# A NOVEL TECHNIQUE FOR ENHANCING THE PHOTOSENSITIVITY OF GERMANOSILICATE WAVEGUIDES

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## Abstract

Thermal treatment of $GeO_2$:$SiO_2$ waveguides, achieved by exposing the waveguides to $CO_2$ laser radiation before grating writing, increases the UV photosensitivity of optical fibres. Gratings written in treated fibres show a refractive index modulation two times greater and a Bragg wavelength shift 2 nm larger than those written in untreated fibres. The thermal treatment carried out on bulk samples showed a pronounced increase of the 242nm absorption band, thus indicating that the increase of germanium oxygen deficient centres (GODC) is believed to be responsible for the higher photosensitivity.

Up to now, several methods have been discovered to increase the photosensitivity of germanosilicate fibres [1]: the most common methods are hydrogen loading [2], flame brushing [3] and co-doping with B [4], Sn [5] or rare-earths [6]. Both hydrogen loading and flame brushing are based on the reaction of hydrogen molecules with a common Ge-O-Si site to produce OH groups and bleachable GODC; although the increased population of GODC enhances fibre photosensitivity, an increase in absorption in the third telecom window at 1.55μm is observed because of the presence of the nearby OH absorption peak. It is therefore desirable to find new techniques to increase the photorefractive response of pure germanosilicate fibres which are less time consuming, cheaper and give lower optical loss at 1.5 μm. Here we propose and investigate a novel post-fabrication technique to increase the photorefractivity of germanosilicate fibres. The fibres (not hydrogenated) were exposed to intense $CO_2$ laser radiation *before* the gratings were written using a high intensity UV laser. As a result, gratings written in treated fibres using the phase-mask technique and a 248 nm UV KrF excimer laser showed higher reflectivity and longer Bragg wavelengths than those written in the same way in untreated fibre (i.e. not exposed before UV grating writing to $CO_2$ laser radiation).

The fibre, produced via modified chemical vapour deposition (MCVD), was side-exposed to ~13.5W of continuous wave $CO_2$ laser radiation for 15 seconds and subsequently rapidly cooled down with liquid nitrogen. Fibre specifics were: external diameter ~ 120μm, numerical aperture (NA) ~0.27 and cut-off wavelength ($\lambda_c$) ~1.36μm. Gratings, produced with a phase-mask, were written exposing the treated fibre for 100s to 248nm Kr-F excimer pulses at 20Hz and 300mJ/cm$^2$ per pulse. Fig.1 shows a comparison of the wavelength response between a grating written in treated and untreated fibres under the same UV writing conditions. Gratings written in the fibre exposed to $CO_2$ laser radiation provide higher reflectivity

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and longer Bragg-wavelength (shift ~1.4nm) than those written in the untreated fibres. The refractive index modulation ($\Delta n_{mod}$) of fibre gratings in the untreated and treated samples were estimated from the reflection curves and calculated to be $1.6 \cdot 10^{-4}$ and $2.27 \cdot 10^{-4}$ respectively.

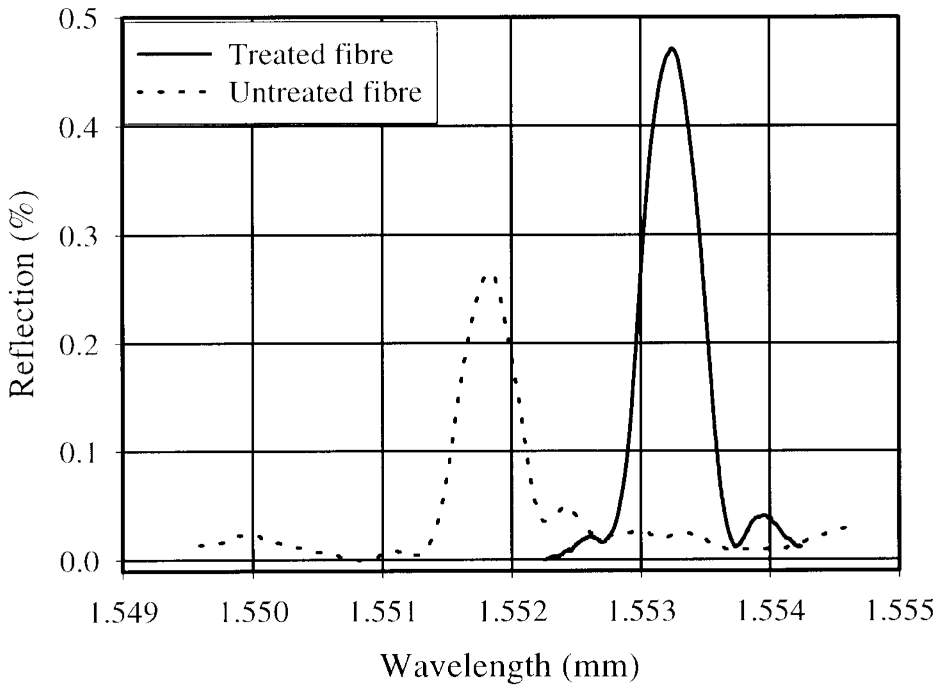


Fig. 1. Reflection spectra of the gratings written in fibre exposed to the $CO_2$ laser for 15s (intensity: 350W/cm$^2$) and in the untreated fibre. NA and external diameter of the fibre are 0.28 and 120μm respectively, UV pulse energy and frequency 200mJ/cm$^2$ and 20Hz.

Fig. 2 shows the induced $\Delta n_{mod}$ and the average refractive index increase with respect to untreated fibre ($\Delta n_{ave}$) of samples exposed for 3 seconds to different levels of $CO_2$ laser intensity; *air* and *liquid* $N_2$ refer to the method of cooling the fibre after the $CO_2$ radiation is switched off. *Air* means that the specimen is cooled down via air convection whereas *liquid* $N_2$ indicates that it is cooled down using a jet of liquid $N_2$. It is evident that there is a significant increase of photosensitivity for increasing $CO_2$ laser intensity; however, no meaningful improvement in the photorefractivity is due to liquid nitrogen treatment. An important observation is that $\Delta n_{ave}$ is always larger than $\Delta n_{mod}/2$ and the difference increases for increasing $CO_2$ irradiation time. In particular an experiment carried out at low UV writing intensity shows that $\Delta n_{ave}$ is mainly due to $CO_2$ laser treatment, i.e. it is already present in the fibre before exposure to any UV light. Moreover, the deviation of $\Delta n_{ave}$ from $\Delta n_{mod}/2$ is more significant at high $CO_2$ laser intensity levels. The photorefractivity seems also to be dependent on the UV intensity: at low UV intensities (<50mJ/cm$^2$ per pulse) there are negligible differences between the fibre treated with $CO_2$ laser and the untreated one, whereas at high UV intensities (>200mJ/cm$^2$ per pulse) $\Delta n_{mod}$ of the fibre exposed to $CO_2$ laser radiation is approximately two times larger than that of the untreated fibre. It was suggested that both in silica [7] and germanosilicate fibres [8-9] two types of defects contribute to the 242nm absorption peak. Since the difference between gratings written in treated and untreated fibres increases with increasing UV intensity, our results seem to be consistent with a model implying two types of GODC defects with different bleaching dependence on UV intensity; one of these defects, the concentration of which is increased by $CO_2$ laser treatment, can be bleached only at high UV intensities, probably through multi-photon absorption. The linear dependence of photosensitivity in untreated fibres on UV laser intensity matches this model.

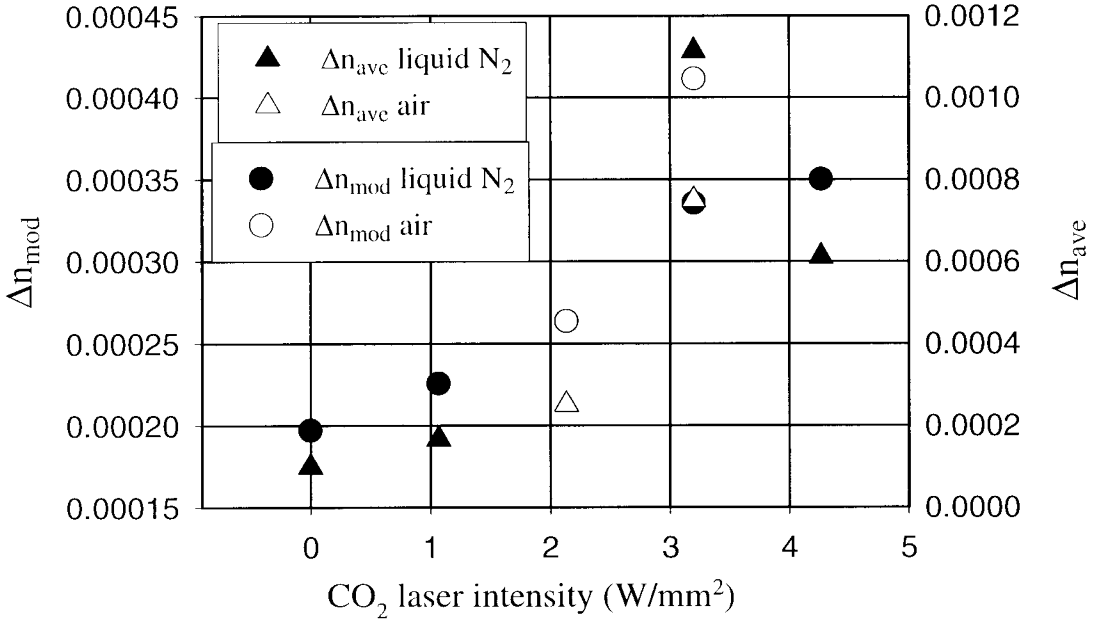


Fig. 2 Dependence of the induced $\Delta n$ on $CO_2$ laser intensity. Filled symbols represent fibres heated up by $CO_2$ laser and cooled by liquid $N_2$, open symbols represent fibres only treated with the $CO_2$ laser. $\Delta n_{mod}$ are deduced from reflection spectra, $\Delta n_{ave}$ from Bragg-wavelength shift. Gratings were written by exposing fibres to a pulsed excimer laser (pulse energy $300mJ/cm^2$, frequency 20Hz, pulse duration 20ns).

To separate the thermal effect on fibre photosensitivity from the effect purely associated to $CO_2$ laser exposure, we treated two different fibres with the same thermal cycle by using the $CO_2$ laser and the furnace used during fibre drawing. The fibre was warmed up to $1800^0C$ in 1 minute, kept at this temperature for 1 minute, cooled down to $1100^0C$ in 75 seconds and finally cooled to room temperature by natural convection. Gratings, written as previously, showed that the increase in photosensitivity due to $CO_2$ laser exposure is closely related to temperature effects, while the Bragg wavelength shift is mainly due to the $CO_2$ laser treatment. In fact, the grating written in the fibre which was heated in the furnace shows a small Bragg wavelength shift, $\Delta n_{ave}$ thus being consistent with the induced $\Delta n_{mod}$ (i.e. $\Delta n_{ave} \sim \Delta n_{mod}/2$), while, as previously pointed out, for gratings written in the fibre exposed to $CO_2$ laser radiation $\Delta n_{ave} >> \Delta n_{mod}/2$. In addition, a significant Bragg wavelength shift is also detected when the grating is written with low excimer laser powers, corresponding to which $\Delta n_{mod}$ is negligible. The reason why such average refractive index variation occurs in the fibre treated with the $CO_2$ laser and not in the thermally treated fibre is still under investigation.

To elucidate the observed features of the fibres we have investigated the effects of thermal treatment on the absorption spectrum of thin preform samples by treating them in a similar way to the fibres that showed photosensitivity enhancement. The samples, cut from the same preform and polished to optical quality, were exposed to a $CO_2$ laser beam ($210W/cm^2$ for 9s) several times and absorption spectra were recorded before and after irradiation. We chose to use a preform with lower numerical aperture (NA ~0.2) and exposed the samples to lower $CO_2$ laser powers than used with the fibre because when the sample thickness is reduced below 100μm it becomes very brittle and the temperature reaches melting values during exposure. Fig. 3 shows the absorption spectra of the sample as a function of total exposure time. It is evident that the absorption of GODC at 242nm constantly increases and reaches a saturation level after long exposures (see inset of fig. 3). It is therefore straightforward to assume that the large increase in fibre photorefractivity can be related to the increase of GODC concentration observed in the UV spectrum.

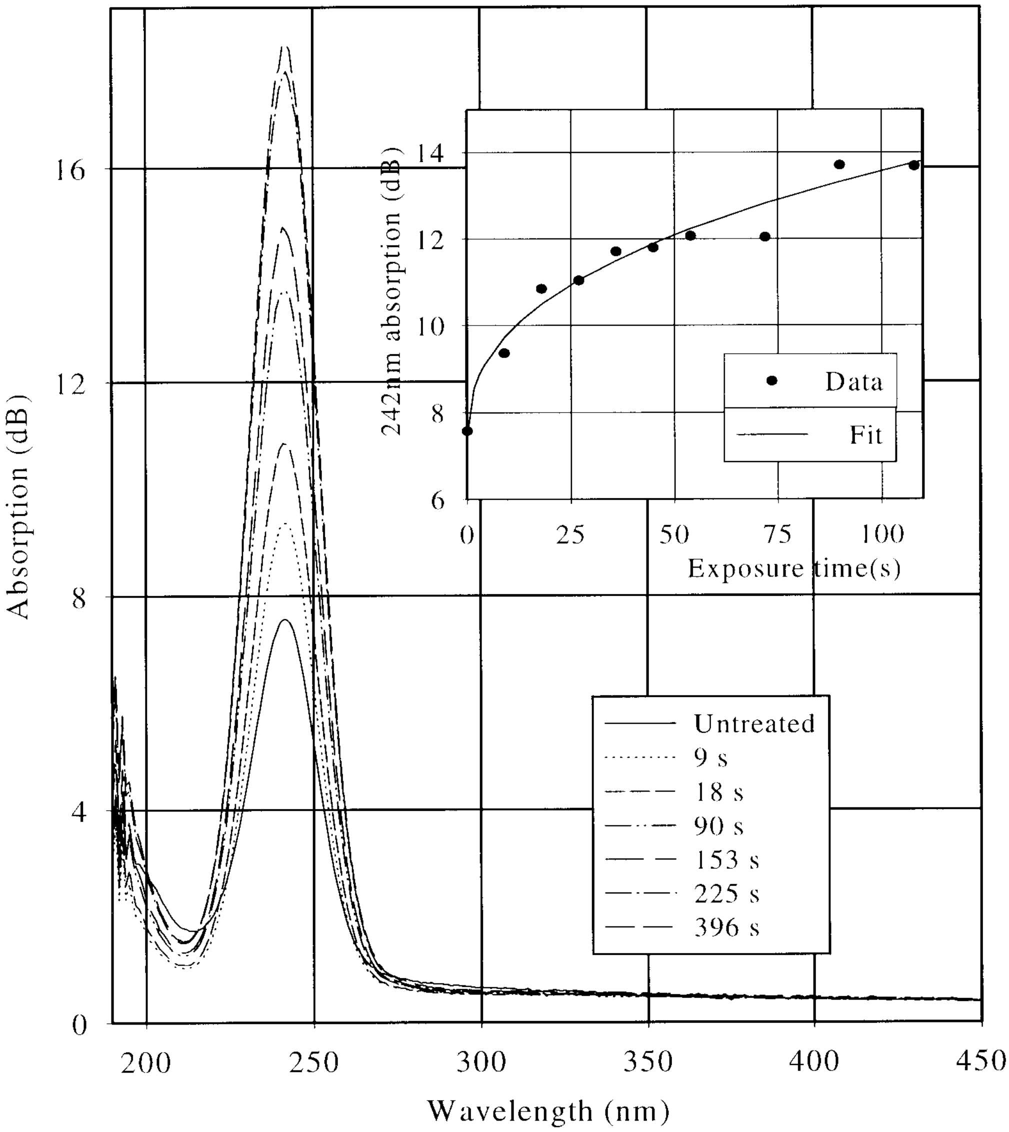


Fig. 3. Absorption spectra of preform slide exposed to the $CO_2$ laser radiation (intensity: $210 W/cm^2$). The inset shows the dependence of the 242nm peak absorption on cumulative $CO_2$ laser exposure time; the fitted curve is a stretched exponential: $A=7.56+12\cdot(1-\exp(-0.0282\cdot t^{0.72}))$.

In summary, the photosensitivity of germanosilicate is considerably increased by a thermal treatment carried out before grating inscription as a consequence of the GODC concentration increase. These defects can be bleached only at high UV laser intensities, suggesting that multi-photon absorption takes place. Although the increase in photorefractivity is still far from the maximum values obtained in the past ($\Delta n=10^{-3}$-$10^{-2}$), the photorefractivity is significantly enhanced by this treatment. Further improvements are expected by optimisation of the exposure parameters and fibre composition. Such a technique could also be exploited for apodisation and chirping of fibre gratings.

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