

Ultraviolet light photosensitivity in Ge-doped silica fibers: wavelength dependence of the light-induced index change

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A novel technique is reported for detecting permanent and transient light-induced refractive-index changes (photosensitivity) in optical fibers. The index change is detected by irradiating one arm of an unbalanced Mach-Zehnder fiber interferometer with UV light, thereby changing its optical path length. From a measurement of the change in the spectral response of the Mach-Zehnder interferometer, the change in the fiber core index as a function of wavelength can be determined. The equilibrium change in the core index is found to have an almost constant value of approximately 2.3×10^{-5} over the measured wavelength range of 700 to 1400 nm.

Photosensitivity in optical fibers was first observed in Ge-doped-core silica fibers by forming a standing wave in the core of an optical fiber.¹ More recently, it was demonstrated that gratings can be written externally by exposing such fibers to UV radiation through the side.² Hand *et al.*³ have measured the photosensitive response of Ge-doped fibers to 488- and 266-nm radiation at 633-, 488-, 784-, and 1550-nm laser lines. In this Letter the application of an unbalanced Mach-Zehnder fiber interferometer to the measurement of the 249-nm light-induced refractive-index changes in Ge-doped-core fibers is reported over a wide spectral range, using a white-light source. The exposure of one of the arms of a Mach-Zehnder interferometer to UV light shifts the characteristic sinusoidal wavelength response of the interferometer either to shorter or longer wavelengths. From a measurement of this wavelength shift, the magnitude and the polarity of the refractive-index change in the fiber core can be deduced.

Figure 1 depicts the experimental setup, which comprise a fiber Mach-Zehnder interferometer (M-Z), a UV light source, and an apparatus to measure the spectral response of the Mach-Zehnder interferometer. The Mach-Zehnder interferometer is fabricated from dissimilar fibers as described previously⁴ by using Corning telecommunication fiber (core radius 4 μm , cutoff wavelength 1.1 μm , estimated GeO_2 fraction 2.55 mol %) and Corning sensor fiber (core radius 2.25 μm , cutoff wavelength 0.75 μm , estimated GeO_2 fraction 3.65 mol %). The fabrication process requires the prepulling of the telecommunication fiber before the dissimilar fibers are fused to form the fused couplers. Thus the Mach-Zehnder interferometer arm formed from the telecommunication fiber has a core size of only 7.2 μm compared with a core size of 8 μm for a standard fiber. The length of the Mach-Zehnder interferometer is ~ 5 cm between the centers of the two fused couplers. The dissimilar-fiber Mach-Zehnder interferometer has the property that at a wavelength of 1500 nm the optical path difference is almost zero, and, consequently, no difference in the optical phase results between light waves propagating by the two

routes through the interferometer. Thus the interferometer is said to be balanced. At 700 nm the interferometer is unbalanced, which results in a phase difference of $\sim 100\pi$. The larger optical path length is the light path through the sensor fiber arm. It is important to fabricate a Mach-Zehnder interferometer with the appropriate degree of unbalance. If the unbalance is too small, the spectral response is too flat to detect wavelength shifts easily. If the unbalance is too large, the coupling ratio changes so rapidly with wavelength that it is hard to determine unambiguously

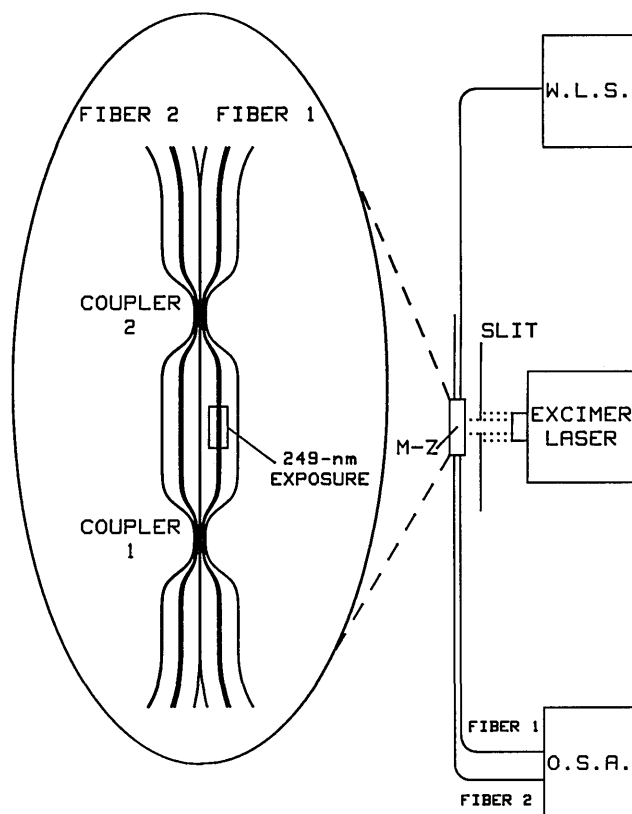


Fig. 1. Experimental setup. On the left is a magnification of the Mach-Zehnder fiber interferometer.

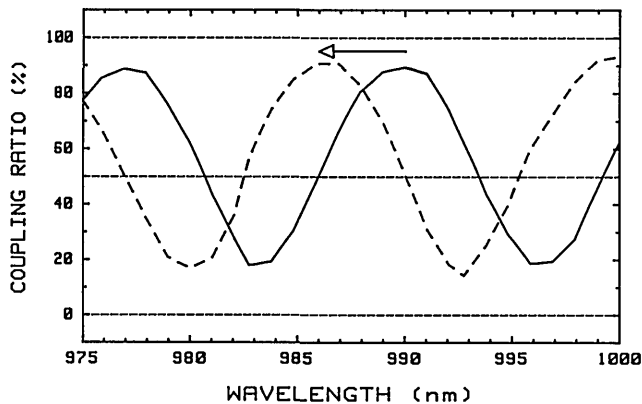


Fig. 2. Coupling ratio of Mach-Zehnder interferometer as a function of wavelength. The solid and dashed curves are, respectively, the coupling ratio before and after exposure to UV light.

ly how the response has shifted. The Mach-Zehnder interferometer fabricated here has an unbalance that is appropriate for carrying out measurements in the 700–1400-nm wavelength range.

In the experiment, a UV light pulse from a Lumonics Series TE-260-2 excimer laser is impinged upon one arm of the dissimilar-fiber Mach-Zehnder interferometer. The UV light beam has a wavelength of 249 nm, a pulse length of 8 nsec, an energy per pulse of 240 mJ, a peak power of 30 MW, and a cross section of $3 \text{ cm} \times 0.7 \text{ cm}$. To control the region of the Mach-Zehnder interferometer that is irradiated by UV light, the interferometer is masked by a slit with a $50 \mu\text{m} \times 0.7 \text{ cm}$ opening. The opening is sufficiently narrow to restrict the irradiation by UV light to only one of the interferometer arms. A white-light source (W.L.S.) and an optical spectrum analyzer (O.S.A.) are used to measure the transmission of the Mach-Zehnder interferometer as a function of wavelength. From a measurement of the Mach-Zehnder transmission through both fiber output ports of the interferometer, the coupling ratio as a function of wavelength can be determined.

The experiment consists of measuring the wavelength dependence of the coupling ratio of the Mach-Zehnder interferometer before exposure and after exposure of one of the interferometer arms. It is found that in the case of the telecommunication fiber, UV irradiation causes the peaks in the spectral response of the interferometer to shift to shorter wavelengths. This case is shown in Fig. 2. If the sensor fiber is irradiated, the opposite effect occurs, and the spectral response shifts to longer wavelengths. A further observation is that the magnitude of the initial shift in the wavelength response is not constant but decreases in time. The spectral response of the Mach-Zehnder interferometer eventually reaches with time a stationary equilibrium value in which its wavelength response is permanently shifted from that of the unexposed fiber. It takes approximately 3 h after exposure for the telecommunication fiber to equilibrate, whereas the sensor fiber equilibrates in only 0.5 h. A final observation is that the rapid irradiation of the fiber by more than one light pulse generates a larger initial

wavelength shift in the Mach-Zehnder spectral response. The increase in wavelength shift is found, however, to saturate at a maximum value after irradiation by several laser pulses. In our case, only two light pulses are required to attain 90% of the maximum achievable value in the initial wavelength shift. Both the time response and the saturation of the initial shift in the Mach-Zehnder interferometer wavelength response are subjects that require further investigation.

The results reported here are for fibers that have been irradiated by 50 laser pulses in order to ensure that a 100% saturation is achieved in the initial shift in the Mach-Zehnder interferometer wavelength response.

The experiment yields the coupling ratio of the Mach-Zehnder interferometer in the wavelength region of 700–1400 nm before and after irradiation of one of the interferometer arms by UV light. The change in the Mach-Zehnder interferometer spectral response is caused by UV light-induced change in the optical path length and thus the optical phase of light propagating through the irradiated arm. The change in optical phase is readily determined from the experimental data by using the fact that a change in the coupling ratio from 0% to 100% corresponds to an optical phase change of π . Thus the measured change in the coupling ratio at selected wavelengths in the experimental data can be converted into a corresponding optical phase change as a function of wavelength. Note that this procedure can be applied even if the interferometer wavelength response curve does not have 100% modulation. In the wavelength region of interest, it is necessary to determine only the local modulation depth that corresponds to a optical phase change of π .

Once the optical phase change is determined, the change in refractive index of the fiber core is calculated as follows. The change in optical path length can originate from a change in the refractive index of the glass and/or a change in the physical length of the optical path. We attribute the change in optical path solely to a change in the core index of the optical fiber in the irradiated region of the interferometer arm. This assumption is consistent with previous observations of light-induced index changes in Ge-doped optical fibers.^{1,2}

The light is assumed to be propagating in the HE_{11} mode of the optical fiber with a propagation constant β . Irradiation of the fiber changes the core index and thus changes concomitantly the propagation constant for the HE_{11} fiber mode and the optical phase of light propagating through the irradiated arm of the Mach-Zehnder interferometer. If $\Delta\beta$ is the change in the propagation constant, and L is the irradiated length, the optical phase change is simply $\Delta\beta L$. The change in the propagation constant $\Delta\beta$ is related to the change in refractive index Δn of the fiber core by using a standard perturbation approach described by Snyder and Love.⁵ According to Ref. 5, $\Delta\beta = \kappa\eta\Delta n$, where η is the fraction of the light power in the HE_{11} mode contained in the fiber core and κ is the $2\pi/\lambda$. The quantity η has been calculated previously as a function of the normalized frequency for step-index fibers (see p. 323 of Ref. 5) and thus can be determined for the particu-

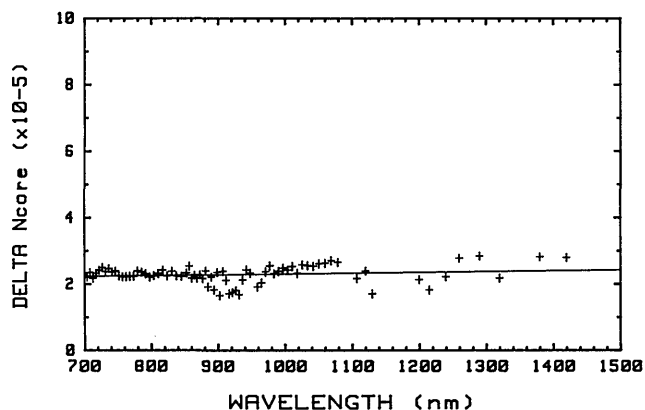


Fig. 3. Plot of the induced index change as a function of wavelength.

lar fibers used in our experiments.

The shifts in the peaks of the spectral responses of the Mach-Zehnder interferometer to shorter wavelengths in the case of an irradiated telecommunication fiber and to longer wavelengths in the case of the sensor fiber indicate that the optical path length of the irradiated arm is increased. Thus the UV light induces an increase in the refractive index of the fiber core.

The change in fiber core refractive index for the wavelength range of 700–1400 nm is shown in Fig. 3 for the case of an irradiated telecommunication fiber. A similar index change is observed when the sensor fiber is irradiated. At 700 nm the index change is approximately 2.3×10^{-5} and is practically constant as a function of wavelength. The index change of 2.3×10^{-5} measured here is similar to the 3×10^{-5} reported by Meltz *et al.*² The solid line in Fig. 3 is a linear least-squares fit to the data and has a slight slope, indicating that the refractive-index change may be slightly larger at longer wavelengths.

The physical origin of the UV light-induced refractive index change in Ge-doped optical fibers is not yet understood. A possible explanation^{2,3} is that the absorption of UV light in the Ge-doped silica fibers creates Ge color centers. A change in the UV absorption of the Ge-doped glass leads, through the Kramers-Kronig relation, to a change in the refractive index. By knowing the resonant wavelengths at which the absorption by the color centers occurs, the change in refractive index far off the resonance can be calculated by using a three-term differential Sellmeier expres-

sion.³ This model predicts that the index change due to irradiation is approximately 1% smaller at 1400 nm than at 700 nm, which, strictly speaking, is inconsistent with our measurements. The two data points in Fig. 3 at 1380 and 1420 nm are somewhat suspect (because of much reduced signal-to-noise ratio in the data in this spectral region) and make the slope positive rather than negative. To reduce the uncertainty in the data, an interferometer specifically designed for measurements in this spectral region is required.

A new technique for detecting UV light-induced refractive-index changes in optical fibers is reported. The technique permits the measurement of the dispersion in the photoinduced index change. In the case of our UV irradiated Ge-doped silica fibers, a change in refractive index of 2.3×10^{-5} at 700 nm is observed, which increases slightly with wavelength in the spectral region to 1400 nm. Our experimental results are not critically inconsistent with the slight drop toward long wavelengths of the index change predicted by models based on Sellmeier's dispersion formula.

The dissimilar-fiber Mach-Zehnder interferometer described in this Letter may also have application in the investigation of the effects of ionizing radiation, such as gamma rays and neutrons, on optical fibers. This device provides a means of detecting changes in the fiber refractive index. Normally the effect of the ionizing radiation on an optical fiber is detected through changes in the optical attenuation. Finally, we note that Mach-Zehnder interferometers that are used as wavelength filters or multiplexers in optical communication systems⁴ can be tuned by exposing one of the fiber interferometer arms to UV light in order to give a maximum (or a minimum) output at a desired wavelength.

References

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