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Photoelastic in-Fiber Birefringence Modulator Operating at the Fundamental Transverse Acoustic Resonance

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A Highly efficient photoelastic in-fiber birefringence modulator is demonstrated. It operates at the acoustic frequency ≈ 23 MHz which corresponds to the fundamental transverse acoustic resonance of a 125 μm diameter silica fiber. Using an analyzer at the output end of the fiber we obtained ≈ 90% amplitude modulation for an RF power of 0.7 W.

Efficient high frequency modulation of the polarisation or intensity of the light guided in an optical fiber has many applications in optical communications, fiber sensors and for Q-switching and mode locking of fiber lasers[1]. One of the most promising means to achieve this is by modulating a transverse mechanical stress applied to the fiber, thus modulating the birefringence[2-6] through the photoelastic (PE) effect[7]. The PE effect in circular optical fibers is known to be strong because the stress in the core is inversely proportional[2-6] to the fiber radius, which is smaller by a factor of 100-1000 than the dimensions of conventional bulk photoelastic modulators (PEMs). For a 2-3 cm long section of single-mode silica fiber with 125 μm diameter, the required uniaxial force to achieve complete modulation ($\pi/2$ rotation of the polarisation of incident linearly polarised light) is only a fraction of a Newton[2-6]. This force is achievable from standard PZT transducers and in fact such a modulation has been demonstrated[8-10] for frequencies up to few MHz. Strong amplitude modulation at higher frequencies has not been reported to our knowledge. In this article we describe a novel in-fiber PEM operating at ≈ 23 MHz, a frequency which corresponds to the fundamental transverse resonance of a silica fiber with a diameter d = 125 μm. The speed of sound in silica is v = 5950 m/s and therefore the fundamental transverse resonance frequency (FTR) is given approximately by $f_r = v/2d = 23.8$ MHz. This mode of operation is usually used with bulk PEMs and known as the half-wave resonance condition[7]. In the case of bulk PEMs however, this frequency is only a few tens of kHz due to the large dimensions of the device. This half-wave resonance is utilised here to build an in-fiber PEM. We refer to this modulator as the fiber fundamental transverse resonance photoelastic modulator (FTR-PEM). With the FTR-PEM we achieved almost complete modulation using RF electrical powers less than 1 W.

A schematic of the FTR-PEM is shown in figure 1. The FTR-PEM was designed to be used with any fiber of 125 μm diameter so that fibers can be mounted and demounted from the modulator easily. An aluminium plate 30 mm long, 20 mm wide and 3 mm thick was polished flat on both sides to a flatness of 0.5 μm. A 250 nm layer of Cr/Au electrode was deposited by evaporation onto the flat polished bottom surface of the aluminium plate. The piezoelectric transducer consisted of a 140 μm thick plate of $LiNbO_3$ (36° rotated Y-cut), corresponding to a resonant frequency of 23.8 MHz, which was indium cold welded onto the Cr/Au layer and centred along the length of the aluminium plate. The top electrode was of Cr/Au in the form of a stripe 1 mm wide and 22 mm long, aligned directly above the transducer. The transducer was connected via a matching network which was tuned so that the device exhibited a 50 Ω electrical load at the resonant frequency. The electrical bandwidth of the transducer was ≈ 1 MHz. The role of the aluminium plate is to provide a hard supporting base onto which a fiber is pressed, to distribute any generated heat efficiently and to transmit the acoustic wave with low attenuation. Aluminium has an acoustic impedance close to that of silica, so that backward acoustic reflections are minimised.

In order to demonstrate amplitude modulation, a single-mode fiber at 633 nm, 50 cm long, was positioned on the top polished aluminium side of the modulator, parallel to the transducer, and pressed with a flat silica block (figure 2). A good acoustic joint between the fiber and the modulator was achieved by varying the pressure of the top silica block. This pressure was carefully controlled by attaching the silica block to an optical micro-positioning translation stage. Light from a HeNe laser was launched into the fiber after passing through a polarizer and a half wave-plate (HWP). A quarter-pitch gradient index (GRIN) lens was used to collimate the output beam, which passed through an analyzer and onto the detector.

Figure 3 shows a typical amplitude modulated signal with a modulation depth of 90 % using 0.7 W RF power at 22.9 MHz. The variation of the modulation depth with the RF power is shown in figure 4. Although the transducer was tuned at 23.8 MHz, the modulation at this frequency was less than 20%. The modulation was found to be the highest for frequencies in the range 22.2-23.2 MHz, corresponding to the actual transverse resonance frequency for the fiber. The VSWR of the device at these frequencies was below 1.2.

The phase of the optical signal relative to the electrical signal changes with the HWP and the analyzer orientations. For each 90° rotation of the analyzer, the phase of the optical signal relative to the electrical signal shifts by 180°, and midway between these positions the modulation disappears. The same changes obtained by rotating the analyzer by a certain angle α can be obtained by rotating the HWP by $\alpha/2$, both rotating the plane of polarisation of the incident light by α. Similar changes were observed by varying the static pressure of the aluminium block on the fiber. The static pressure induces a static component of the birefringence which causes the light polarization state to evolve through the fiber in the interaction region. The acoustic wave adds a dynamic component, thus modulating the birefringence. The phase shifts between the electrical signal and the optical response are then attributed to the fact that the maximum and minimum of the transmittance depends on the vector sum (in the Poincare sphere representation) of the static and time-varying birefringences, and on the relative orientation of the HWP and analyzer. It is worth noting here that this behavior is similar to that reported[5-7] for periodic coupling in hi-bi fibers using PZT transducers at frequencies up to a few MHz.

The modulation depth (MD), the output level and the contrast ratio are all functions of the HWP-analyzer orientation. A modulation depth over 90% can always be achieved by changing the HWP-analyzer orientations, but then the output is not necessarily high. In our case the MD is defined as MD = $(I_{max} - I_{min})/I_0$, where I_{max}, I_{min}, are the maximum and minimum levels of the modulated signal and I_0 is the transmitted light level obtained when the analyzer is removed. The analyzer was orientated so that I_{max} is as close as possible to I_0, to minimise the losses. With such orientation, I_{max} is lower than I_0, only because of some losses in the analyzer itself and because the light is not exactly linearly polarised at the end of the fiber. We found that it is always possible to adjust the HWP-analyzer orientations so that these losses are less than 10%. The behavior of the modulation with the HWP-analyzer orientations supports the proposition that the optical modulation is simply due to polarisation modulation.

The induced birefringence in response to uniaxial transverse stress T_y applied along the y-axis is:

$$\Delta n = n_0^3(P_{12}-P_{11})(S_x-S_y)/2 \tag{1}$$

Here n_0 is the refractive index in the core, P_{11}, P_{12} are the photoelastic constants parallel to the applied stress and perpendicular to it respectively and S_x, S_y are the associated components of the strain. For a circular fiber it is known[2-5] that $T_y = -3T_x = -3F/\pi r$ where F is the applied force per unit length and r is the radius of the fiber. The strain components are related to the stress components by $S_{x,y} = (T_{x,y} - \nu_p T_{y,x})/E$, where E is Young's modulus and ν_p is Poisson's ratio. This yields $S_x - S_y = 4(1 + \nu_p)S_y/(3 + \nu_p)$. The strain component S_y is the peak value of the time-varying strain applied to the fiber core when the FTR condition is fulfilled. To find S_y we use the expression for the acoustic Poynting vector $I_a = \rho v^3 S_a^2/2$ where ρ is the density, v is the acoustic velocity and $S_a = S_y/\sqrt{2}$ is the rms value of the strain. Using these expressions in equation (1), we arrive at the following expression for the peak value of the birefringence:

$$\Delta n = -4n_0^3(P_{11} - P_{12})(1 + \nu_p)I_a^{1/2} / (3 + \nu_p)\rho^{1/2}v^{3/2} \tag{2}$$

For fused silica: $P_{11} = 0.12$, $P_{12} = 0.27$, $n_0 = 1.46$, $\nu_p = 0.17$, $\rho = 2200$ kg/m^3, v = 5950 m/s, and we get $\Delta n = 3.19\text{x}10^{-8}\sqrt{I_a}$ [SI]. Assuming that an acoustic power of $P_a = 0.7$ W is available, then with the transducer dimensions L = 22 mm and H = 1 mm we get $\Delta n = 5.69\text{x}10^{-6}$. The induced phase lag between the fast and the slow eigenwaves is $\beta = 2\pi\Delta nL/\lambda = 0.39\pi$. The total peak-to-peak modulation of the phase lag is then $\gamma = 2\beta = 0.78\pi$. If the HWP-analyzer orientations are such that I_{max} is maximised then MD = $\sin^2(\gamma/2)$. This yields MD = 89% in agreement with the observations.

In conclusion, a novel in-fiber photoelastic birefringence modulator has been demonstrated at 23 MHz. Its principle is based on tuning the acoustic frequency to satisfy the fundamental transverse resonance condition of the optical fiber. The birefringence modulation induces polarisation modulation which is converted to intensity modulation using an analyzer at the output. We obtained almost complete intensity modulation at RF powers less than 1 W. This modulator can be used as a polarisation modulator in ellipsometry or as an amplitude or phase modulator for mode locking of fiber lasers.

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References

[1] Jean-Pierre Goure, Isabella Verriere, Jean-Pierre Meunier, "Linear and nonlinear optical fiber devices", J.Phys.D:Appl.Phys., Vol. 22, PP. 1791-1805, 1989.

[2] Y. Namihira, M. Kudo, and Y. Mushiake, "Effect of mechanical stress on the transmission characteristics of optical fiber", Elect.Commun.Jap., Vol. 60-C, PP. 107-115, 1977.

[3] M. Johnson, "In-line fiber-optical polarization transformer", Appl.Opt., Vol. 18, PP. 1288-1289, 1979.

[4] N. Chinone, R. Ulrich, "Elasto-optic polarisation measurement in optical fiber", Opt.Lett., Vol. 6, PP. 16-18, 1981.

[5] S.C. Rashleigh, "Origins and control of polarization effects in single mode fibers", J. Lightwave Technol., Vol. LT-1, PP. 312-331, 1983.

[6] A. J. Barlow, D. N. Payne, "The stress-optic effect in optical fibers", IEEE J.Quant.Electr., Vol. QE-19, PP. 834-839, 1983.

[7] E. K. Sittig, "Elasto-optic light modulation and deflection", in Progress in Optics, Ed. E. Wolf, Vol. 10, Ch. VI, (North Holland Publishing Company, Amsterdam 1972).

[8] For a review see, R.C. Youngquist, J.L. Brooks, W.P. Risk, G.S. Kino, H.J. Shaw, "All-fiber components using periodic coupling", Proc.IEE, Vol. 132, PP. 277-286, 1985.

[9] J.L. Brooks, R.C. Youngquist, G.S. Kino, H.J. Shaw, "Active polarization coupler for birefringent fiber" Opt.Lett., Vol. 9, PP. 249-251, 1984.

[10] W.P. Risk, G.S. Kino, "Acousto-optic polarization coupler and intensity modulator for birefringent fiber" Opt.Lett., Vol. 11, PP. 48-50, 1986.

Figure captions

Figure 1. Schematic showing the main parts of the 23 MHz modulator.

Figure 2. Schematic showing the experimental setup used for amplitude modulation measurements.

Figure 3. Photograph of oscilloscope traces for the applied electrical signal and the modulated optical response at 22.9 MHz and 0.7 W RF power.

Figure 4. Variation of the modulation output with the applied RF power under similar conditions to figure 3.

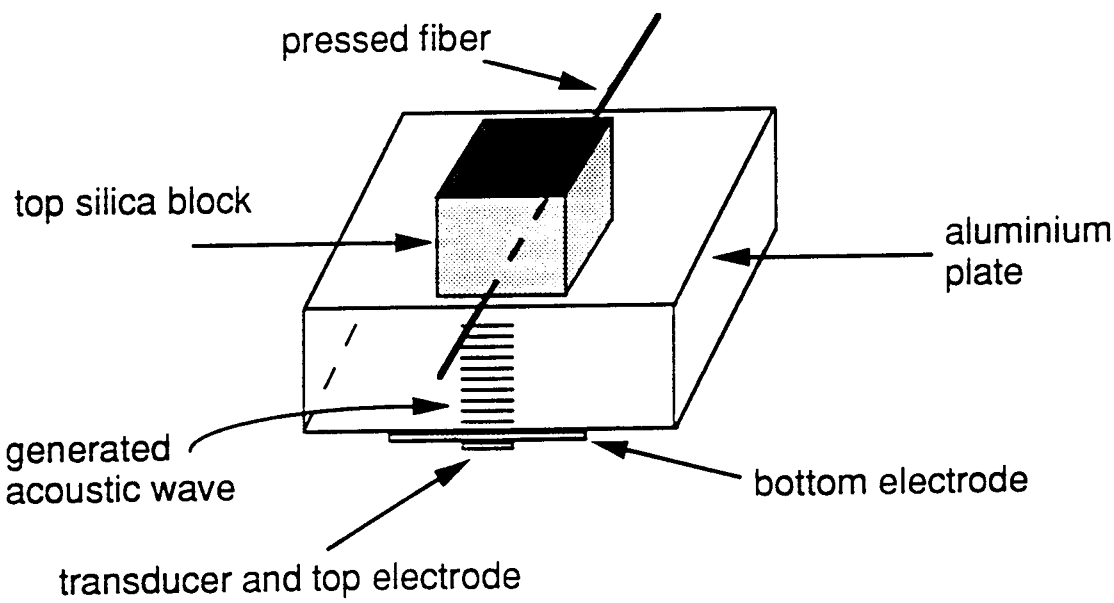
pressed fiber
top silica block
aluminium
plate
generated
acoustic wave
bottom electrode
transducer and top electrode

fig. 1.

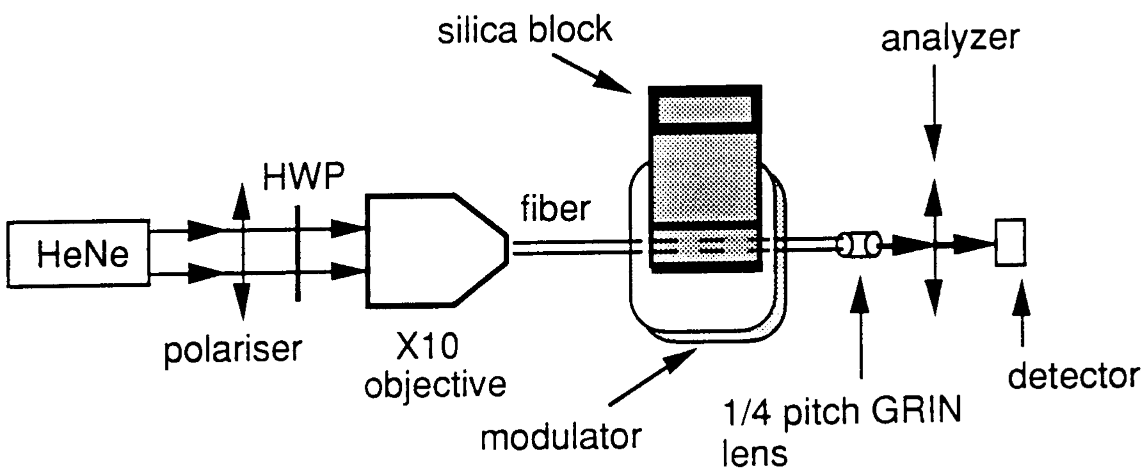
silica block
analyzer
HWP
fiber
HeNe
polariser
X10
objective
modulator
1/4 pitch GRIN
lens
detector

Fig. 2

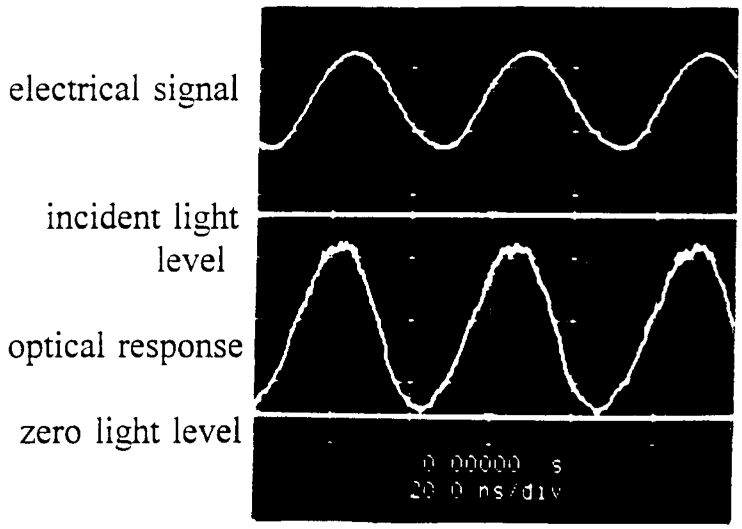
electrical signal
incident light level
optical response
zero light level
0.00000 s
20.0 ns/div

fig. 3

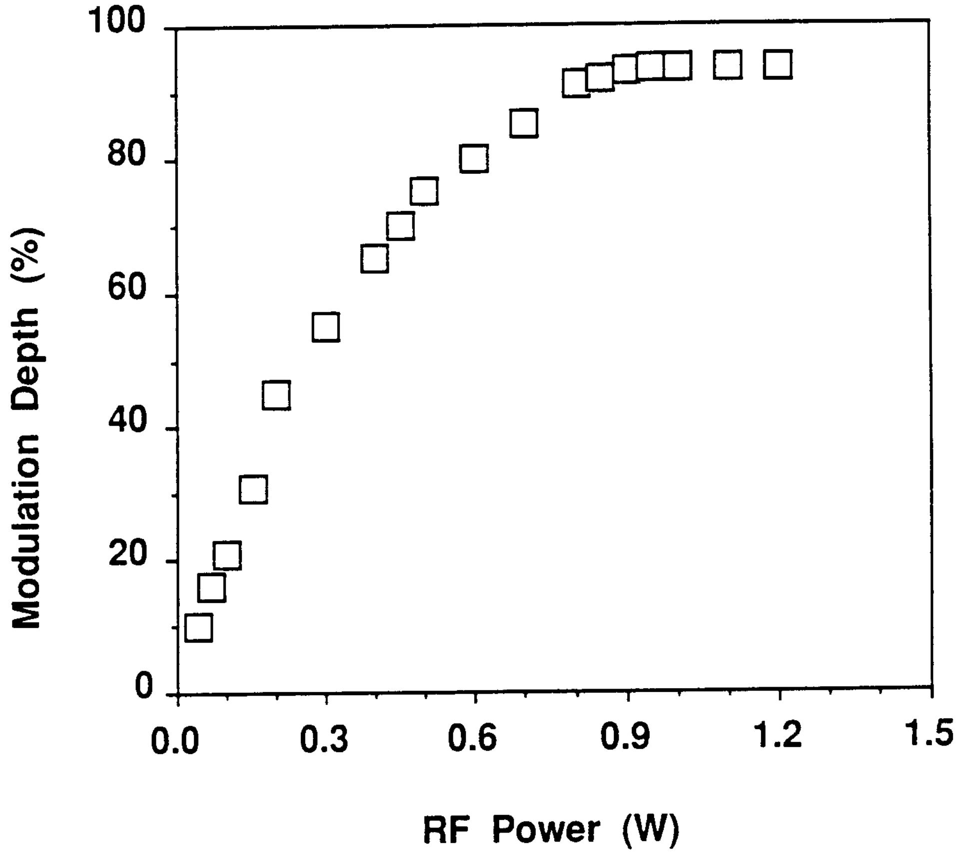

fig.4