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Photoelastically Induced Light Modulation in Gradient Index Lenses

I. Abdulhalim and C.N. Pannell

Optoelectronics Research Centre
Optical Fibre Group
University of Southampton, Highfield,
Southampton, SO9 5NH, UK.

A new photoelastic light modulator is demonstrated based on the modulation of the birefringence and of the index profile in graded index lenses. Using the birefringence modulation we obtained 35% modulation depth in a quarter-pitch lens and 65% using a half pitch lens at acoustic frequencies up to the MHz range. Using the index profile modulation in a half-pitch lens as a fibre-to-fibre connector we obtained 15% modulation without the incorporation of any polarizer.

The photoelastic effect has been known for a long time as the birefringence induced in a material due to stresses.[1] Based on this, photoelastic modulators (PEMs) have been built using a variety of materials over a wide range of modulating frequencies (10-300 kHz).[2-10] So far, PEMs have been used as birefringence modulators in commercial spectro-dichrometers[11,12] or as polarization modulators for measuring rotatory powers, circular or linear dichroism[3-10] and in ellipsometry.[2,13-15] To incorporate a PEM into a micro-optic or fibre-optic system, there is a need for a material with high stress-optic coefficient which can be incorporated into a fibre-compatible device. In this letter, we report on a large photoelastically induced amplitude modulation in graded index (GRIN) lenses which are widely used in micro-optic systems.[16] These lenses are usually made from borosilicate glasses which fortunately posses relatively high stress-optic coefficient.[17,18] We have obtained polarization modulation due to stress-induced modulation of the birefringence. In addition, amplitude modulation without the incorporation of any polarizer was obtained using a half pitch GRIN lens when used as a fibre-to-fibre connector.

A schematic of the experimental set-up is shown in figure 1. The GRIN lens was pressed directly on top of a PZT disc using an aluminium block. The PZT disc is of the type 5A (Vernitron-U.K. Ltd.), having the dimensions of 22 mm diameter and 1.8 mm thick, designed to resonate at 1 MHz in thickness mode. The PZT was bonded at points near its circumference to metallic supports using thermally conducting but electrically insulating glue. The bottom side of the transducer was air-backed to maximise the electromechanical conversion efficiency. Light from a HeNe laser at 633 nm was launched into a 85 cm long single mode fibre after passing through a polarizer and a half-wave plate (HWP). The end of the fibre was butted to one face of the GRIN lens. For the case of the quarter pitch GRIN lens (QPL) we used a lens of diameter 1.8 mm and length 4.6 mm, AR coated on its faces and gold coated on its cylindrical surface. The collimated beam passed through an analyzer and to the detector. In the half pitch case, a GRIN lens of 8 mm length and 2 mm diameter was used. On the output face of the lens a second identical fibre was butted to receive the light coupled to the lens from the input fibre (figure 1b). The fibre-to-fibre coupling efficiency to the second fibre was approximately 50%. In the case of a half-pitch lens (HPL) we report on two modes of operation. The first mode is based on the birefringence modulation (BM) similar to that in the quarter pitch case and the second mode is based on the index profile modulation due to the stress distribution in the graded index medium. This modulates the coupling efficiency to the output fibre with no need for an analyzer. We refer to the latter mode of operation as the mode of launch efficiency modulation (LEM).

Figure 2 shows typical amplitude modulated optical response in the BM mode of operation. The optical modulation depends on the HWP-analyzer orientation, on the acoustic energy coupled to the photoelastic medium and on the stress anisotropy. The stress anisotropy is maximised when the applied force is uniaxial. The acoustic coupling depends on the electromechanical conversion of the PZT which is maximised at the resonance frequencies. Away from the resonances the modulation disappears. In addition to the thickness mode resonance at 1 MHz, the PZT exhibited some low frequency resonances. Near the 200 kHz resonance, we obtained the maximum possible modulation using $\approx$ 1.5 W electrical power, and at ~ 1 MHz the required electrical power was $\approx$ 2.5 W. The phase of the optical signal relative to the electrical signal changed with the HWP and the analyzer orientations. By each 90° rotation of the analyzer, the phase of the optical signal relative to the electrical signal shifts by 90° and in the midway between these positions the modulation disappears. The same changes that are obtained by rotating the analyzer at an angle θ, can be obtained by rotating the HWP by θ/2, which means that the plane of polarization of the incident light is rotated by θ. This behaviour can be understood if the squeezed GRIN lens is considered as a variable birefringent plate in the BM mode of operation. Similar, although static, changes were observed by varying the static pressure of the top aluminium block. Note that the modulation in the HPL case is higher than that in the QPL case. This is due to the fact that the half-pitch lens is longer and therefore the accumulated phase shift between orthogonal polarisation states is larger. According to this behaviour, we expect that a lens of the same type and length ~ 20 mm will exhibit complete modulation under the same conditions. No major differences were observed when the position of the input fibre was varied across the lens face. This indicates that the induced anisotropy is not varying significantly in the radial direction, although the stress itself can be nonuniform. To make sure that the modulation is not a result of mechanical vibrations of the fibre, we checked that the same modulation is achieved when the light was coupled directly from a microscope objective to the lens and the output was collimated using a second microscope objective.

In the LEM mode of operation, the analyzer was removed and we detected the light coming directly from the output fibre butted to the HPL. Figure 3 shows a typical oscilloscope traces of the modulated optical response. The modulated optical response is highly stable as far as the launch efficiency itself is stable before applying the electrical signal. The launch efficiency to the output fibre can be modulated due to two reasons. The first is due to deflection and the second is due to widening of the beam on the output face of the GRIN lens. The launch efficiency is highly sensitive to both of these parameters.[16]

In order to decide which of these parameters is being modulated, we measured the radius of the output beam for the two cases of QPL and HPL before and after turning the electrical signal ON. The measurement was performed at a distance of 3 cm from the output face of the HPL and at different distances in the QPL case using the knife edge technique.[19] Assuming a gaussian distribution we found that the beam radius decreases when the electrical signal is ON in the QPL case and it increases in the HPL case. This shows that the beam divergence decreases when the electrical signal is ON in the QPL case and it increases in the HPL case. This indicates that the launch efficiency modulation is at least partially due to the modulation of the beam radius on the output face of the HPL which is due to the modulation of the focal length of the GRIN lens. The possibility of deflection modulation is not excluded, but we did not observe any experimental indication of it.

The stress distribution in the graded index medium may be modelled similar to the problem of a uniaxial force F per unit length applied diametrically to a cylinder of radius R. Assuming the applied force is along the y direction, the stress components are given by:[20]

$$\sigma_x = \frac{-2F}{\pi}\left\{\frac{(R-y)\,x^2}{r_1^4} + \frac{(R+y)\,x^2}{r_2^4} - \frac{1}{2R}\right\}$$
$$\sigma_y = \frac{-2F}{\pi}\left\{\frac{(R-y)^3}{r_1^4} + \frac{(R+y)^3}{r_2^4} - \frac{1}{2R}\right\} \qquad (1)$$

where $r_{1,2}^2 = x^2 + (R \mp y)^2$ and we assumed that the GRIN lens is axially constrained and hence the z-component of the strain is zero. In this case the associated strain components are $\varepsilon_x = (\sigma_x - \nu_p\sigma_y)/E$ and $\varepsilon_y = (\sigma_y - \nu_p\sigma_x)/E$ where ν_p is Poisson's ratio and E is Young's modulus. The stress components in equation (1) correspond to the peak values of the time dependent stress. The refractive indices in the strained material are then:

$$n_x = n_b(1 - \frac{n_b^2}{2E}((P_{11} - \nu_p P_{12})\sigma_x + (P_{12} - \nu_p P_{11})\sigma_y))$$

$$n_y = n_b(1 - \frac{n_b^2}{2E}((P_{12} - \nu_p P_{11})\sigma_x + (P_{11} - \nu_p P_{12})\sigma_y)) \qquad (2)$$

where $n_b = n_0\,(1 - (A/2)\,(x^2 + y^2))$ is the index profile before the strain is applied and P_{11}, P_{12} are the photoelastic coefficients of the material. The induced birefringence is therefore given by:

$$\Delta n = \frac{n_b^3}{2E}(P_{11} - P_{12})\ (1 + \nu_p)\ (\sigma_x - \sigma_y) \qquad (3)$$

The stress components as given by equation (1) vary along x and y and vanish at the circumference. Their maximum values are developed on the axis x = y = 0 and are equal to $\sigma_{x0} = F/\pi R$ and $\sigma_{y0} = -3F/\pi R$. The constant $K = \Delta n/(\sigma_x - \sigma_y) = n_b^3/2E\ (P_{11} - P_{12})\ (1 + \nu_p)$ is identified as the stress-optic coefficient. For light propagation perpendicular to the stress direction in borosilicate glass,[17] $K = 2.74 \times 10^{-6}$ mm^2/N.

For the HWP-analyzer orientation in which the modulation is maximized, the modulation depth is equal to $\sin^2\beta/2$ where $\beta = 2\pi d\Delta n/\lambda$. Hence to obtain a 50% modulation in a lens of length d = 1 cm, the required induced birefringence is $\Delta n \approx 0.75 \times 10^{-5}$ and the required force is $F \approx 2$ N/mm for R = 1 mm. This force is achievable from the PZT when driven in its resonance with a power of 2 - 3 W in agreement with the observations. Under the same pressure and the same conditions, a lens of length $d \approx 2$ cm is required for complete modulation.

From the nonradial, asymmetric and anisotropic shape of the stress distribution, we expect intuitively the beam waist on the output face of the HPL to be larger. For a more quantitative estimate, we make the approximation $n_b^3 \approx n_0^3(1 - 3A(x^2 + y^2)/2)$. In this case, equation (2) yields to a first approximation the following:

$$n_x \approx n_0 \left(1 - \left(\frac{A_x^*}{2}\right) (x^2 + y^2)\right)$$
$$n_y \approx n_0 \left(1 - \left(\frac{A_y^*}{2}\right) (x^2 + y^2)\right) \qquad (4)$$

where

$$A_x^* = A\left(1 + \frac{3n_0^2}{2E}\left((P_{11} - \nu_p P_{12})\sigma_x + (P_{12} - \nu_p P_{11})\sigma_y\right)\right)$$
$$A_y^* = A\left(1 + \frac{3n_0^2}{2E}\left((P_{12} - \nu_p P_{11})\sigma_x + (P_{11} - \nu_p P_{12})\sigma_y\right)\right) \qquad (5)$$

Hence under the strain, the parameter A is now a function of x and y and it is different for the two orthogonal polarization states and therefore the pitch and other parameters of the graded index medium are modified.[16] Although these changes are small, they can cause aberrations, wavefront distortions, beam widening and deflection in particular when the interaction length (the length of the lens) is large.[16] All of these parameters contribute to the LEM mode of operation. For a quantitative description, an exact solution of the wave equation with the profiles in equation (4) has to be performed. Near the axis, where the variation of σ_x and σ_y with x and y is weak, we can define an effective pitch $P = 2\pi/\sqrt{A^*_{x,y}}$ which can be smaller or larger under the strain, depending whether $p_{11} > p_{12}$ or $p_{11} < p_{12}$. In either case, this means that the beam in the HPL case is not focused on the output face and therefore its width is larger. This again contributes to the launch efficiency modulation. If the effective pitch is smaller, then this yields less divergence for the output beam in the QPL case and more divergence in the HPL case which explains the results of the beam radius measurements.

In conclusion, a new photoelastic modulator has been demonstrated based on the use of graded index lenses. This modulator may operate in one of two modes. A birefringence mode in which a polarizer and analyzer are required and a mode with no need for any polarizer in which the launch efficiency to an output fibre butted to a half pitch lens is modulated. This modulator is useful for polarization modulation in any micro-optic system and as an intensity modulator in fibre-optic systems.

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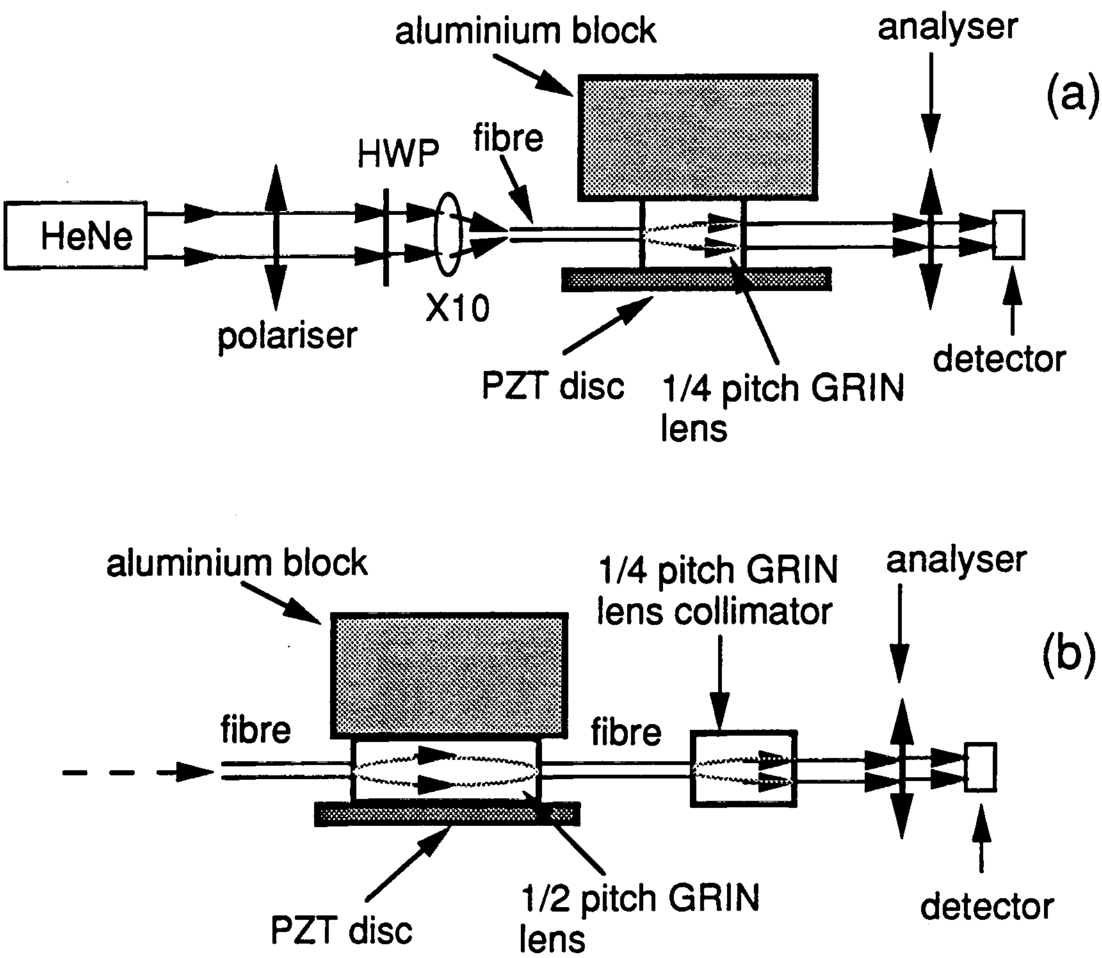
Figure Captions

Figure 1. (a) Schematic of the experimental setup used in the quarter pitch lens case. (b) Shows only the modified parts used in the case of a half pitch lens. The experimental setup is similar to (a) except that a second fibre was butted to its output face. The light from the fibre end was collimated by a different quarter pitch lens to the analyzer and the detector. In the launch efficiency mode of operation this analyzer was removed.

Figure 2. Photographs showing oscilloscope traces of the applied electrical signal to the PZT and the optical response in the birefringence mode of operation. (a) For quarter pitch lens and (b) for half pitch lens. The analyser axis is at 90° with respect to the direction of the incident polarisation. The incident polarisation is making an angle of ~ 45° with the direction of the applied stress. The frequency is 1.078 MHz and the electrical power is 2.5 W.

Figure 3. A photograph showing oscilloscope traces of the applied electrical signal and the optical response from a half pitch lens in the launch efficiency mode of operation. The zero level is out of scale and the incident light level is within the range of the optical response sinusoid. The frequency is 1.089 MHz and the electrical power is 2.5 W.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analyser
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analyser
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fibre
PZT disc
1/2 pitch GRIN lens
detector

fig. 1

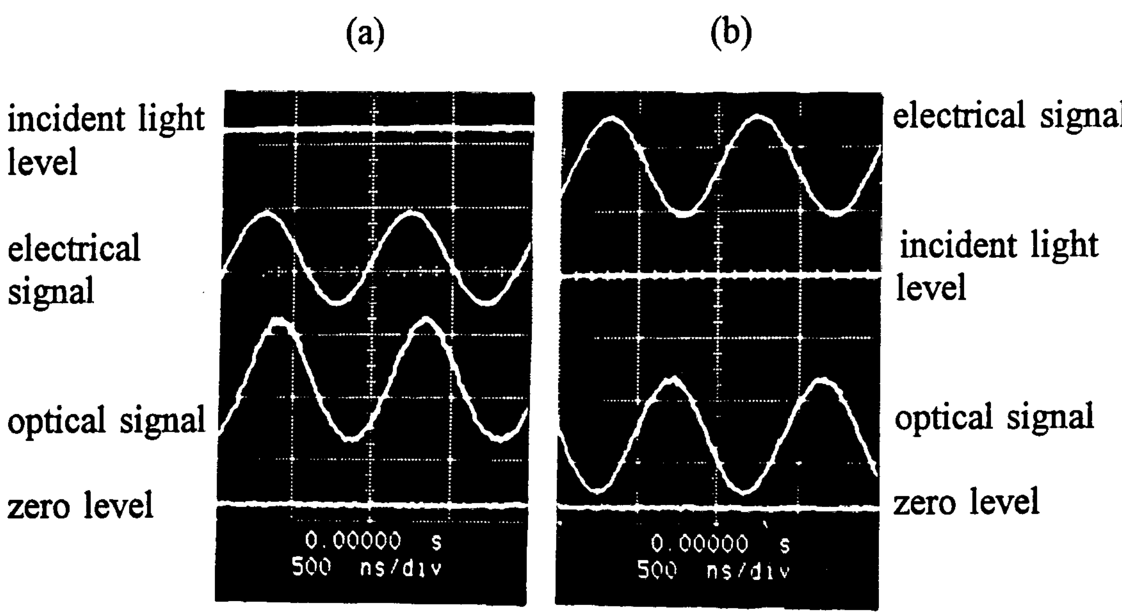
(a)
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fig. 2

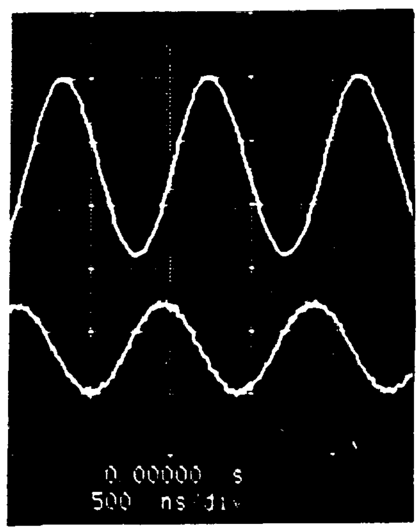

fig.3