Excimer laser production of fibre Bragg gratings

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ABSTRACT

Using a KrF excimer laser operating at λ=248 nm, we have demonstrated that fibre gratings having essentially 100% reflectivity can be manufactured using a single 20 ns pulse. In the course of studying the dynamics of the grating formation process, it was found that transient optical gains of as much as 8 dB/cm could be obtained in germanosilicate fibre. The first distributed feedback (DFB) fibre laser has been made using this mechanism.

INTRODUCTION

The introduction of KrF excimer lasers to the production of fibre Bragg gratings has resulted in the development of the single-pulse writing technique, whereby useful gratings can be inscribed in a fibre with just a single 20 ns excimer laser pulse [1,2]. This new technique is of considerable interest for mass-producing gratings on-line, during the fibre fabrication stage, as was recently demonstrated [3]. This enables long arrays of gratings to be written in a very short time for mass production or sensor applications. There is no longer any need to strip the fibre coating before grating manufacture, and the strength of the host fibre is preserved as the gratings are written just before the fibre is coated.

Our recent work has brought to light two distinct regimes of single-pulse grating formation [4]. Below a sharply defined UV pulse fluence level, weak, conventional photorefractive gratings are formed with index modulations usually of order 10^{-5}, giving a reflectivity of only a few percent. Above this threshold, very strong gratings with index modulations in excess of 10^{-3} can be written. The reflectivity of these gratings is usually >99%. We refer to these two types of gratings as Type I and Type II respectively. Type II gratings distinguish themselves from Type I in several respects: they have a much higher thermal stability, surviving temperatures up to 800°C while Type I gratings can be annealed out at 400°C; a damage track, located on the exposed surface of the core is often observed and can result in significant excess loss, depending on the type of fibre used and exposure conditions. Also, Type II gratings can resonantly tap light out of a fibre at wavelengths shorter than the grating Bragg wavelength. These observations suggest that Type II gratings consist of periodic optical damage localised at the core-cladding interface caused by interaction of the UV pulse with a free-electron plasma. So far, Type II grating formation has only been observed in germania-doped silica (GS) fibres and it is clear from our experiments that the UV fluence threshold required for grating production decreases with increasing Ge concentration.

Here, we report on recent measurements aimed at investigating the mechanism responsible for Type II grating formation in GS fibres. In this experiment, an infrared probe beam launched into a GS fibre is monitored by a fast detection system while the fibre is exposed from the side to a 20 ns excimer laser pulse at 248 nm. It is known [5] that in GS fibres, defect centres such as Ge-Ge and Ge-Si bonds create a strong absorption band centred at 241 nm. Electrons from these sites, excited by the absorption of UV photons, can either decay to their original ground state or fall into neighbouring traps, creating new colour centres. This process gradually modifies the absorption spectrum of the fibre during a prolonged UV exposure, bleaching the 241 nm absorption band and creating strong absorption at 195 nm [6]. We therefore expected that exposing a GS fibre core to

a high intensity UV pulse would result in a significant increase in absorption in the timescale of the pulse due to the presence of a large population of excited electrons in the fibre.

EXPERIMENT AND RESULTS

Experimental setup

Fig. 1 describes the experimental setup. The beam from a Lambda Physik EMG 150 KrF excimer laser is partially focused onto an uncoated section of GS fibre via a cylindrical lens (CL). Only a single beam was used and no attempt was made to fabricate a fibre grating at this stage. With each 20 ns pulse, an 18 mm fibre section was exposed to a fluence of ~0.5 J/cm^2 at 248 nm. The pulse energy was adjusted using a half-wave plate and polariser arrangement and monitored using an energy meter by tapping off some of the beam. Light from a CW laser (Nd:YAG or Ti:Sapphire) was launched into the fibre, with typically 50 mW reaching a fast (400 MHz) Si or InGaAs photodiode at the output end. The signal from the detector was sent to a 350 MHz analogue oscilloscope. Each trace was captured by a digitising camera attached to the oscilloscope screen and downloaded to a computer. The oscilloscope was triggered via a delay generator by the excimer laser synchronisation output. This setup thus enabled us to measure changes in the fibre transmission due to a single excimer pulse on a nanosecond timescale. Several GS fibres were used through this experiment with numerical apertures ranging from 0.12 to 0.35, all of which were fabricated in Southampton using the MCVD process.

Transient gain and loss measurements

In the first set of measurements, a diode-pumped Nd:YAG was used to probe a 0.35 N.A. GS fibre which had a cut-off wavelength of 1.05 μm. A typical 100 ns transmission measurement is shown in Fig. 2. Rather than the 1.06 μm transmission being reduced as was expected, the excimer pump beam actually produced a gain of almost 15 dB, or 8 dB/cm. This gain appears for a fraction of the excimer pulse duration, about 10 ns, and is followed by substantial loss, a signification fraction of which remains long after the pulse. The gain was observed to be very repeatable from pulse to pulse and did not seem to fade even after over 20,000 UV pulses had been fired, corresponding to an integrated exposure of more than 10^4 J/cm^2. On the other hand, the induced loss appeared to be very irregular, showing large variations from pulse to pulse and therefore was difficult to characterise.

The dependence of the 1.06 μm gain with excimer pulse energy is shown in Fig. 3. As the pulse energy is increased, the gain tends exponentially to a saturated value of 8 dB/cm, indicating that the excimer pump is significantly depleting the ground state population. To characterise the gain spectrum, the experiment was repeated using a probe beam from a Ti:Sapphire laser, tunable from 0.75 to 0.85 μm and again from 0.95 to 1.1 μm. This time, a fibre with slightly lower N.A. (0.33) and lower cutoff (0.74 μm) was tested. The Ti:Sapphire wavelength was tuned in 10 nm increments; at each wavelength, a single excimer pulse was fired and the detector output recorded. Over the long wavelength tuning range (0.95 to 1.1 μm), traces similar to that of Fig. 2, featuring gain and loss, were observed. Over the short wavelength range (0.75 to 0.85 μm), however, only loss was observed. The peak gain measured from 0.95 to 1.1 μm is shown in Fig. 4. As can be seen, the gain was almost flat right across this 150 nm tuning range at about 4 dB/cm. On the other hand, the loss seemed to increase rapidly as the probe wavelength decreased. A loss of 50 dB/cm at 0.75 μm and 10 dB/cm at 0.82 μm was measured by exposing only a 2 mm section of the fibre.

A section of the 0.33 N.A. fibre was given a prolonged UV exposure at 20 pulses/sec. with a probe beam at 1.06 μm. A 100 ns trace was recorded every 1 to 2 minutes to monitor the evolution of the gain and loss (Fig. 5). Again, the gain remained almost constant throughout the exposure, while the loss was very irregular. We also observed a permanent background loss building up during the exposure (Fig. 6). The increase of the background loss with the exposure was surprisingly regular and is well fitted by a linear function. This phenomenon could be related to the mechanism responsible for Type II grating formation.

Similar exposures were given to GS fibres with N.A.'s of 0.12, 0.21 and 0.28 and cutoff wavelengths respectively of 0.75, 0.64 and 1.0 μm. In the case of the 0.12 N.A. fibre, no measurable gain was observed, as seen in Fig. 7. The loss peaks about 20 ns after the arrival of the pulse and then decays with an exponential lifetime of approximately 50 ns. With the 0.21 N.A. fibre, no gain was observed for the first 2000 pulses (Fig. 8). However, when the fibre was further exposed, a gain peak appeared and gradually levelled at around 0.1 dB/cm. At the same pump intensity level, the 0.28 N.A. fibre exhibited around 1.6 dB/cm gain throughout the exposure (Figs. 9 and 10). In neither of these two last cases did the gain appear to diminish during the long exposure.

The peak of the transient loss induced by a single excimer pulse as function of the UV exposure is shown in Fig. 11 for the 0.12, 0.21 and 0.28 N.A. fibres. In all three cases, this loss was gradually bleached, down to a steady-state value of about 0.3 dB/cm. Interestingly, the decay was quicker in the higher N.A. fibres. This may be because higher N.A. fibres have a larger density of defect centres and hence excited electrons have a higher probability of being displaced from their original site to a neighbouring one where they cannot be re-excited by 248 nm photons.

In contrast with the higher N.A. fibres, no permanent background loss was induced in the 0.12 and 0.21 N.A. fibres, within the accuracy of our measurements. Also, the transient loss measurements were much more repeatable in this case, as seen in Fig. 11. These observations could be signs that in the case of the three lower N.A. fibres, the U.V. fluence level was below the threshold required for the onset of Type II gratings.

While the dominant feature of the measurements made in high N.A. fibres was the large gain, low N.A. fibres exhibit mostly transient loss at 1.06 μm while the excimer pulse is present. This observation suggests that the UV induced gain and loss could be due to distinct electron populations located in different types of defect centres. The fact that the loss could be bleached while the gain remained more or less constant during long exposures also supports this view. Comparing the different measurements, it seems that the induced gain is roughly proportional to the fourth power of the germania concentration, although there is a large uncertainty due to the small number of samples tested so far. This nonlinear relationship indicates that the gain is likely to occur in defect centres where two or more Ge atoms are regrouped.

Distributed feedback fibre laser

This newly found gain was used to create the world's first DFB fibre laser. A section of the 0.35 N.A. fibre was placed in a UV interferometer tuned to write gratings at 1.33 μm. A stream of 20 pulses/second was fired at the fibre. The growth of the grating was monitored in reflection using an optical spectrum analyser with a 1.31 μm LED as the light source. With the grating present and the LED switched off, lasing was observed over a ~3 nm region centred at ~1.5 nm above the grating Bragg

wavelength (Fig. 12). Fig. 12 is actually a superposition of successive traces. This lasing is believed to be caused by the combination of the UV-induced gain and refractive index gratings. The broad emission band seen in Fig. 12 was probably caused by a transient shift in the grating Bragg wavelength while the excimer pulse was present - a temperature change of only 350°C would account for the observed shift. A time resolved measurement of this DFB fibre laser is shown in Fig. 13. As expected, the fibre laser emits pulses that are a fraction of the UV pulse duration in length. The pulses had a peak power of about 1 W which is quite poor in terms of efficiency, considering that the fibre core is exposed to ~10 kW on average.

CONCLUSION

Transient gain and loss measurements have been carried out on a range of GS optical fibres using a KrF excimer operating at $\lambda=248$ nm laser as the excitation source. It has been shown that the gain increases with increasing Ge concentration. These measurements have provided us with new insights into the interaction of UV pulses with GS fibres. The gain and loss are likely to be associated with distinct species as their properties - bleaching, recombination time, *etc.* - are clearly different. The results demonstrate that large densities of excited electrons are generated by 248 nm light which can then amplify light at 950 nm and above or absorb at shorter wavelengths. It is possible that strong excited state absorption could also occur at 248 nm, which might be a route for the onset of optical damage as observed in Type II gratings.

Clearly, more measurements are needed before we can obtain a good understanding of these phenomena. Apart from extending the measurements presented here, some new areas should be explored. In particular, it would be extremely interesting to see the dependence of the gain on the pump wavelength; this might result in much more efficient pumping. Also, fast fluorescence measurements in the 1 μm region should provide valuable information.

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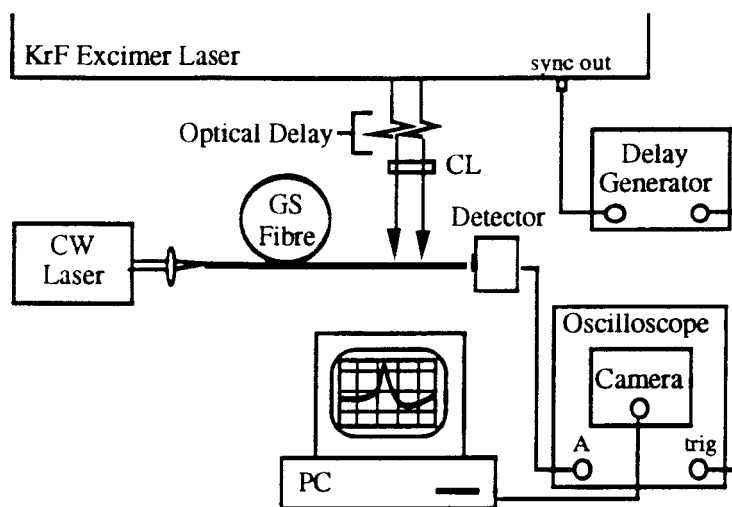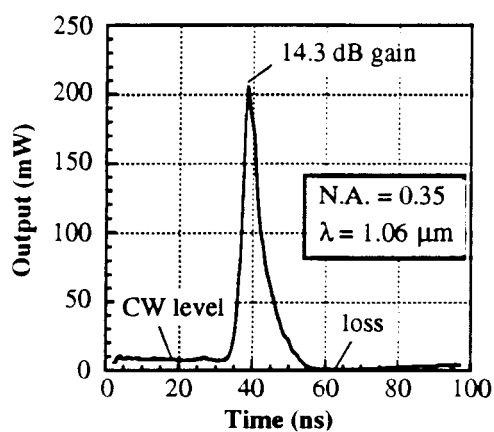
Fig. 1 - Diagram of pump-probe experiment.

Fig. 2 - Observation of gain and loss at 1.06 μm in 0.35 N.A. fibre exposed to a single excimer pulse.
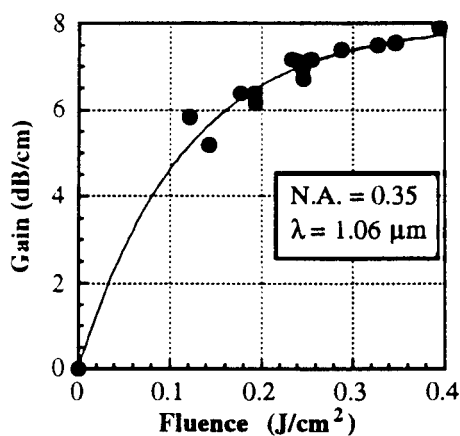

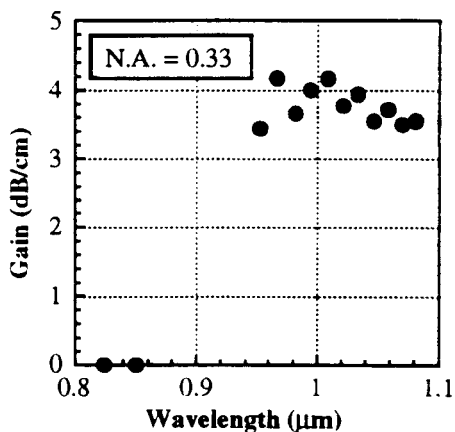Fig. 3 - Dependence of peak gain with excimer pulse fluence. Solid line is an exponential fit.

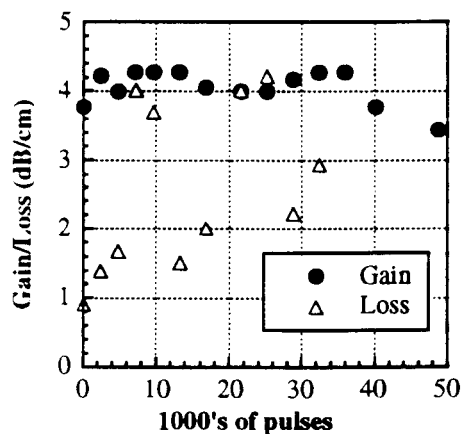Fig. 4 - Gain spectrum measured with a tunable Ti:Sapphire laser.

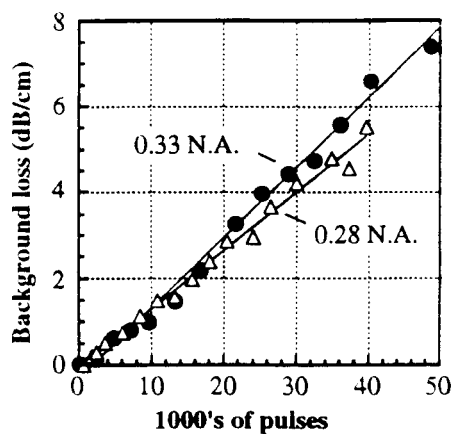Fig. 5 - Evolution of transient gain and loss over a long exposure (N.A. = 0.33, λ = 1.06 μm).

Fig. 6 - Permanent loss at 1.06 μm induced during long exposure of 0.28 and 0.33 N.A. fibres and linear fits.
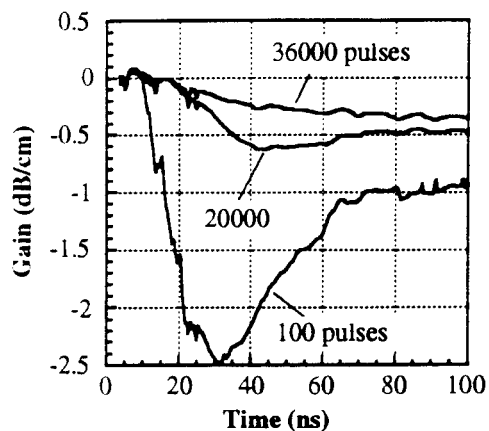
Fig. 7 - Single pulse traces during long exposure of 0.12 N.A. fibre. (λ = 1.06 μm).
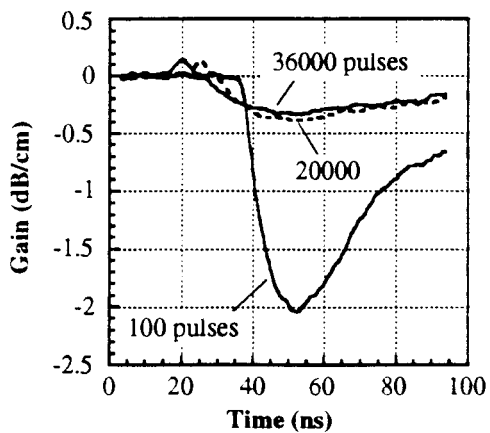
Fig. 8 - Single pulse traces during long exposure of 0.21 N.A. fibre (λ = 1.06 μm).
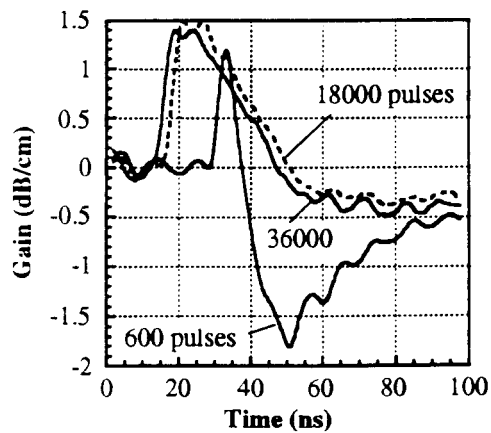
Fig. 9 - Single pulse traces during long exposure of 0.28 N.A. fibre (λ = 1.06 μm).
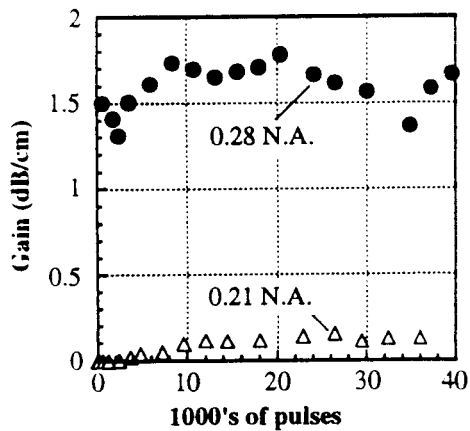
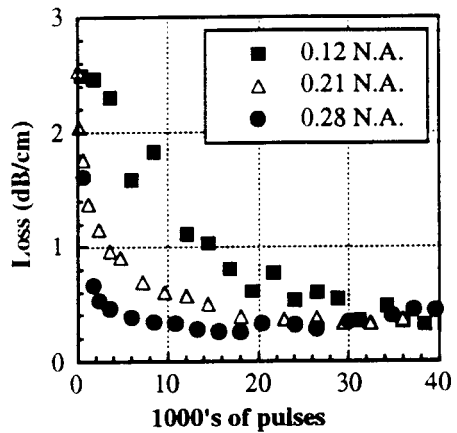Fig. 10 - Evolution of 1.06 μm gain during long exposure of 0.21 and 0.28 N.A. fibres.

Fig. 11 - Evolution of 1.06 μm transient loss during long exposure of 0.12, 0.21 and 0.28 N.A. fibres.
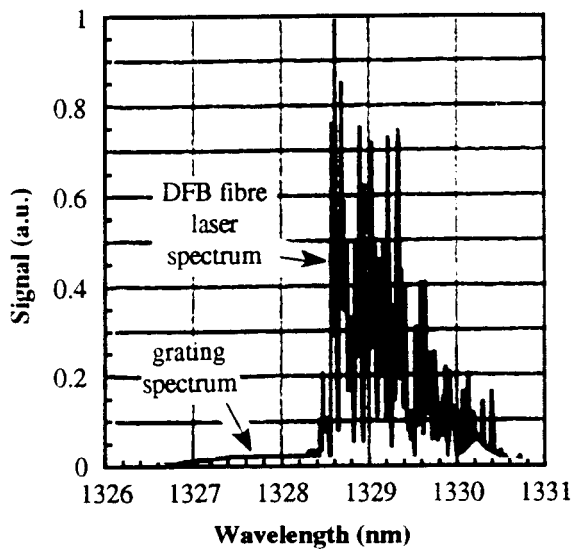

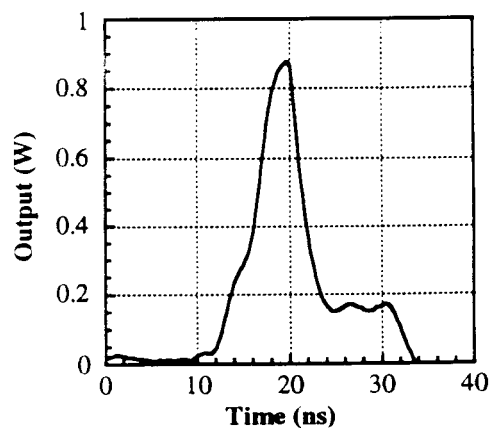Fig. 12 - Spectra of fibre grating and excimer-pumped DFB fibre laser.

Fig. 13 - 1.33 μm pulse of excimer-pumped DFB fibre laser.