increased electro-optic effect now allows the construction of a 6m-long Pockels modulator with a $\pi/2$ voltage of only 60V.

Conclusion

Permanent linear electro-optic effects have been observed in fused silica fibres following application of intense electric fields. The effect implies the creation of a permanent second-order non-linearity of 2.1×10^{-15} m/V, equivalent to a residual dc-bias field of 230 kV/cm which appears to be present even after removal of the poling field. The physical mechanism involved in these observations is still unexplained and it is expected that better understanding will lead to an improvement in poling efficiency. The discovery of this effect provides useful information on the processes involved in second-harmonic generation in fibres[1-5]. The effect has potential applications in efficient electro-optic devices and other non-linear fibre effects.

References

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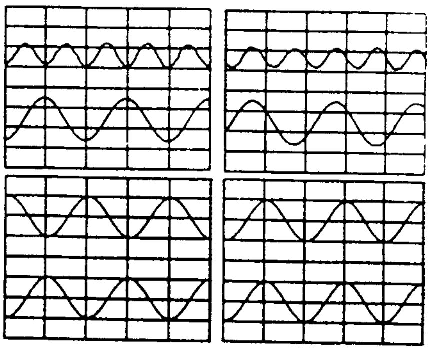
(a) (b)

Fig.1 Photographs of typical fibres containing internal-electrodes. Fibre (a) contains two electrodes and fibre (b) has one.



(a)

(b)

Fig.2 Waveforms of modulated optical signals. Upper and lower traces are optical and applied-field waveforms, respectively. (a) Quadratic electro-optic effect and (b) Electric-field-induced linear electro-optic effect

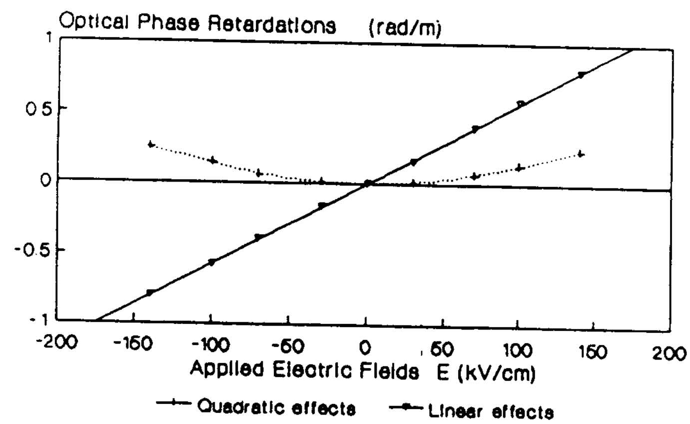


Fig.3 Optical phase retardation produced by quadratic and linear electro-optic effects versus applied field.

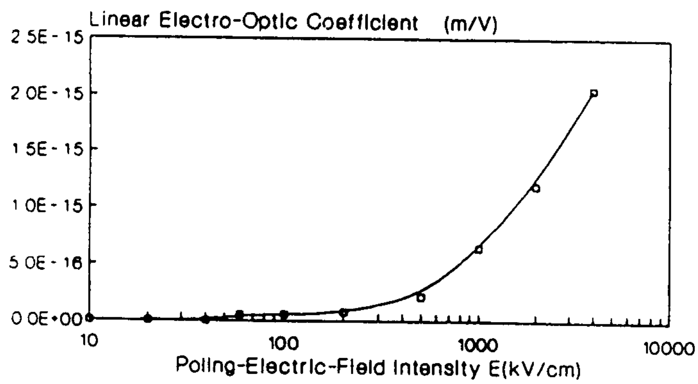


Fig.4 Induced linear electro-optic effects versus poling-field intensity.