A practical study of the effects of exposure conditions on the quality of fibre Bragg gratings written with excimer and argon-ion lasers

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ABSTRACT

An experimental study is presented which evaluates the effects of various important exposure parameters on the quality of fibre Bragg gratings. The parameters addressed include laser repetition rate, fluence and intensity, total exposure dose, numbers of shots, fibre-mask separation and beam scanning speed. In the case of excimer laser writing of gratings, it is seen that the balance between exposure fluence and total dose is crucial in how strong a grating can written and its writing time. It is also observed that the laser repetition rate does not affect the grating quality and that a fibre-mask separation of around 50-200µm is desirable for optimum gratings. The changes in grating quality with argon ion beam scanning speed and exposure power are presented.

Keywords: FBGs, excimer lasers, argon ion lasers, coherence length.

1. INTRODUCTION

Fibre Bragg gratings (FBGs) [1] have become a vital component in many optical telecommunications systems and their use in components such as DWDM filters, gain flattening filters, pump stabilizers and dispersion compensators, amongst others, continue to grow. In addition, FBGs have also emerged recently as a key element in optical sensor devices, such as temperature, pressure, stress and strain measuring systems [2]. Although most of the current generation of commercially available FBG-based products are subject to strict product specifications, as defined by the Telcordia or ITU guidelines and regulations, there exists no specified methodology for the actual production of the FBGs themselves.

The major manufacturers of FBGs have largely tended to develop their own individual solutions for FBG writing and little or no public information is available on the processing conditions used. Although much academic and commercial research has been published on the details of FBG performance and exposure conditions [3,4], there is still a lack of availability of experimental information on the effects of the different exposure parameters on the quality of FBGs. To address this deficiency, an experimental study is presented which quantifies the effects of important exposure parameters from both excimer lasers and argon ion lasers. The parameters which were studied were:

- Excimer laser energy density on fibre.
- Excimer laser repetition rate.
- Total dose supplied to the fibre with excimer laser.
- Separation of the fibre from the phase mask with excimer laser.
- Laser beam scanning speed with argon ion laser.
- Total argon ion laser power.

The aim of this work was to establish practical constraints on the importance, or otherwise, of the different exposure parameters, with the goal to aid FBG engineers in determining optimum production conditions for their products.

The main emphasis of this work was to characterise the use of excimer lasers for FBG production since the large number of available options with excimer lasers provides a bigger parameter space to explore and, therefore, the potential to provide the largest improvement in performance. In particular, the issues of fibre positioning (which is related to the spatial coherence of the excimer laser) and FBG writing time (which is linked to the repetition rate, fluence and dose) were of special concern since excimer lasers are commonly used for the production of high volume products such as pump stabilisers and sensor gratings. The relaxation of the fibre position with respect to the fibre would have a significant bearing on the complexity of production set-ups and the reduction in writing times would make the manufacture of such gratings more cost-effective.

The use of argon-ion lasers is largely confined to the production of higher specification, "top-end" FBG products like 100GHz (or lower) DWDM filters and dispersion compensators, where the volumes concerned are much lower than with excimer laser-based FBGs and their production times not as critical. There are also fewer parameters which are normally used to adjust the grating properties - the exposure intensity (altered by the laser power) and the total dose supplied to produce parts of the grating (usually controlled by either varying the speed of scanning and or the power of the laser). Therefore, only the laser power and scanning speed issues were addressed in this work.

2. EXPERIMENT

All FBG exposures were conducted using two separate Exitech laser exposure systems: the excimer laser GWS-200E tool (used at 248nm) and the argon ion laser GWS-200I tool (used at 244nm). Both these tools are semi-automated FBG writing systems and they offer a high level of reproducibility in the FBGs which they produce. Since the effects of changes of a single parameter were required to be evaluated in the work presented here, it was vital that all other conditions for exposure remained unchanged and under control, and the GWS-200 tools allowed this to occur. The consistent and reproducible performance of the GWS-200E/I tools is achieved via a range of diagnostics such as beam profilers, dose controllers, fluence monitors, fibre positioners, mask positioners and laser beam alignment aids.

All the exposures were performed using hydrogen-loaded Corning SMF28 fibre and the FBG spectral information was obtained using an Agilent 86140B optical spectrum analyser. The strength of the FBGs was measured in transmission using a broad band light source centered around 1550nm The fibres were mechanically stripped and cleaned with alcohol before being exposed using a Lasiris 1 inch phase mask.

It should be noted that this work is an exploration of the trends provided by the various parameters present in FBG writing systems and is not intended to define the definitive set of conditions for FBG manufacture. There are other very important factors – such as choice of fibre and post-exposure annealing, for example - which affect the final FBG specifications and these have not been quantified here.

Also, due to the very large amount of highly precise data which was required for this work, this study required many weeks of experimental work to complete. As a consequence, not all the data can be said to have been taken with exactly the same level of fibre photosensitivity, since only a single batch of hydrogen-loaded fibre was used. Although the fibre was kept frozen until required, there was nevertheless deterioration in the sensitivity of the fibre. This was particularly evident in the experiments with the excimer laser dose (section 2.1.2) which was the last experiment to be completed and where the distinct reduction in fibre sensitivity is clearly evident. Despite this aspect, however, all the studies are still valid individually as long as only the important trends are evaluated and no absolute measure is made of parameters such as writing time or total dose required for a particular strength of grating. Such absolute 'recipes' can be arrived at by using the trends which have been measured but are outside the remit of this study.

2.1. Excimer laser exposure at 248nm

A Lambda Physik FIBEX laser operating at a wavelength of 248nm was coupled to the GWS-200E tool for the excimer laser trials. The Fibex laser has a specified spatial coherence length of >1.25mm. The beam was focused using a cylindrical lens to give a beam size of 20mm (along the fibre axis) by 0.338mm at the fibre plane. The following sections detail the parameters whose influence was quantified.

In all the graphs presented in this work, the measurement of the centre wavelength provided a useful check on the strength of the grating, since the central wavelength shifts to longer values as the strength of the FBG increases in many Type I-type gratings [5]. The spectrum relating to each data point was also recorded and this allowed the quality of the grating to be also assessed.

2.1.1 Fluence

Exposures were performed using a total exposure dose of 1500J/cm^2, a laser repetition rate of 25Hz and a fibre-mask separation of 50µm. The exposure fluence at the fibre was altered by using a CNC attenuator (which consisted of dielectric-coated plates) and FBGs were produced at different fluences. Three exposures were made at each fluence and the average values of the strengths and centre wavelengths are plotted in figure 1.

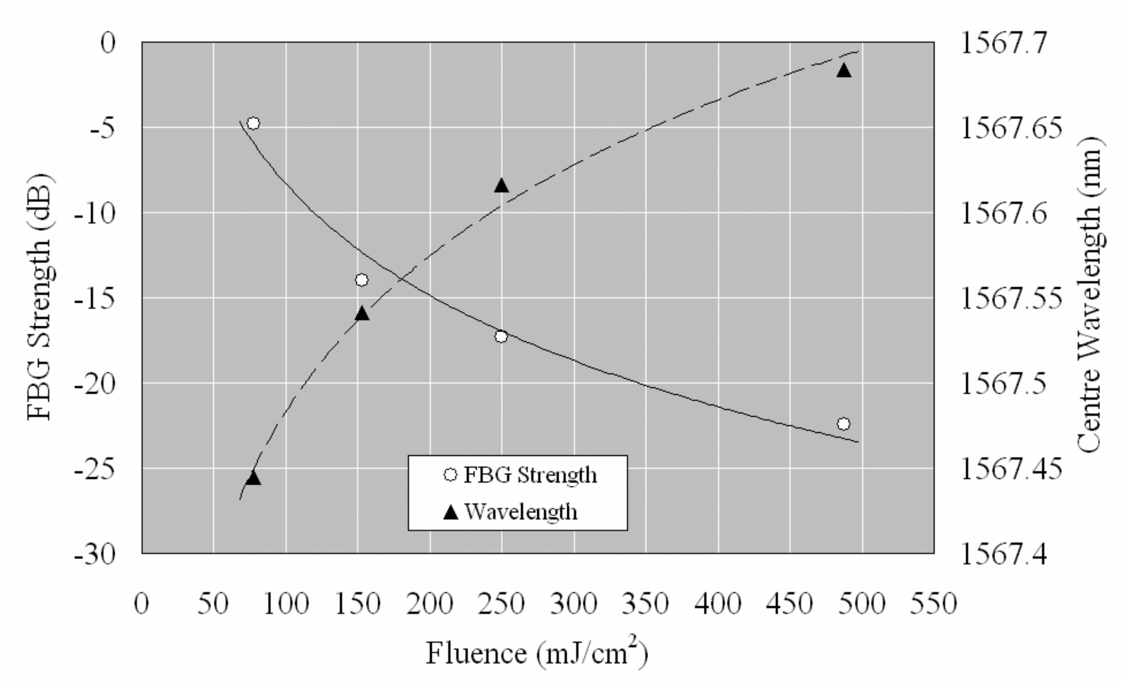

Figure 1. Graph showing variation in the strength of FBGs in H-loaded SMF28 fibres versus exposure fluence.

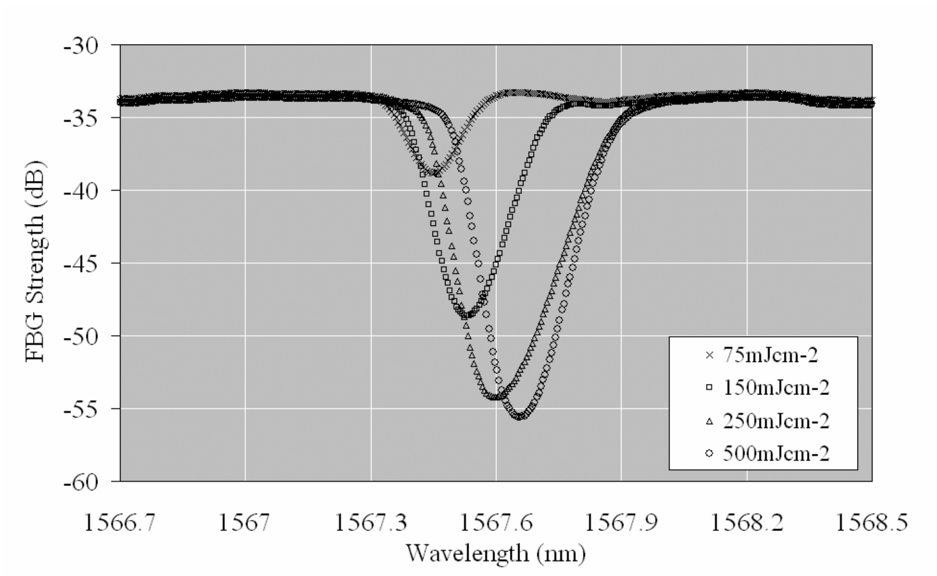

Figure 2. Spectral evolution of FBGs as exposure fluence is increased for a fixed dose.

The transmission spectra of the FBGs relating to the experimental conditions of figure 1 are shown in figure 2. It can be seen that the reflectivity of the FBGs becomes stronger with increasing exposure fluence, despite the fact that the total dose which the fibres are receiving is the same (1500J/cm^2). In terms of shots, the FBG written at a fluence of 500mJ/cm^2 required 3000 shots whereas the FBG written at 75mJ/cm^2 needed 20000 shots. The change in centre wavelength as the grating strength increases is also as expected for increasingly stronger gratings.

The results in figure 1 show that the exposure fluence is an important parameter in terms of both the speed of writing and the ultimate strength which can be achieved, given that other conditions are the same. It should be noted that the exposure dose used (1500J/cm^2) was not the optimum one to give the highest possible reflectivity of FBGs but was chosen as a reasonably practical and representative one.

The spectra in figure 2 show that all the FBGs which were produced were highly symmetric and narrowband, i.e. viable for many FBG applications. The writing times for the four gratings (at a laser repetition rate of 25Hz) were 800s (75mJ/cm^2), 400s (150mJ/cm^2), 240s (250mJ/cm^2) and 120s (500mJ/cm^2).

The data from figures 1 and 2 shows that high reflectivity, good quality FBGs can be written if the laser can fluence can be maintained at sufficiently high levels. The only limitation in increasing the operating fluence comes from the damage threshold of the phase mask. Good quality phase masks have damage thresholds of >1J/cm^2 [Stocker Yale data sheet] but operating well below this threshold is usually advisable to prolong the lifetime of the mask. Therefore, it appears that an exposure fluence of around 500mJ/cm^2 is a good compromise between obtaining a high strength grating with relatively high speed of writing and operating the phase mask at fluences which will not degrade its performance unduly.

2.1.2 Total Exposure Dose

Exposures were performed using a laser repetition rate of 25Hz, a fibre-mask separation of 50μm and three exposure fluences of 100mJ/cm^2, 200mJ/cm^2 and 300mJ/cm^2. The strength of the grating was measured in transmission as the total dose was monitored and figure 3 shows a plot of the FBG strength versus increasing dose for the three fluence values.

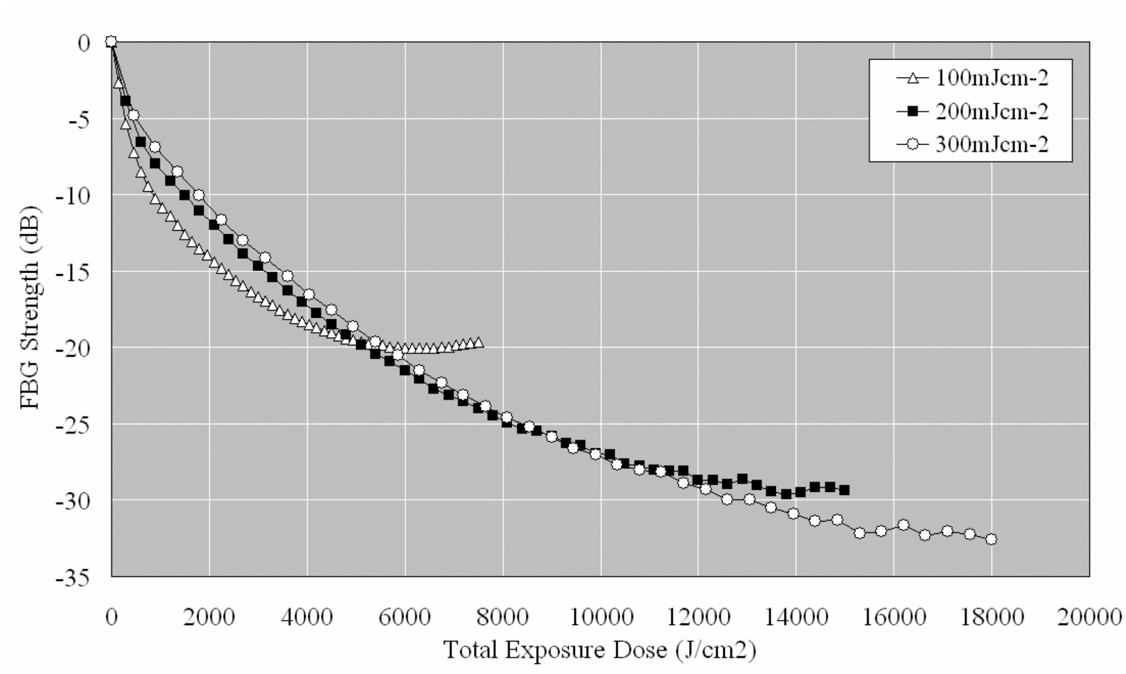

Figure 3. Variation of grating strength with increasing dose for three exposure fluence levels.

Two aspects of the grating production are noted from figure 3: (i) there is a maximum dose at each exposure fluence, beyond which value no increase in the FBG strength is observed, and (ii) the maximum FBG strength which is reached increases with the exposure fluence and occurs at increasingly higher doses. Therefore, if a 30dB grating is required, it cannot be obtained using a fluence of 100mJ/cm^2, irrespective of how much dose is supplied, but it can be attained at 200mJ/cm^2 or 300mJ/cm^2. However, for the 200mJ/cm^2 fluence, it will take around 2000J/cm^2 more to reach 30dB than with the 300mJ/cm^2 fluence.

A similar exercise can be performed to characterise the writing times of gratings and figure 4 shows a plot of FBG strength versus exposure times at three different fluences. The exposure time and total dose are quantities which are equivalent (given that the fluence and laser repetition rate are fixed) but it is informative to plot the data as shown in figure 4.

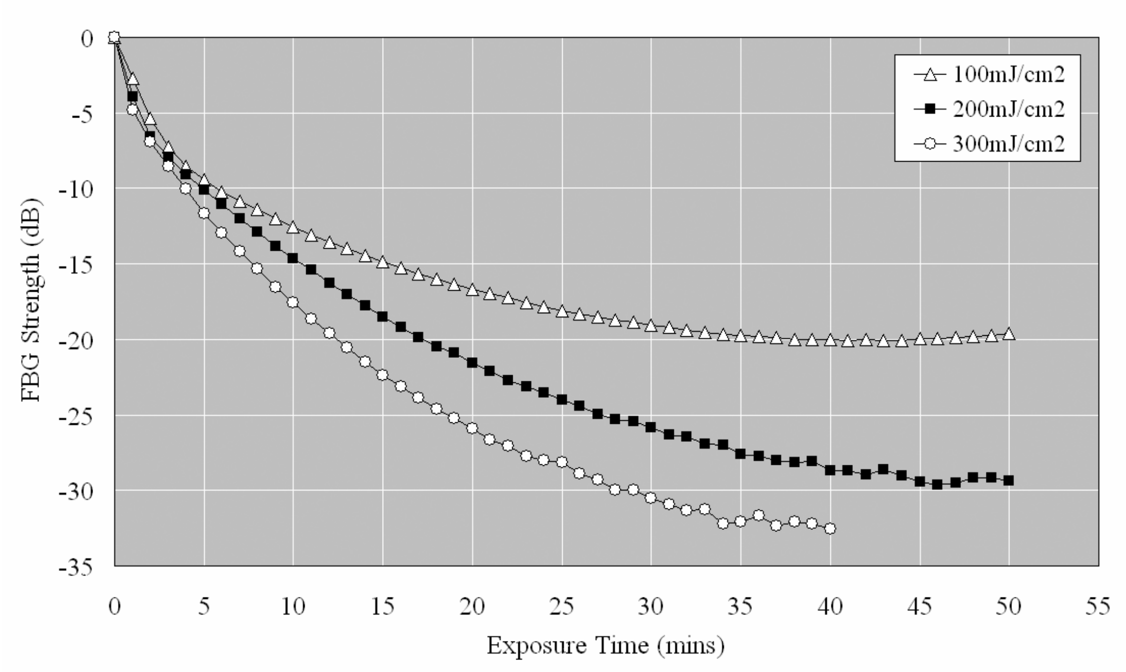

Figure 4. Variation in grating strength with increasing exposure times for three exposure fluences.

It can be noted from figure 4 that if a grating strength of 25dB is required, for example, then either of the two higher fluences can be used but that it will take around 8 minutes longer to reach a 25dB grating with the 200mJ/cm^2 rather than the 300mJ/cm^2 fluence.

2.1.3 Laser Repetition Rate

Gratings were produced at various laser repetition rates using an exposure fluence of 250mJ/cm^2, a total dose of 1500J/cm^2 and a fibre-mask separation of 50µm. Each exposure was repeated three times for each laser repetition rate and figure 5 shows the results of FBG strength (measured in transmission) and centre wavelength versus repetition rate. Each data point represents the average of the three measurements taken for each repetition rate. The main aim of this test was to evaluate whether operating at increasing repetition rates causes any degradation to the quality of the gratings, possibly due to increased thermal effects.

Figure 5 shows that increasing the laser repetition rate does not have any detrimental effect on the reflectivity of the gratings and, in fact, it appears that the grating reflectivity becomes slightly higher as the laser repetition rate is increased to 100Hz. The Lambda Physik Fibex excimer laser is not designed to operate above repetition rates of 100Hz and so higher repetition rate data could not be obtained. Further work is planned to quantify the effects of even higher repetition rates since high quality FBG production at very high repetition rates would reduce production times significantly.

Figure 6 shows the spectra from FBGs produced using 10Hz and 100Hz to demonstrate that the use of high repetition rates does not degrade the quality of the gratings. It can be seen from these spectra that the form and overall quality of the FBGs is not affected by using elevated repetition rates.

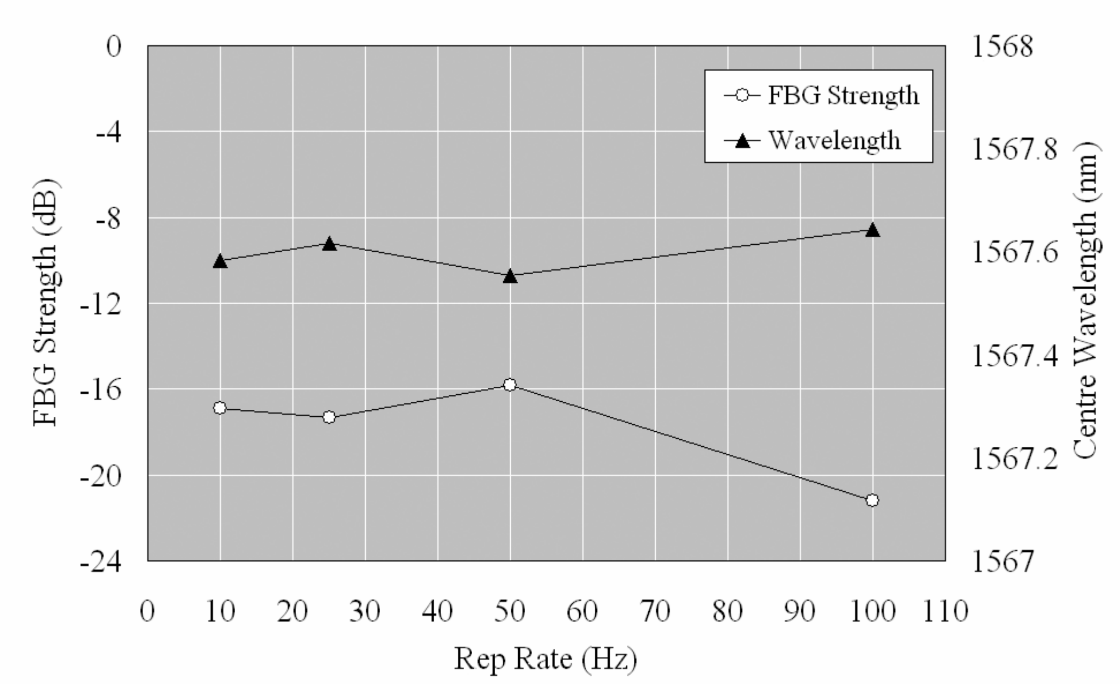

Figure 5. Variation of FBG strength and centre wavelength versus laser repetition rate for fixed exposure conditions.

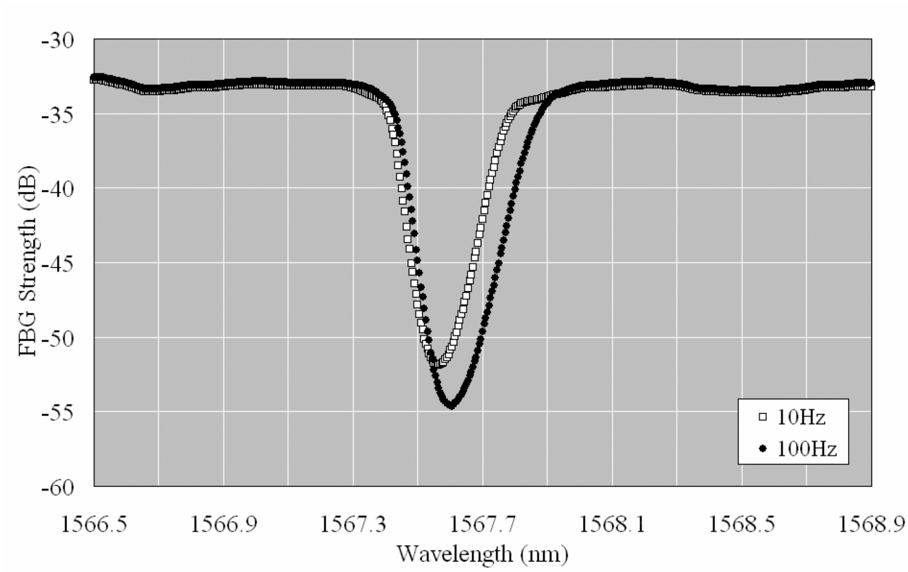

Figure 6. FBG spectra obtained with increasing laser repetition rate, with all other exposure parameters being fixed.

2.1.4 Fibre-Mask Separation

The issue of how far the fibre can be from the phase mask is of crucial importance in any production set-up and the tolerance of the grating quality to this separation is an important indicator of how much care has to be taken in positioning the fibre. In addition, the coherence length of the laser is also an important parameter for the laser manufacturers and much effort has been spent by them in increasing the coherence length of 'FBG-optimised' excimer lasers.

To explore the issue of fibre-mask separation, exposures were performed with increasing separation between the fibre and phase mask using an exposure fluence of 250mJ/cm^2, a laser repetition rate of 25Hz and total exposure dose of 1500J/cm^2. At each fibre-mask separation, the exposures were repeated three times and figure 7 shows the averaged results of these tests.

Figure 7 shows that there is clearly an improvement in the grating strength in increasing the fibre distance from around 15µm to 50µm, this also being evidenced by the increase in the centre wavelength. Subsequently, as the separation is increased, the reflectivity of the grating decreases almost linearly with distance. Due to the lack of data points between 50µm and around 300µm, it is not clear whether the grating reflectivity increases further in this separation region but it is possible that a separation around 200µm might be the optimum distance for highest reflectivity gratings.

There are two clear conclusions from the data set shown in figure 7: (i) it does not seem necessary to position the fibre within a few microns of the phase mask for the best results, and (ii) it is not adequate to place the fibre at many hundreds of microns from the phase mask, as might be indicated by the coherence length of the laser, since this reduces the reflectivity of the grating which can be achieved.

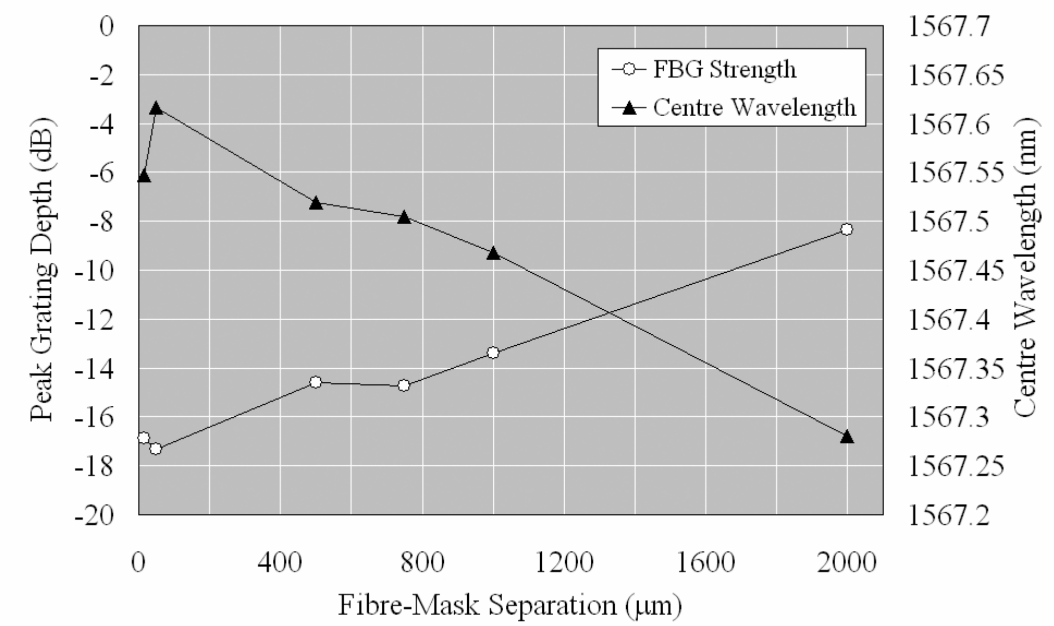

Figure 7. Variation of FBG strength and centre wavelength versus fibre-mask separation for fixed exposure conditions.

2.2. Argon ion laser exposure at 244nm

Exposures were performed using a Coherent Innova 300C MotoFRED cw frequency-doubled argon ion laser operating at 244nm. The laser beam was scanned along the length of the fibre by translating a mirror mounted on an Aerotech ABL-20020 air-bearing stage at different speeds.

The size of the unfocussed argon ion laser beam was measured to be 380μm (FWHM) before the fibre, using a CCD-camera based beam profiler system. A 79mm focal length cylindrical lens was used to focus the beam into the fibre core to give a focused spot size of 380μm x 86.5μm (FWHM) at the fibre, with the longer beam dimension being parallel to the fibre axis. Gratings were produced using a 10mm scan of a Lasiris 1 inch phase mask. The power of the laser beam was measured before the fibre using a Coherent power meter. This meter was cross-calibrated against the laser controller, which then allowed the power at the fibre to be changed and monitored at any time using the laser controller.

2.2.1 Feedrate

Exposures were performed at various scanning speeds to give different exposures to the fibre while maintaining a fixed exposure power of 25mW. Figure 8 shows the variation in the strengths of the FBGs produced versus the scanning speed of the beam, as well as the change in the centre wavelength of the gratings.

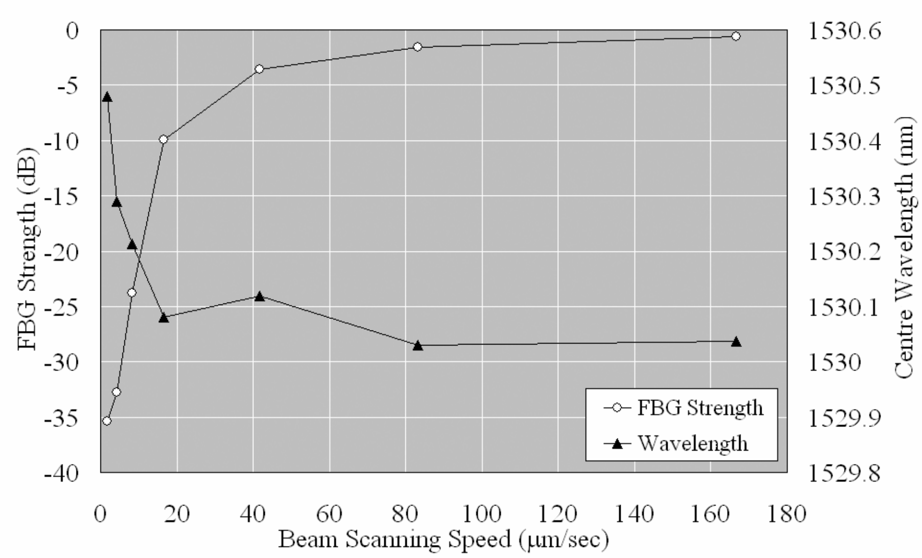

Figure 8. Variation of the strength and centre wavelength of FBGs for different beam scanning speeds from an argon ion laser.

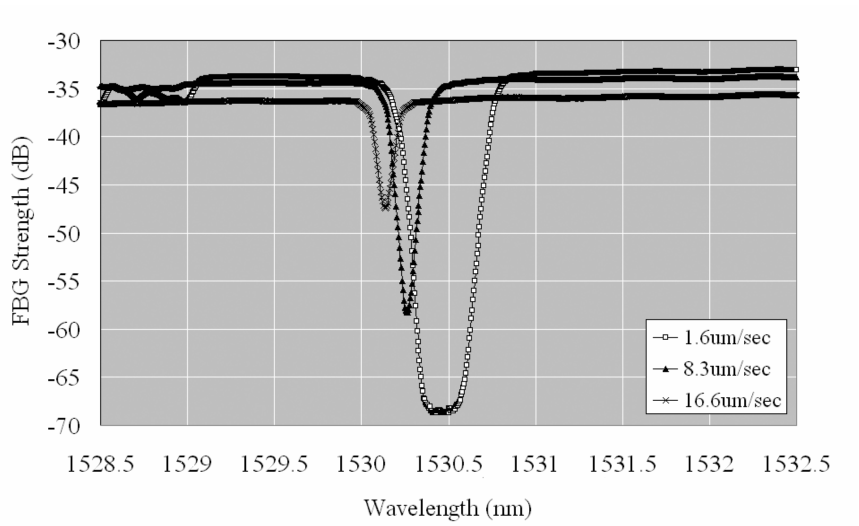

Figure 9. Transmission spectra of gratings produced with varying scan speeds using an argon ion laser.

The effect on grating strength provided by changing the scanning speed (as shown in figure 8) is equivalent to altering the exposure dose to the fibre and it can be seen that the form of the variation is similar to that seen in the excimer laser dose variation (as shown in figure 3, bearing in mind that increasing dose equates to decreasing scan speed).

Figure 9 shows that spectra from three gratings produced with different scan speeds showing the effects of increasing total dose on argon ion laser grating writing. A small amount of saturation is evident for the 16.6µm/sec feedrate.

2.2.2 Power

Using a fixed scanning speed of 83µm/sec, gratings were produced for different exposure powers at the fibre, and the changes are plotted in figure 10. The exposure conditions used are obviously seen to be in a linear regime of grating writing since a linear dependence on power is observed.

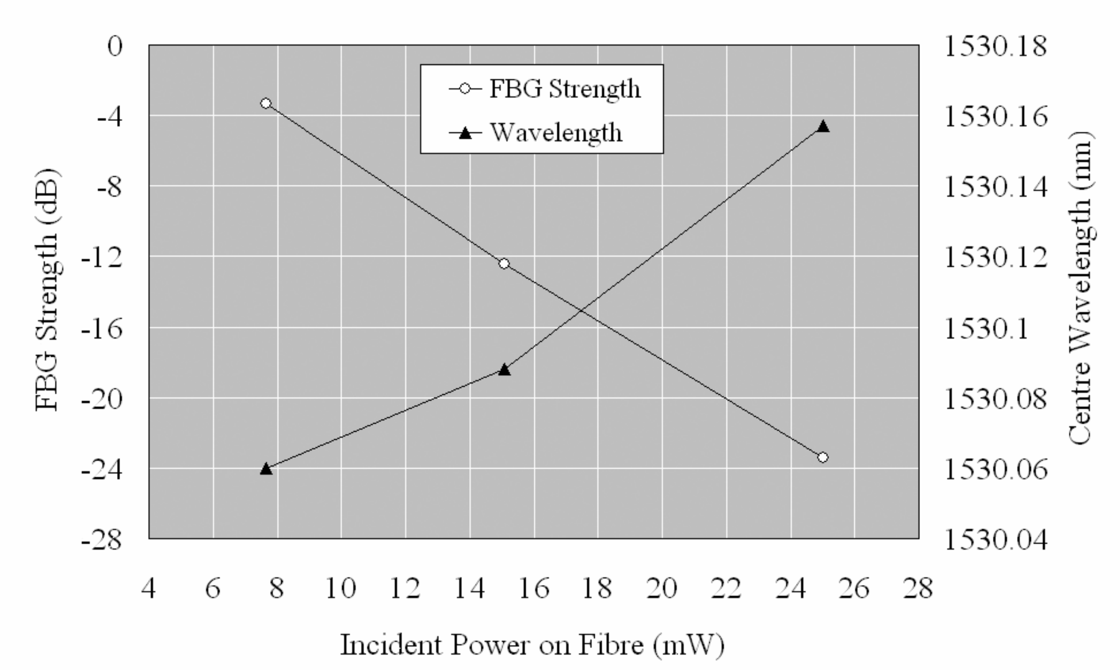

Figure 10. Variation of the strength and centre wavelength of FBGs for different beam powers from an argon ion laser.

3. SUMMARY

An extensive practical study has been carried out which has characterised the important experimental parameters used in the laser writing of FBGs, particularly in the case of excimer lasers. The issues of exposure fluence, total exposure dose, excimer laser repetition rate and separation between fibre and phase mask have been addressed and clear trends established in each case for their effects on the grating properties.

Important conclusions have appeared from this work with regards to the excimer laser systems:

(i) The balance between exposure fluence and total dose supplied to the fibre needs to be adjusted carefully, since this affects the maximum reflectivity of grating which is achievable and the speed at which that grating can be written for a chosen laser repetition rate.

(ii) The laser repetition rate does not appear to affect the grating quality. This is an important verification, bearing in mind that one of the easiest ways to reduce the writing time of gratings is to operate at the highest available repetition rate. Further work is required to extend the current data to repetition rates of 500Hz or so.

(iii) It appears that the maximum practical separation between fibre and phase mask needs to around 200µm or less for optimum grating reflectivity, given the other exposure parameters are fixed. This places in context the issue of coherence length of lasers, where the trend has been to extend the coherence lengths excimer lasers to many mi llimeters. Such extended coherence lengths cannot be fully utilized and it may be more fruitful to limit the coherence length and increase other parameters such as pulse energy or repetition rates.

It has to be noted that this work relates to hydrogen loaded SMF28 fibre and that other fibres (especially intrinsically photosensitive ones) may behave differently. However, a clear methodology has been shown which should allow the grating writing conditions to be established and optimised for any combination of laser and fibre.

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