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Photoinduced birefringence in optical fibers: a comparative study of low-birefringence and high-birefringence fibers

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A study of photoinduced birefringence in bow-tie (stress-induced) high-birefringence (Hi-Bi) and low-birefringence (Lo-Bi) germanosilicate optical fibers is conducted by using 532-nm light. The study reveals that Hi-Bi fibers are insensitive to light polarized along the fast axis, in contrast to Lo-Bi fibers, which are photosensitive along both axes. The induced birefringence in Lo-Bi fibers is reversible, whereas the change in Hi-Bi fibers is permanent. The sign of the induced birefringence is established experimentally for the first time to our knowledge, and the significance of the results to models based on stress and/or glass defects is briefly discussed.

Since the first demonstration of photorefractive grating formation in GeO_2-doped silica fibers,[1] a considerable amount of effort has been devoted to elucidating the physical mechanisms that give rise to the observed photosensitivity (refractive-index changes are observed on exposure to blue, green, and ultraviolet light) and to exploiting the effect in practical fiber grating devices. Although some progress has been made in understanding the role of Ge-associated defect centers, a fully satisfactory explanation has still not emerged.[2] A further curious feature of the photoinduced index change is its anisotropy or birefringence. This effect, reported some time ago by Parent *et al.*,[3] was recently used for the first time to our knowledge to fabricate (through polarization-mode interference) rocking filters in high-birefringence (Hi-Bi) fibers that function as polarization-mode converters in a narrow spectral band.[4] These devices have subsequently been demonstrated in elliptical-core fibers at 514.5, 488, and 532 nm (Ref. 5) and by periodic side illumination with ultraviolet light polarized at an angle of 45° to the intrinsic axis of birefringence.[6]

In this Letter we report the results of a detailed comparative study of the photoinduced birefringence (PIB) in low-birefringence (Lo-Bi) and stress-induced Hi-Bi fibers. One motivation for this study was the desire to explain why rocking filters fabricated in elliptical-core Hi-Bi fibers prove to be more efficient than those made in fibers with stress-induced high birefringence. Ouellette *et al.* recently characterized the PIB in Lo-Bi germanosilicate fiber[7]; the comparison between Lo-Bi and Hi-Bi fibers presented in this Letter reveals a number of interesting differences, in particular regarding the reversibility of the birefringence change. The significance of our results for various stress-relief and glass-defect models is briefly discussed.

A pump–probe setup, illustrated in Fig. 1, was used to measure the birefringence changes. Linearly polarized, cw, mode-locked 532-nm light from a frequency-doubled Nd:YAG laser was launched into the fiber with its polarization state aligned along one of the principal axes of the fiber. The induced birefringence was monitored by launching a linearly polarized, 633-nm, He–Ne probe beam at 45° to the principal axes. By measuring the power transmitted through an analyzer (AN), also aligned at 45°, changes in the birefringence could be measured. The power meter (PM) monitors the transmitted green light (532 nm), and detector D1 monitors the total red light (633 nm). A filter (F) was inserted to block the green light. Both the glass plate (GP) and the beam splitter (BS2) were oriented at close to normal incidence to minimize the effect of polarization-dependent reflection. The signal from detector D2 was divided by the signal from detector D1, which yielded a normalized signal from the analyzer that was independent of the launch conditions.

The stress-induced Hi-Bi fibers used in the experiments were of bow-tie construction, with a core diameter of 1.5 μm and a GeO_2 concentration of 13.9 mol.%. Their intrinsic birefringence ($B_i = n_s - n_f$) was 7×10^{-4}. The Lo-Bi fiber had a core diameter of 1.2 μm and a GeO_2 concentration of 17.7 mol.%; its intrinsic birefringence was measured to be approximately 2.5×10^{-6}.

The experimental results are shown in Fig. 2. In Fig. 2(a) the normalized transmission through the analyzer is plotted as a function of time for a 22-cm length of Hi-Bi fiber. In Fig. 2(b) the corresponding result with a 15-cm length of Lo-Bi fiber is shown. In both experiments the average green intensity in the core was approximately 50 mW/μm^2, the pulse repetition rate was 76 MHz, and the pulse width was approximately 100 ps. After the first 45 min the polarization of the green light was rotated by 90°, i.e., from the x direction to the y direction. Then after another 45 min the polarization of the green light was turned back to the x direction; after a further 45 min the green light was blocked. We see that during the first 45-min period the behavior for the Hi-Bi and Lo-Bi fibers is similar. When the polarization is rotated, however, the Hi-Bi

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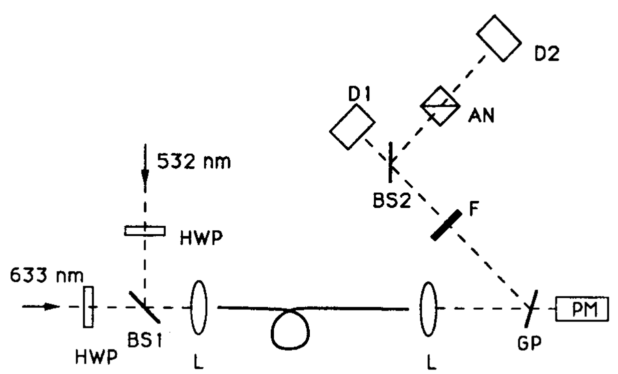

Fig. 1. Experimental setup. HWP's, half-wave plates; BS1, BS2, beam splitters; L's, lenses.

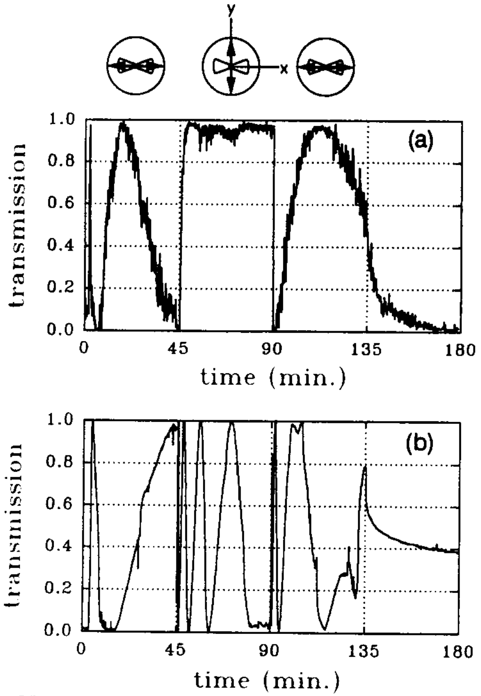

Fig. 2. Normalized signal transmitted through the analyzer as a function of exposure time in (a) Hi-Bi fiber and (b) Lo-Bi fiber. After 45 min the polarization of the green light is rotated 90°, after 90 min it is rotated back, and at 135 min the green light is blocked.

fiber exhibits a rapid transient change, after which there is no further change in the birefringence. Then, when the pump polarization is returned to its original direction (the x direction), the induced birefringence ΔB continues to grow as it did during the first 45-min period. Note also that ΔB continues to grow after the green light is blocked. The monitored signal was much noisier in the Hi-Bi case. This is because birefringence fluctuations caused by changes in temperature are much more severe in Hi-Bi fiber owing to the higher coefficient of thermal expansion in the stress-producing elements.

In the Lo-Bi fiber there is, as expected, no significant difference between the two directions. Note the increased number of cycles during the second 45-min period, i.e., after the polarization was switched for the first time. This is probably due to the combined effects of erasure of the ΔB created by the pump along the x direction and the creation of new ΔB by the pump along the y direction. This is illustrated more clearly in Fig. 3, where the actual change in B (calculated from the data in Fig. 2) is plotted. Some digital filtering was applied to the data presented in Fig. 3. A PIB of 10^{-5} has been attained in both the Hi-Bi and the Lo-Bi fibers. The sign of the birefringence and the change of the sign when the polarization is switched between the x and y directions cannot be established from Fig. 2, so additional experiments were performed to clarify this. By using a Michelson interferometer with a quarter-wave plate inserted in one of the arms, and a polarizer at the output, the interference pattern of the two polarization modes of the probe light could

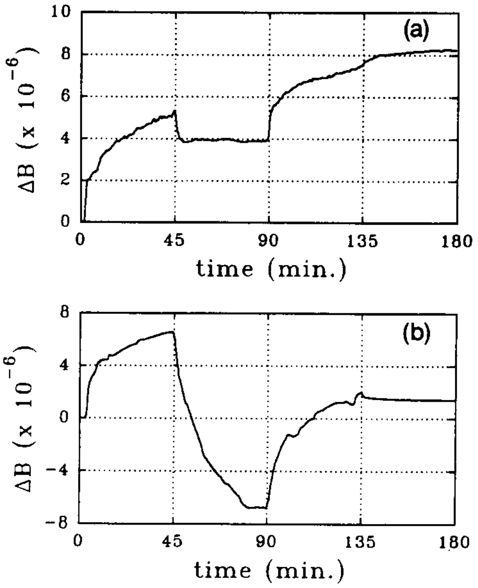

Fig. 3. Normalized transmission in Fig. 2 converted to birefringence change ΔB for (a) Hi-Bi fiber and (b) Lo-Bi fiber.

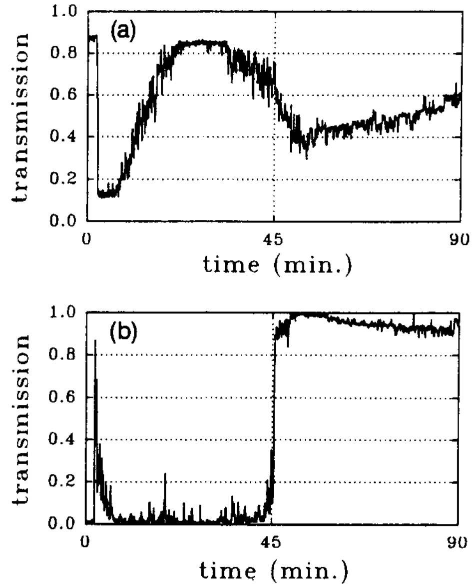

Fig. 4. Normalized signal from the analyzer in Hi-Bi fiber when the green light is polarized in the nonsensitive y direction. (a) Fresh sample, (b) sample previously exposed to x-polarized light for 45 min.

be observed. The direction of the fringe movement owing to the PIB was compared with the direction of the fringe movement caused by an increase in the length of one of the arms of the interferometer. In this way the PIB was found to be negative. The relative optical path length decreases in the direction of the pump electric field.

In the case of Hi-Bi fiber the x and y directions correspond to the slow and fast axes, respectively. To check whether the fiber is also insensitive along the fast axis (y direction) when it has not been exposed previously to a pump beam polarized along the slow axis (x direction), we exposed a fresh sample of the fiber to y-polarized light. Figure 4(a) shows the probe signal transmitted through the analyzer as a function of exposure time in that case. Figure 4(b) shows the measured transmission in another sample that had been previously exposed to the pump polarized in the x direction for 45 min, after which it had been allowed 45 min to stabilize while the pump was blocked. For the data shown in Fig. 4 the pump beam was blocked after an exposure of 45 min. We see that for the fresh sample exposed to y-polarized light, there is also a slow change in addition to the rapid one, but this change is considerably less than what was observed in the x-polarization case. We also notice that the relaxation when the green light is blocked is different for the two cases in Fig. 4. There is clearly an asymmetry and an irreversibility in the PIB in the Hi-Bi fiber. This is in contrast to the case of the Lo-Bi fiber, where the PIB seems to be reversible. The changes caused by light polarized along one direction can be erased and induced many times without any significant change in the value of ΔB or the relaxation behavior.

Because the behavior of the PIB in the germanosilicate fibers is quite complicated, it is difficult to give a complete explanation of all the observed features. Some general remarks may be made, however. In the Hi-Bi fiber there seem to be at least two different physical processes leading to the change in birefringence. The first is not related to the stress distribution in the fiber and has a characteristic response time of approximately 30 s. The second, slower, contribution may be linked to the distribution of the stress. A recent study has shown that Ge E' defect centers are concentrated at the edge of the core, which suggests that their creation is favored in regions of high stress gradients.[8] Our results, on the other hand, seem to suggest that the uniform stress associated with one of the birefringent axes of the Hi-Bi fiber may be responsible for the irreversible part of the birefringence change. We suggest two different possible mechanisms, emphasizing, however, that these are at present merely speculations:

(1) Breakage by two-photon absorption is more likely to occur at sites where the oxygen-deficient bonds are oriented appropriately to the local optical field; in addition, mechanically stressed bonds are more likely to break if the stress and the electronic polarization are parallel, and after breakage the glass matrix will pull apart (or compact) irreversibly. Since the intrinsic birefringence of Hi-Bi fibers is due to stress, any stress relief will change the birefringence.

(2) All or most of the oxygen-deficient bonds in one direction are already broken by stress; only when the light is polarized in the orthogonal direction will Ge E' centers be created, releasing electrons that can be trapped in an anisotropic manner at other defect sites.

For the Lo-Bi fiber a picture based on reversible bond breakage and anisotropic trapping of electrons seems to be most appropriate. Nonlinear transmission and light-induced absorption in germania-doped silica fibers have been studied previously[9] and are attributed to a redistribution of electrons between different species of defect center. However, a detailed study of the dynamics of PIB is necessary before a direct comparison with the absorption study can be carried out.

In conclusion, we have demonstrated that stress-induced Hi-Bi fibers are relatively insensitive to light polarized along the fast axis. This explains why the conversion efficiencies of rocking filters made in this fiber are much less (~10%) than those in elliptical-core fibers (~100%). Our results suggest that two possible mechanisms may be involved. While stress seems to be playing a role in the observed asymmetry of PIB in Hi-Bi fibers, the reversibility of PIB in Lo-Bi fibers suggests an electronic redistribution-type mechanism. Further experimentation, including a more detailed study of the dynamics of the process, is necessary before more certain conclusions can be drawn.

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