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A STUDY OF UV PHOTOSENSITIVITY IN GERMANOSILICATE PREFORMS AND FIBRES

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Background

Due to the numerous applications of in-fibre Bragg gratings, there is urgent need both to understand the mechanism of the photosensitive effect in optical fibres and to optimise grating writing process. To understand the mechanism, we have been studying both UV-induced absorption and refractive index changes in germanosilicate preforms and fibres. It is well known that the main absorption feature of germanosilicate fibres in the ultraviolet is a band centred at ~242 nm arisen from germanium-related oxygen-deficient centres. It has been reported that the strength at the peak of the band can be written as[1,2]:

$$\alpha_{242} = K \rho_{GeO_2} \quad (1)$$

where α_{242} is the absorption in dB/mm at the peak wavelength of 242 nm, K=36 dB/(mm × mol% GeO_2) and ρ_{GeO2} is the GeO_2 concentration in mol%. It has also been reported by several authors[3,4,5] that the 242 nm band is reduced after UV exposure, and, at the same time, several other bands have grown with the main bands being at 195 nm and 256 nm[4]. The refractive index change as a result of the absorption change from Kramers-Kronig relation can be calculated from the absorption change in the three main bands at 242 nm, 195 nm and 256 nm[5]:

$$\Delta n(1.55um) = (2.34\Delta\alpha_{242} + 4.96\Delta\alpha_{195} + 5.62\Delta\alpha_{256})\times 10^{-7} \quad (2)$$

where $\Delta\alpha_{242}$, $\Delta\alpha_{195}$ and $\Delta\alpha_{256}$ are the absorption changes at the peaks of the three bands at 242 nm, 195 nm and 256 nm respectively. The following relations was also found to hold approximately[5]:

$$\Delta\alpha_{195} = -2\Delta\alpha_{242} \quad (3)$$

$$\Delta\alpha_{256} = -0.15\Delta\alpha_{242} \quad (4)$$

Experiments

We recently studied the dynamics of absorption change in germanosilicate fibres by monitoring the transmission of a 248.5 nm excimer laser through preform samples using the excimer laser both as the exposing radiation and the probe beam. The samples consist of a thin germanosilicate film (tens of μms thick) on a ~2 mm thick high purity silica substrate. The germanosilicate film is deposited using the standard chemical vapour deposition technique for fibre manufacture. The silica substrate has been tested not to produce any significant absorption change at the interested wavelengths for the amount of exposure to be used in the following experiment. A line-narrowed KrF excimer laser operates at 248.5 nm was used. The beam dimension from the laser is ~15 mm × ~7 mm and was focused to give a pulse intensity of ~250 mJ/cm^2. The pulse width is 20 ns and the repetition rate was set at 20 Hz. The result of the experiment is shown in figure 1. The initial loss at 242 nm in this sample, α_{242}, is ~455 dB/mm. A very fast decay of the absorption at 248.5 nm was observed in the first several minutes of UV exposure, followed by a slower decay. The absorption dynamics is well fitted with the following stretched exponential fit (see figure

1):

$$\alpha_{248.5}(t) = \alpha_{248.5}(\infty) + (\alpha_{248.5}(0)-\alpha_{248.5}(\infty))e^{-(t/t_0)^{\beta}} \quad (5)$$

where $\alpha_{248.5}(0)$=340 dB/mm, $\alpha_{248.5}(\infty)$=119.7±0.8 dB/mm, t_0=0.55±0.09 min and β=0.315±0.016.

Recently both stretched exponential with $\beta<1$ and power law functions have been used to fit index modulation growth in gratings and blue fluorescence decay with UV exposure in germanosilicate fibres[6,7]. Both of the functions change very fast near t=0 followed by a slower change. In fact, the rate of change at t=0 approaches infinite for the stretched exponential function with $\beta<1$. The functions are commonly used when describing systems with parameters having a dispersive nature, as these in glasses and semiconductors. For fluorescence decay, the β was found to be around 0.30 in the stretched exponential function for both CW and pulsed UV laser exposures[5,6,7].

Assuming the absorption change at 248.5 nm was from sum of the changes in the three major bands at 195 nm, 242 nm and 256 nm, the change in the 242 nm band can be calculated using the relations given in equations 3 and 4, and the bandwidths given in [5]. We obtained $\Delta\alpha_{242}$=~-360 dB/mm. Contrary to some previous observation that a substantial part of the band is unbleachable[8], at least ~80% of the original absorption in the 242 nm band has been bleached. The estimated refractive index change at 1.55 μm from equation 2 in this case is $\sim 3\times10^{-4}$.

The growth of the refractive index change arisen from the stretched exponential growth of absorption change has some interesting effect on grating growth. If we write down the first three terms of Fourier expansion for the refractive index change:

$$\Delta n(z) = n_0 + n_1\cos(\frac{2\Pi}{\Lambda}z) - n_2\cos(\frac{4\pi}{\Lambda}z) \quad (6)$$

where Λ is the grating pitch. we have assumed that there is no radial and wavelength dependence in the refractive index change without a loss of generality. n_0 is the average index change responsible for the drift of Bragg wavelength while writing, n_1 is the index modulation responsible for the first order Bragg gratings, n_2 is the index modulation responsible for the second order Bragg gratings. The normalised index changes n_0/n_{max}, n_1/n_{max} and n_2/n_{max} are plotted against relative fluence F/F_0 in Figure 2 for a sinusoidal UV fringe with 100% contrast. n_{max} is the maximum possible refractive index change and F_0 is the fluence required to reach 1-1/e of n_{max} (also the fluence to bleach out the 242 nm band strength by 1/e). F_0 can be estimated to be 165 J/cm^2 from figure 1.

In figure 2, n_0, n_1 and n_2 increase very fast at the beginning, and the index modulation for first and second order Bragg gratings n_1 and n_2 reach their maximum at around F=~$2F_0$, and start to decrease after that, with the average index change n_0 increasing monotonously to over 90% of n_{max} at F=~$60F_0$. One important point to note is that, even for the 100% fringe contrast, the n_1 can only reaches ~20% of n_{max} (This value is 50% for an ideal linear growth). This is because that, near t=0, the index around peak of the fringes undergoes a fast growth, so does the index around the trough of the fringes. The overall effect is an index modulation increasing at a reduced rate. When the index around the peak of the fringes increases slower than the index around the trough of the fringes does, the index modulation actually starts to decrease. If the fringe contrast is 90%, n_1 can only reach ~13% of n_{max}.

The index modulation growth in fibre gratings has been regularly observed to have a similar behaviour to that of n_1 in figure 2 with average index changes estimated from Bragg wavelength shifts being at least several times lager than the index modulations. In figure 3, we have plotted n_{max} predicted for fibres with

different amount of germanium when assuming a total bleach of the 242 nm band (solid line) and n_{max} taken as five times the measured index modulations (saturated) for the first order Bragg gratings in several different fibres (dots). The maximum index modulations measured from gratings are scattered, but it is a reasonably good fit to the predicted index change considering there was little effort to keep the grating writing conditions identical.

Conclusions

We have studied the dynamics of the absorption changes in germanosilicate preforms and have also simulated the index change growth in fibre gratings. It is found that the index modulation for the first order Bragg gratings can only reach 20% of the maximum index change at $F=\sim 2F_0$ and decreases for longer exposure times. The measured maximum refractive index changes in several different germanosilicate fibres fits well with the maximum refractive index changes predicted from the UV absorption change assuming total bleach of the 242 nm band.

References

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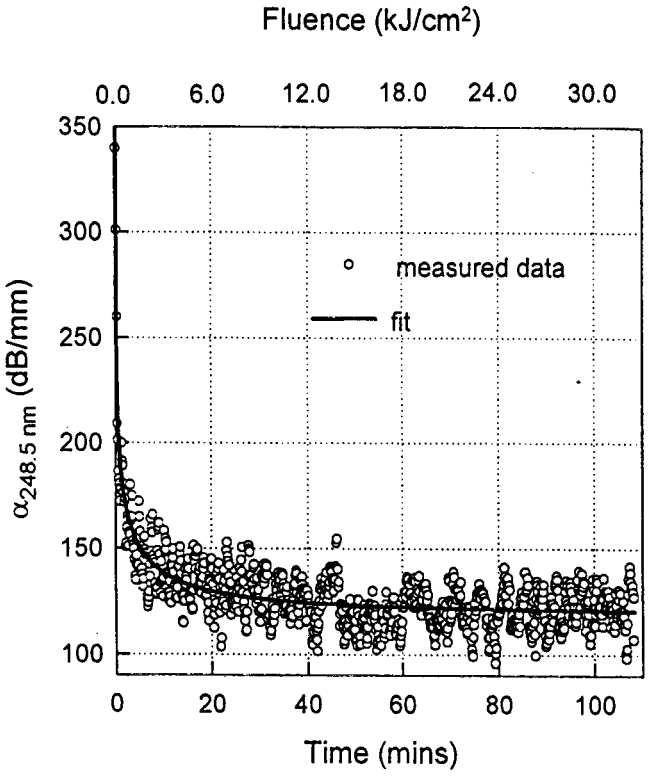

Figure 1 Absorption change at 248.5 nm in a 12.5 mol% germanosilicate preform sample when exposed to KrF laser pulses at 20 Hz with intensity of 2.5 mJ/mm²/pulse.

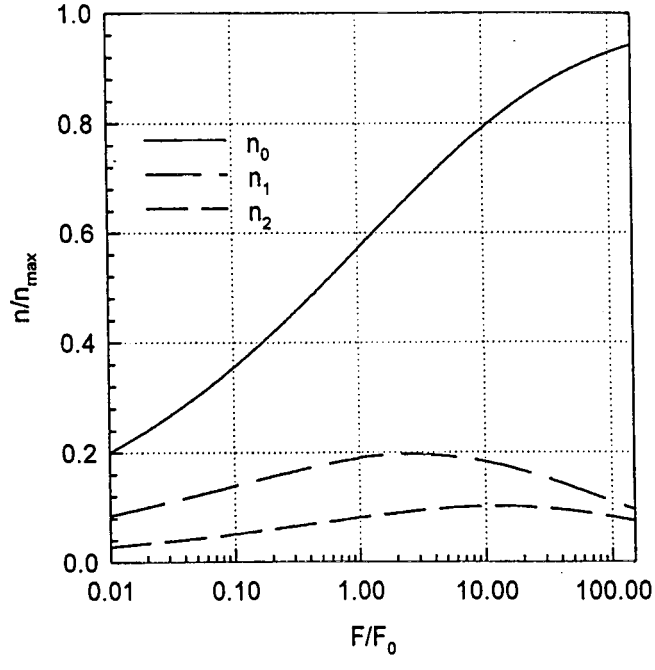

Figure 2 The dynamics of refractive index change in germanosilicate fibres when writing with a 100% contrast sinusoidal fringe.

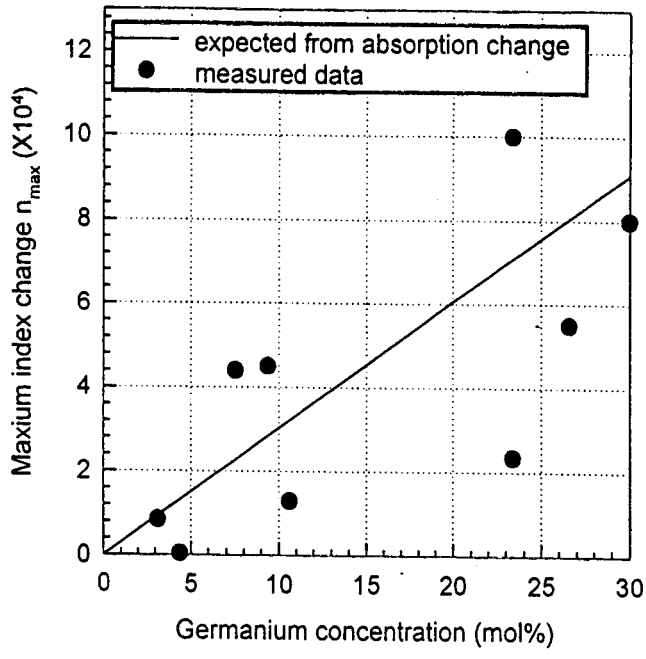

Figure 3 Predicted maximum refractive index changes in germanosilicate fibres from the absorption changes and the maximum refractive index changes from the measured refractive index modulations in gratings.