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UV-Induced Refractive Index Changes in Germanosilicate Fibres

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Abstract

Photo-induced guided index changes approaching 10^{-4} at both 633nm and 1.55μm, measured using a simple interferometric technique, are reported in germanosilicate single-mode optical fibres exposed to 266nm from the side.

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Introduction

Photorefractivity in germanosilicate fibres was first reported by Hill and co-workers over a decade ago[1]. They were able to produce holographic gratings 60 cm long by interfering counterpropagating modes at 488 and 514.5 nm. Further measurements by Lam and Garside[2] indicated that reflection efficiencies approached 100% for interaction lengths of 1-2cm[2] implying refractive index modulations of the order of 10^{-5}. They were unable to estimate the spectral variation of the index change $\Delta n(\lambda)$ because the reflection band was restricted to the recording wavelength. It is clear that, for distributed reflectors at communications wavelengths, the effect is only useful if i) a substantial index change extends out to beyond 1 μm and ii) a satisfactory method of side-writing gratings can be found.

Although the exact origins of this photorefractivity are still the subject of some controversy, it is known that two-photon absorption at around 500nm by oxygen deficient Ge-Si bonds (with an absorption band at 240nm) plays an important role. It is therefore reasonable to predict that index changes can be induced much more easily by single-photon absorption at UV wavelengths. This conjecture has recently been confirmed by Meltz et al[3], who exposed fibre from the side to a two-beam interference pattern at 244nm, producing an index modulation of 3×10^{-5} at 576nm.

In this paper we address two main issues: the strength of the index modulation at 1.55μm, and the origins of the index change. We extend a simple in-fibre interferometric technique (originally developed for measurements at 488, 633 and 784 nm[4]) to chart changes in $\Delta n(\lambda)$ induced by lateral exposure to light of 266 nm.

Experimental details

Fused tapered couplers were manufactured using two different 'pulls' of a germanosilicate fibre known to be photosensitive at 488nm. One fibre had a single-mode cutoff at 450nm, and was used to produce a coupler with a 50:50 splitting at 633nm, while the other (780nm cutoff) was used to produce a coupler with 50:50 splitting at 1.55μm. These couplers were mounted in the experimental arrangement shown in Fig 1. Light of the appropriate wavelength (633nm from a HeNe laser, or 1.55μm from a DFB diode laser) was launched into the coupler through port A. The coupler outputs were cleaved to have lengths identical to within a few mm. Light reflected from these cleaved ends interferes when recombined at the coupler, so the power present at port B is a periodic function of the optical path difference between these two fibres. Provided the Fresnel reflectivities are identical, high visibility interference is obtainable at this port, regardless of the coupler splitting ratio. In order to minimise thermal effects, the coupler and its two output arms were placed inside an aluminium enclosure. Fused silica windows in the enclosure allowed one of the fibre arms to be exposed, from the side, to unfocused 266nm pulsed light from a frequency-quadrupled Nd:YAG laser (6ns pulse width, 30Hz repetition rate, average power 0.3W). Any change of core refractive index in this fibre can be deduced by monitoring the cycling up and down of the output at port B. To increase the length of fibre exposed, the thermally-isolated cell was mounted on a moveable stage giving a scanning range of 23mm.

To determine the sign of $\Delta n(\lambda)$, a small resistance wire heater was wound round the end of the UV-irradiated fibre port. Switching this on produces a positive Δn in this fibre, with an associated fringe movement at port B; a comparison can then made with the direction of fringe movement caused by the UV. This heater can also be used to determine the maximum and minimum output signals from port B, thus permitting fractional fringe shifts to be translated accurately into index changes.

Results

The 780 nm cutoff fibre was initially tested at 1.55 μm. The signal at port B was observed to be very stable before the fibre was irradiated with UV at 266 nm. On unblocking the UV beam and translating the fibre across it, the signal at port B scanned through 0.51 fringes. This change was positive, as shown by the increase in signal when the heater was momentarily switched on. A thermal index change also occurred whose influence was eliminated from the measurement by blocking the beam and letting the cell return to thermal equilibrium. Exposure of the 450 nm cutoff fibre resulted in a positive index change and a total scan of 3.25 fringes. For a movement of one fringe, the index change seen by the propagating fibre mode is $\Delta n = \lambda/2L$ where L = length of exposed fibre. This gives $\Delta n(633\text{nm})=4.49\times10^{-5}$ and $\Delta n(1.55\mu\text{m})=2.19\times10^{-5}$. It is necessary, however, to take into account that a large proportion of the light (depending on the probe wavelength and fibre cutoff) is actually propagating in the cladding. If it is assumed that no index change occurs in the silica cladding (experiments with silica-cored fibre indicate that this is so), the actual index change of the core material Δn_c is approximately $\Delta n_c(\lambda) = \Delta n(\lambda)/\{1-\exp[-(0.83a/w(\lambda))^2]\}$ (assuming a Gaussian mode profile) where a is the core radius and w is the HWHM spot-size (a function of wavelength). This gives $\Delta n_c(633\text{nm}) = 1.96\times10^{-4}$ and $\Delta n_c(1.55\mu\text{m}) = 2.55\times10^{-4}$. Owing to inaccuracies in the cut-off wavelength and non-uniformity in intensity profile across the core, these values are accurate to perhaps ±10%. These index changes, produced after only a couple of seconds exposure (average intensity 250Wm^{-2}), are comparable to those produced by 488nm light[4] after an <u>in-core</u> exposure of 8 hours (average intensity $5.5\times10^{10}\text{Wm}^{-2}$); UV irradiation reduces the exposure by an astonishing factor of $\sim10^{12}$.

Discussion

It is known that the absorption of photons in the region of 240nm in germanosilicate fibre cores creates large changes in the loss spectrum, primarily in the UV but also in the visible. Indeed, induced losses as high as $10m^{-1}$ at 633nm have been measured in fibres identical to those used in this experiment. The loss does, however, decrease with increasing wavelength, and so should not prove to be a problem at IR communications wavelengths. Also, the lengths required for irradiation to produce efficient gratings are very short, only ~1cm, so even at shorter wavelengths the loss would not be unreasonable. The mechanism behind this induced loss is believed to be similar to that due to two-photon absorption at 488nm[5]. The 266nm light partially bleaches the intrinsic absorption band at 240nm by breaking Ge-Si bonds, the electrons released in this process being trapped at other defect sites, forming both Ge(1) and Ge(2) colour centres. The Ge(1) centres have a broad absorption band centred at 281 nm, and it is the tail of this which is responsible for the loss increase observed in the visible. The $10m^{-1}$ loss measured at 633nm ($43m^{-1}$ if the Gaussian mode/ core overlap is taken into account), corresponds to a peak of $3020m^{-1}$ at 281nm.

We postulate that these loss changes are directly responsible for the refractive index changes via the Kramers-Kronig relation. Assuming λ to be sufficiently off-resonance, the following three-term differential Sellmeier expression can be used to model the induced Δn as a function of λ:

$$\Delta n(\lambda) = \sum_{i=213,240,281} \frac{\Delta\alpha_i W_i \lambda_i}{E_i 2\pi^{3/2}(1 - (\lambda_i/\lambda)^2)} \qquad (1)$$

where $\Delta\alpha_i$ is the change in peak absorption at $\lambda=\lambda_i$ (m^{-1}), E_i the transition centre frequency in eV, and W_i the FWHM absorption line width. We do not have enough data points to fit to this equation, and as mentioned above there are inherent errors in the measurement of spot-size and fibre cut-off. So, although the guided index values are accurately measured, the same is not necessarily true of Δn_c, which could be in error by as much as 10%. Reasonable values for Δn_c may be obtained assuming the following absorption peak changes: $\Delta\alpha_{213} = 2.6\times10^5 m^{-1}$, $\Delta\alpha_{240} = -8.29\times10^5 m^{-1}$ and $\Delta\alpha_{281}=3020m^{-1}$, using the values for E_i and W_i given by Friebele at al[6]. The resulting $\Delta n_c(\lambda)$ is plotted in Fig 2, yielding $\Delta n_c(633nm)=2.6\times10^{-4}$, and $\Delta n_c(1.55\mu m)=2.55\times10^{-4}$.

Conclusions

Refractive index changes of the order of 10^{-4}, exhibiting very little dispersion over the range from 500 to 1500 nm, can be induced within seconds in the cores of germanosilicate exposed through the cladding to intensities of $250Wm^{-2}$ at 266 nm. The effect has its origin in substantial changes in the absorption spectrum in the UV spectral region that are caused by colour-centre creation and transformation. These give rise, via the Kramers-Kronig relation, to the observed changes in refractive index.

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Figure 2 Plot of induced refractive index change with wavelength, calculated using the Sellmeier equation, assuming the peak absorption changes given in the text.

Figure 1 Experimental arrangement for determining absolute refractive index change.