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Elasto-Optically Induced Modulation of In-Fiber Grating

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We report on strong effects of uniaxial stress applied on in-fiber grating. Under the stress the reflection peak splits into two due to the elasto-optically induced birefringence. The separation between the two peaks increases with the stress, they broaden and shift. By modulating the pressure using a PZT disc at frequencies up to 1 MHz, we obtained modulation of the reflectivity which varies with the wavelength within the grating reflection band.

In-fiber gratings (IFGs) are highly promising components for building in-fiber interferometers, fiber lasers and sensors. The sensitivity of IFGs to external parameters such as temperature and pressure make them useful for sensing, frequency tuning and as a mean for building in-fiber amplitude modulators via modulating the external parameters. Active and passive fiber temperature, strain, and hydrostatic pressure sensors have been demonstrated[1-5] based on the associated change of the grating period and the refractive index. The effect of uniaxial pressure on IFG has not been reported to our knowledge. In this letter we report on strong modification of the reflection spectrum of IFG upon applying both a static uniaxial stress and the resulting amplitude modulation obtainable when the stress is modulated using PZT transducers.

The IFGs used were holographically written with UV light in germania and boron-doped silica fiber to give a single Bragg reflection peak near the wavelength $\lambda \approx 1550$ nm. For static stress measurements the gratings were spliced to one of the output ports of a 2 x 2, 50/50 directional fiber coupler (figure 1). We distinguish between the two cases of static stress and dynamic stress when the stress is modulated using a PZT transducer. In the static case the light source used was a pigtailed broadband LED with an output power of ≈ 10 μW spliced to one of the input ports of the coupler. The reflected light from the return port was fed into an optical spectrum analyzer (ANDO AQ-6310B). The stress was applied by pressing the grating with a flat aluminium block on top of a flat glass slide. The stress was carefully controlled by attaching the aluminium block to an optical micro-positioning translation stage in such a way that it can pivot to lay flat on the fiber. The applied stress was measured by positioning the grating and the lower glass slide on top of an electronic balance while pressing with the top aluminium block. This measurement of the stress was also confirmed by directly pressing the grating with weights.

Figure 2 shows the main effects induced by the applied stress on the reflection peak. The full width at half maximum of the grating reflection peak without pressure is 0.21 nm. The original peak splits into two peaks. For small stresses, the two peaks are not resolved but their existence is predicted by the observed broadening of the original peak. Nonuniformities in the pressure causes asymmetry in the peaks heights and shape. Such nonuniformity effects were observed in particular when the stress was small (dotted curve in figure 2). As the stress increases the splitting becomes larger and the existence of two peaks becomes clearer in particular when the original peak width is enough narrow (dashed curve in figure 2). The height of each of the two peaks becomes equal to half the height of the original peak. For a grating which exhibited a full width at half maximum (FWHM) of the reflection peak of $\approx$ 0.33 nm, the induced peak appeared as a hump in the high λ shoulder of the original peak.

The splitting of the reflection band under a uniaxial stress can be explained as a result of the stress induced birefringence[6]. Upon applying a uniaxial force F diametrically on an optical fiber the induced birefringence is given by[6]:

$$\Delta n = 2n_o^3 (P_{11} - P_{12})(1 + \nu_p) F/(\pi r \ell E) \qquad (1)$$

Here n_o is the refractive index of the core, P_{11}, P_{12} are the photoelastic constants parallel to the force and perpendicular to it respectively, ν_p is Poisson's ratio, E is Young's modulus, r is the fiber radius, ℓ is the pressed length of the fiber. For fused silica: $P_{11} = 0.12$, $P_{12} = 0.27$; $n_o = 1.465$, $\nu_p = 0.17$, $E = 7.6 \times 10^{10}$ N/m^2 and for $\ell = 2$ cm we get $\Delta n = 3.66 \times 10^{-6}F$. The splitting is given by $\Delta\lambda = \lambda_p \Delta n/n_o$ where λ_p is the wavelength which corresponds to the peak position before applying the stress. For $\lambda_p \approx 1545$ nm and using the measured value of the splitting of $\Delta\lambda \approx 0.4$ nm we find an induced birefringence of $\Delta n \approx 3.8\text{x}10^{-4}$. The measured force which yields the maximum splitting of $\Delta\lambda \approx 0.4$ nm is $F \approx 30$ N, which gives $\Delta n \approx 1.1 \times 10^{-4}$ according to equation (1). This is smaller than the experimental value by a factor of ≈ 3.4. The most likely reason for this discrepancy is perhaps because the parameters used in equation (1) which correspond to silica can be different from those for the actual core which is germania and boron-doped, in particular its Young's modulus, Poisson's ratio and the difference between the photoelastic constants. This may also be the cause for the shift of the two peaks (figure 2) simultaneously in the same direction to higher wavelengths which suggests that the changes in the refractive indices along the force (δn_y) and perpendicular to it (δn_x) are both positive. In silica the change of the refractive index in response to a uniaxial force is expected[6] to be negative along the force ($\delta n_y < 0$) and positive perpendicular to it ($\delta n_x > 0$) according to: $\delta n_{x,y} = -n_0^3F[(1 + 3\nu_p)P_{11,12} - (3 + \nu_p)P_{12,11}] / 2\pi rlE$. The sign of $\delta n_{x,y}$ is determined by the expression in the square brackets $g_{x,y} = (1 + 3\nu_p)P_{11,12} - (3 + \nu_p)P_{12,11}$. In our case we calculated $g_x = -0.674$, and $g_y = +0.027$. Since g_y is small, then any small difference in the values of the photoelastic constants and Poisson's ratio can change its sign. Experimentally measured values of the stress-optic coefficient show a strong dependence on the wavelength and the germania concentration in the fiber core[7,8]. We should mention here that similar discrepancy between measured and calculated parameters of the grating was reported in the results of the strain[1] and hydrostatic pressure[5] sensor experiments. These facts led us to conclude that the discrepancy between the expected and the observed behaviour of the stress-induced birefringence and shift of the peaks are mainly due to different values of the photoelastic constants and Poisson's ratio of the germania-doped and boron-doped fiber core. The effect of the UV light which is related to defect formation in the core may be another reason for the change in its mechanical and photoelastic parameters.

From the appearance of the additional reflection peak, the broadening of the reflection band and the shifts in the two peak positions with the stress, we expect wavelength-dependent amplitude modulation to occur if the applied stress was modulated. To demonstrate this we replaced the LED with a narrowband source (HP 8168A) tunable in the range 1500-1565 nm. The IFG was pressed on top of a PZT disc of the type 5A (Vernitron - UK) having 22 mm diameter and 1.8 mm thick designed to resonate in thickness mode at 1 MHz. The polarization controller positioned just before the grating (figure 1) affected the stress induced reflectance modulation because the incident light from the HP tunable source is polarized. The polarization state of the light entering the grating was measured by analyzing the state of polarization of the transmitted light which was collimated with a quarter pitch GRIN lens through a calcite polarizer and to the detector. The modulated optical signal was detected with a photodiode and displayed on an oscilloscope. Optical modulation at low resonant frequencies of the PZT and near the 1 MHz resonance was observed both in transmission and in reflection. Figure (3) shows typical oscilloscope traces of the modulated optical signal at different wavelengths within the reflection band. The variation of the modulation depth with the wavelength correlates with the changes observed in the reflectivity under static pressure, however the modulation in the dynamic case is weaker than in the static case. This is because in the dynamic case, the applied stress from the PZT is smaller and also because of the static component of the stress which appears once the IFG is assembled between the top aluminium block and the PZT. Consequently, in response to the elastic wave the birefringence oscillates around a mean value which is different from zero.

Effects of varying the polarization state of the incident light have also been observed. The maximum modulation was obtained when the polarization controller was adjusted so that the reflectance at $\lambda \approx 1545.65$ nm was maximised. The polarization state was confirmed to be linear in the direction nearly perpendicular to the applied stress by analyzing the polarization of the transmitted light (figure 1). With this polarization state the reflectance near the original peak, $\lambda \approx 1545.2$ nm, and the modulation depth were negligible. When the polarization controller was adjusted to obtain a transmitted light with polarization state nearly linear and parallel to the applied stress, the reflectance near the peak at $\lambda \approx 1545.65$ nm was negligible while that near $\lambda \approx 1545.25$ nm was maximised. The modulation in this case was weak at any wavelength. This is because the change in the reflectivity near the original peak is weaker than outside its region.

In conclusion, we report strong effects of a uniaxial stress on in-fiber grating reflectivity. The reflection peak splits into two which then shift and broaden with the applied stress. Amplitude modulation was demonstrated by modulating the stress using PZT transducer at frequencies up to 1 MHz.

Acknowledgements

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Figure Captions

Figure 1. Schematic diagram of the experimental setup.

Figure 2. Reflection spectrum at different static pressures. solid line with no pressure applied, dotted line is with small force of ≈ 5 N, and the dashed curve is obtained with a force of ≈ 30 N.

Figure 3. Photograph of oscilloscope traces showing the modulated signal at different wavelengths in response to an ac electric field applied to the PZT disc. The voltage is 20 V peak-to-peak and the frequency is 1.12 MHz. The vertical scale for the signal which corresponds to λ = 1545.2 nm is higher by a factor of 2 than those for the other wavelengths.

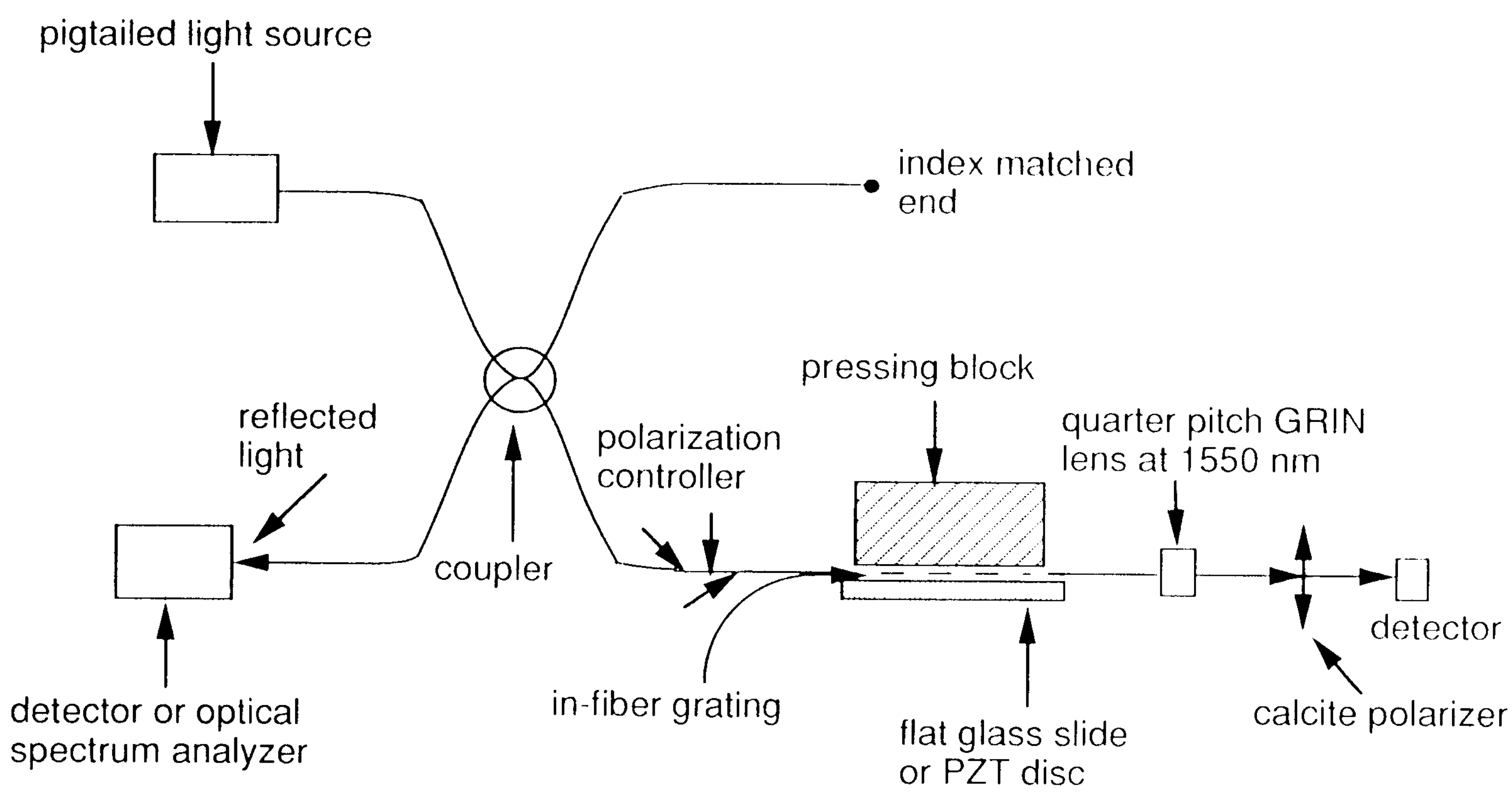
pigtailed light source
index matched end
pressing block
reflected light
polarization controller
quarter pitch GRIN lens at 1550 nm
coupler
detector
in-fiber grating
calcite polarizer
detector or optical spectrum analyzer
flat glass slide or PZT disc

Fig. 1

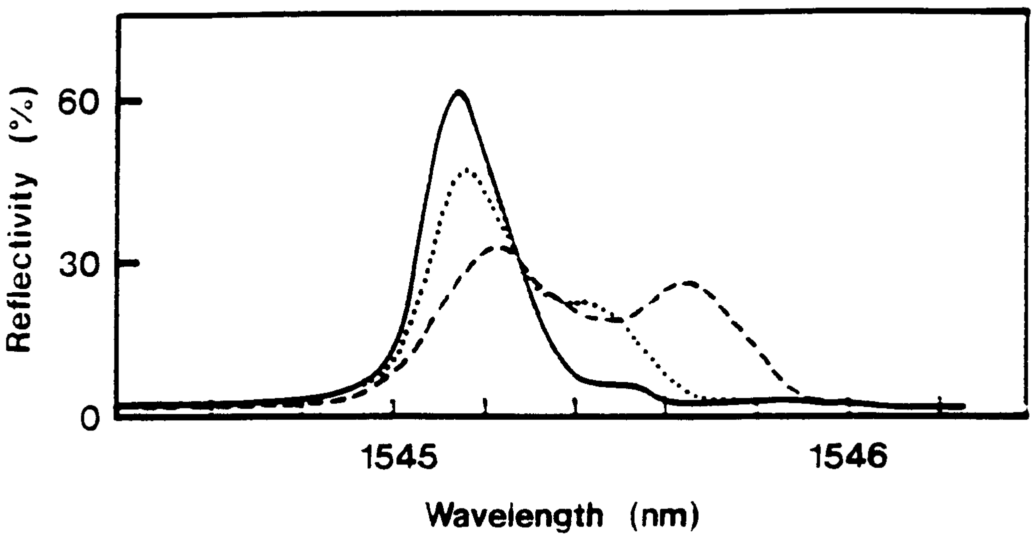

fig. 2

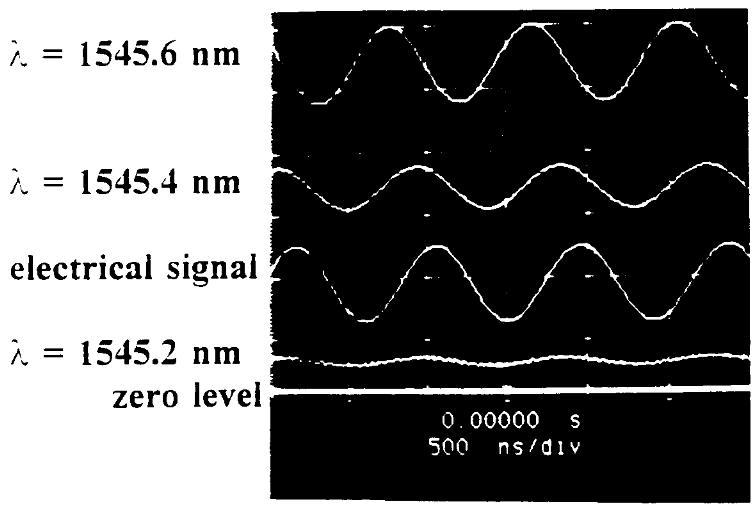
λ = 1545.6 nm
λ = 1545.4 nm
electrical signal
λ = 1545.2 nm
zero level
0.00000 s
500 ns/div

fig. 3