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Infrared erasure of self-organized $\chi^{(2)}$ gratings in high germania content optical fibers

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We demonstrate that the self-organized $\chi^{(2)}$ grating in a high germania content optical fiber can be erased by prolonged exposure to 1.064 μm radiation only. The decay rate, which is proportional to the fourth power of the 1064 nm intensity, is attributed to two-photon absorption of the second-harmonic light generated in the fiber.

Efficient second-harmonic generation (SHG), which has been observed in glass optical fibers,[1–3] is of interest both with regards to the underlying materials science of glass, and from a practical perspective. While efficient SHG from an initially isotropic glass fiber implies a laser-induced modification in the glass structure, the precise origin of the effect is not yet clear. Recent evidence[4] suggests that the induced $\chi^{(2)}$ is in fact the result of some internal dc electric field acting on the $\chi^{(3)}$ of the glass. Such a dc electric field would perhaps come from charges released from certain defect sites in the glass, and trapped at other sites. This picture has been suggested by several workers.[5–7] If so, it might be possible to release the trapped charges and thus erase the $\chi^{(2)}$ grating. Indeed, it has been observed that short wavelength visible light can erase a prepared fiber.[5,8] Although a phenomenological description of this short wavelength light-induced erasure has been developed[5] the precise nature of the process is still unclear.

In this letter we study the erasure of the $\chi^{(2)}$ grating by prolonged exposure to infrared light *only*, but find that this effect is only pronounced in a high GeO_2 (germania) content fiber. By fitting the data we are able to argue that this erasure is due to two-photon absorption (TPA) of the second-harmonic light, itself generated by the $\chi^{(2)}$ grating. We interpret this erasure as due to the release of charges from shallow traps.

The two kinds of germania-doped silica optical fibers used in this study were fabricated by the standard vapor-phase axial deposition method. The high germania content fiber[9] (fiber A) has a 2.8-μm-diam core. The refractive index profile of the core is quadratic, and the maximum refractive index difference between core and cladding is 1.9%, which corresponds to a GeO_2 concentration of approximately 19 mole %. The cutoff wavelength of the second mode is 0.85 μm. The low germania fiber (fiber B), which was used for comparison, is step index with a 3.2-μm-diam core. The core-cladding index difference is about 0.4%, implying a 4 mole % germania content. The cutoff wavelength of fiber B is about 0.55 μm. Neither fiber contains any phosphorus. The fiber length used for the SHG measurements was 16 cm.

The experimental setup for measuring SHG in the fibers is shown in Fig. 1. The fibers were prepared with the Nd:YAG laser operating Q-switched and mode locked. The mode-locked pulses [110 ps full width at half maximum (FWHM)] had a 76 MHz repetition rate. The Q-switch envelope rate was 1 KHz, with an envelope width (FWHM) of 320 ns. For an average power of 10 mW at 1064 nm, the peak power was estimated to be 3.6 kW. The fibers were seeded for 1.5 h in the usual way,[3] with the 1064 nm fundamental light, and also 532 nm light generated by a KTP crystal. The seed average powers were adjusted such that similar power densities were obtained in the cores of fibers A and B: that is, 17 mW at 1064 nm and 0.17 mW at 532 nm for fiber A, and 23 mW at 1064 nm and 0.23 mW at 532 nm for fiber B, all measured after the fiber. The 1064 nm light intensity was adjusted using a waveplate and polarizer combination, and the 532 nm light intensity was changed by adjusting the KTP crystal. After the preparation stage, a long wavelength pass filter was inserted before the fiber. During this, the reading phase of the experiment, a mechanical chopper was added before the fiber and the green power generated by the fiber was measured with a Si photodetector and lock-in amplifier, interfaced to a computer. The chopper reduced the duty factor of the pulses by two, so that now 5 mW average infrared power corresponded to about 3.6 kW peak.

The SHG conversion efficiencies were saturated after 1.5 h of seeding. The efficiencies of fibers A and B were 2.5×10^{-3} for 15 mW average 1064 nm reading power, and 1.2×10^{-3} for 20 mW average reading power, respectively. No significant SHG was observed from fibers exposed to

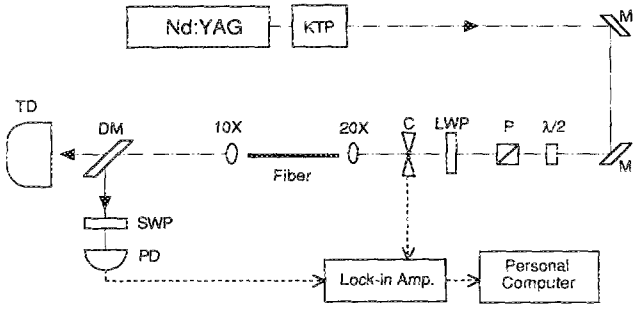

FIG. 1. Schematic diagram for measuring the SH power in optical fibers: (M) mirrors, ($\lambda/2$) waveplate, (P) polarizer, (C) chopper, (LWP) long wavelength pass filter, (DM) dichroic mirror, (SWP) short wavelength pass filter, (PD) photo detector, (TD) thermal detector. The LWP and chopper are only present during the reading phase.

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infrared only (unseeded), even after 6 h of preparation. Note that the peak final conversion efficiencies of the two fibers were similar, despite the quite different germania concentrations. Precise comparisons are difficult, however, because of the difference in mode profiles.

The SH power in the prepared fiber A (high germania content) decreased with time while reading with the 1064 nm light only. Such a decay has not been observed in fiber B (low germania content), even with the same 1064 nm power density. This is consistent with the report of Ouellette *et al.*,[5] who were not able to erase their 3 mole % germania-doped fiber with 1064 nm only. On the other hand, Lucek *et al.*[7] have recently reported competition between writing and erasing with infrared only. They do not specify the composition of their fiber, but from the core-cladding index difference of 0.015 we estimate 10 mole % germania. This would put their fiber as an intermediate case between our fibers A and B.

The SH power from a prepared fiber is plotted as a function of the time t in Fig. 2(a), for various 1064 nm average reading powers (measured after the fiber). The SH power was normalized to its initial value (at $t = 0$). It can be seen that while the SH power of fiber B remains essentially unchanged at a 1064 nm average power of 10 mW, the SH power of fiber A decays significantly at the same power density (average power of 7.5 mW). Moreover, the decay rate of the SH power in fiber A increases with increasing 1064 nm reading power.

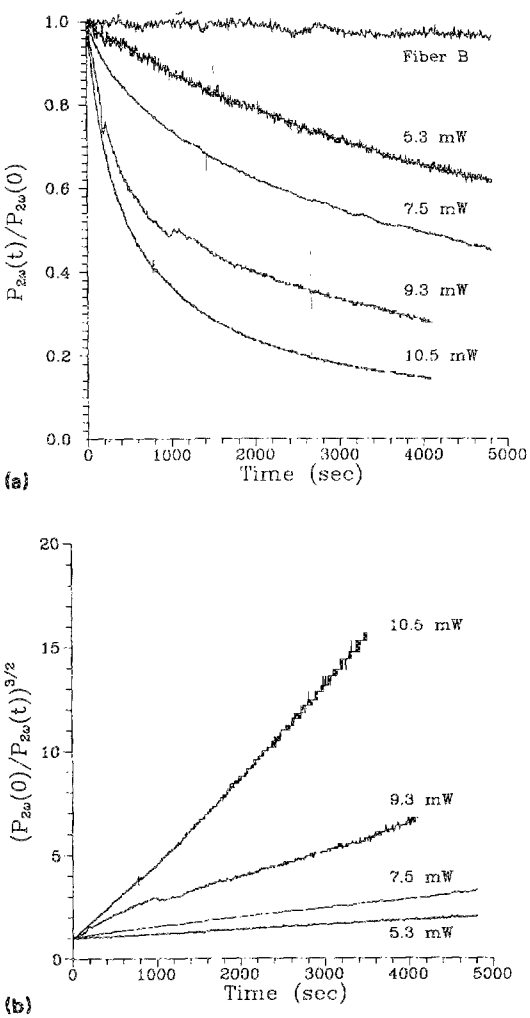

FIG. 2. (a) Normalized average SH power generated in fibers vs infrared exposure time t. The solid curves represent the data of fiber A for various 1064 nm average powers, and the dashed curve represents the data of fiber B for the 1064 nm average reading power of 10 mW. (b) Fiber A data from (a) rescaled to demonstrate the validity of Eq. (3).

To check the reversibility of the phenomena in fiber A, reseeding was carried out under the same conditions after the SH power had decayed for 2 h. The reseeding resulted in the same SH power and subsequent decay curve. This suggests that the relevant microstructural transformation of the glass is reversible.

The decay of the SH power as a function of time, shown in Fig. 2(a), does not follow a simple exponential law. A qualitatively similar decay, resulting from exposure to 532 nm light alone, has been observed in fibers with low GeO_2 content.[5,8] Ouellette *et al.*[5] showed that the resulting decay could be well described by assuming that

$$\frac{dA(t)}{dt} = -\beta(P_{2\omega})A^2(t), \tag{1}$$

where A is the amplitude of the phase-matched $\chi^{(2)}$ grating, and β is a parameter which they found to vary approximately as the fourth power of $P_{2\omega}$, the power of the green bleaching light at 532 nm. It has been suggested[10] that this erasure is due to second-harmonic generation of the 532 nm light (to create 266 nm light). Such a process, which would not be phase matched, would result in β being a quadratic function of $P_{2\omega}$ which contradicts the findings of Ouellette *et al.* There is therefore still some question about the precise origin of this erasure.

In our case we find that the decay of the $\chi^{(2)}$ grating, which results from exposure to the infrared light at 1.064 μm only, is well described by

$$\frac{dA(t)}{dt} = -\gamma P_{\omega}^4 A^4(t), \tag{2}$$

where γ is a constant, and P_{ω} is the power of the infrared fundamental used during the reading phase of the experiment. Since the SHG efficiency is proportional to A^2, it follows from Eq. (2) that

$$[P_{2\omega}(0)/P_{2\omega}(t)]^{3/2} = 1 + 3\gamma A^3(0)P_{\omega}^4 t, \tag{3}$$

where $P_{\omega}(t)$ is the second-harmonic power generated by the fiber at time t, and $t = 0$ marks the beginning of the reading phase of the experiment (during which the 532 nm seed beam has been turned off). The data has been replotted in Fig. 2(b), where the validity of the functional form given by Eq. (3) is now evident.

In order to demonstrate the fourth power dependence on the infrared reading power P_{ω} in Eq. (3), we have plotted the slopes of the lines from Fig. 2(b) as a function of P_{ω} on a log-log plot (see Fig. 3), along with additional data [not shown in Fig. 2(b) to avoid crowding]. A least-squares fit to this data yields a slope of 4.1 ± 0.5, consistent with our assumption of a fourth power dependence.

Our interpretation of Eq. (2) is that some 532 nm light is first created by SHG from the infrared by the phase-

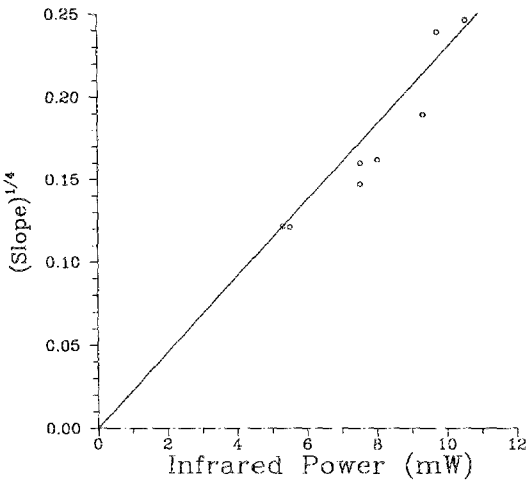

FIG. 3. Slope of the curves from 2(b), plus additional data vs 1064 nm power used during the reading phase of fiber A. The solid line is the result of a linear least-squares fit.

matched $\chi^{(2)}$ grating in the fiber ($P_{2\omega} \propto A^2 P_\omega{}^2$), and then some of this light is absorbed through two-photon absorption[11] ($\propto P_\omega{}^2$). This TPA would, in this picture, result in the release of the trapped charges which are responsible for the internal macroscopic dc field that gives rise to the $\chi^{(2)}$. Since the effect is almost absent in fiber B, we presume that such TPA is germania related. Note that the erasure process of Ouellette *et al.*, described by Eq. (1), which is quartic in the green power as compared with our quadratic dependence, is ignored in Eq. (2) due to the relative weakness of the generated SH, as compared with the seed green intensity.

A broad linear absorption band centered at 245 nm is known to exist in germania glass,[12] and is well placed for TPA of the 532 nm light.[11] While the defect structure responsible for this band is still the subject of discussion, it is considered to be due to an oxygen vacancy neighboring a Ge atom.[12] This therefore suggests that the origin of the decay might be related to the local environment of the Ge atoms. Bonds such as —Ge—Ge— or —Ge—Si— are weaker than other bonds in silica glass[13] (such as —Si—O—Si—), and may therefore be more easily affected by TPA of the 532 nm light. Furthermore, it should be noted that while the 1064 nm and 532 nm light together can create the SHG grating, the 1064 or the 532 nm light alone erases the SHG grating in fiber A. Perhaps during seeding electrons (or holes) are ionized from any Ge-related defects (including e.g., —Ge—Si—), and so can contribute to the SHG grating in the seeding process. (An increase in the Ge E' center concentration has been reported in fibers that have been prepared for SHG.[14]) During the infrared-induced decay, however, principally only the —Ge—Ge— bonds are affected as they are more unstable, and since the generated SH is rather weaker than the seed green. Thus, the SHG behavior is found to depend on the GeO_2 concentration in optical fibers, indicating the necessity of investigating a wider concentration region.

In conclusion, we have investigated SHG in a high germania content fiber, seeded with Q-switched mode-locked pulses at 532 and 1064 nm. The SHG from the fiber was observed to decay upon exposure to 1064 nm light alone, which we have not observed over short times in fibers with low GeO_2 content. The decay rate was proportional to the fourth power of the 1064 nm power, which is consistent with a model based on TPA of the generated SH light. This result suggests that the germania is important in the decay. To obtain more stable SHG in fibers, and to understand its formation mechanism, it appears necessary to investigate the SHG of optical fibers with various GeO_2 concentrations.

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