Gratings in all-silica photonic crystal fibres using 193nm

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ABSTRACT

A review of grating writing in silica photonic crystal fibres using high intensity 193nm emission from an ArF laser is presented.

Introduction:

Microstructured fibres are a class of optical fibre waveguides that possess numerous material vacancies, aligned coaxially, to generate optical confinement[1]. The simplest design uses air for the vacancies, being cost effective and offering the highest refractive index difference, but other materials with a lower refractive index to that of the host can be used. Alternatively, higher index materials can be used to define all-solid bandgap fibres. The optical waveguides are classified by the geometrical arrangement of the air-silica structure; more recent examples include photonic crystal fibres[2] (PCFs), which have a periodic arrangement of air holes, or Fresnel fibres[3] where the air holes are positioned on the Fresnel zones. Waveguide confinement originates from a missing vacancy introduced into the air-silica structured fibre (ASSF) and is generally located at the core. The air-silica structure permits a relatively inexpensive fibre to be fabricated without the need for addition chemical dopants to create the small refractive index change necessary to confine light. Optical guidance can be customised because of the wide variety of geometric patterns capable with ASSFs. Total internal reflection[1] and hollow core photonic bandgap[4] are the two main forms of guidance. The advantage of solid core ASSFs based on total internal reflection is the propagating core modes can couple to fibre Bragg gratings (FBGs).

Germanium doped core ASSF permit inscription of FBGs using low intensity 242nm radiation.[5] However, germanium increases fabrication costs and can also interfere with the desired properties of the ASSF. Albert *et al*[6] reported writing FBGs in a step-index pure silica core (fluorine depressed cladding) optical fibre using a two-photon absorption regime with high intensity 193nm laser radiation. Following on from this, FBGs were written in pure silica ASSFs using high intensity 193nm radiation.[7]

Underlying Mechanism:

High purity fused silica is optically transparent down to ~150nm [8] (Figure 1a) because of the absence of single photon absorption bands which have a spectral edge around 150nm. However, increasing the radiation intensity can cause a multiphoton absorption process that has previously been used to write FBGs. For example, two photons at 264nm,[9] and 193nm [6] or six photons at 800nm.[10] The bandgap for high purity silica is shown in Figure 1b along with various absorption pathways.

The fibre fabrication process results in intrinsic stresses that can result in silica relaxation when provided with sufficient energy. High intensity laser radiation can excite silica allowing it to relax resulting in densification.[11] Although there is some evidence that an excited state intermediary may be involved with the two step absorption process, numerical simulations substantiate overall densification based on stress relaxation analogous to glass quenching.[12] When silica absorbs high intensity radiation, it momentarily melts locally around the excited state which is quickly followed by quenching, causing intrinsic stresses to relax. Usually this leads to denser material. The periodic intensity variations created when using a transmission diffractive phase mask allow periodic densified regions. The volume of densification is dependent on pulse duration: the longer, nanosecond, pulses from exciplex lasers will alter larger volumes of glass than shorter, femtosecond, pulses which are commensurate with the excitation timescale such that photon decay does not spread far beyond the immediate structural relaxation following excitation.

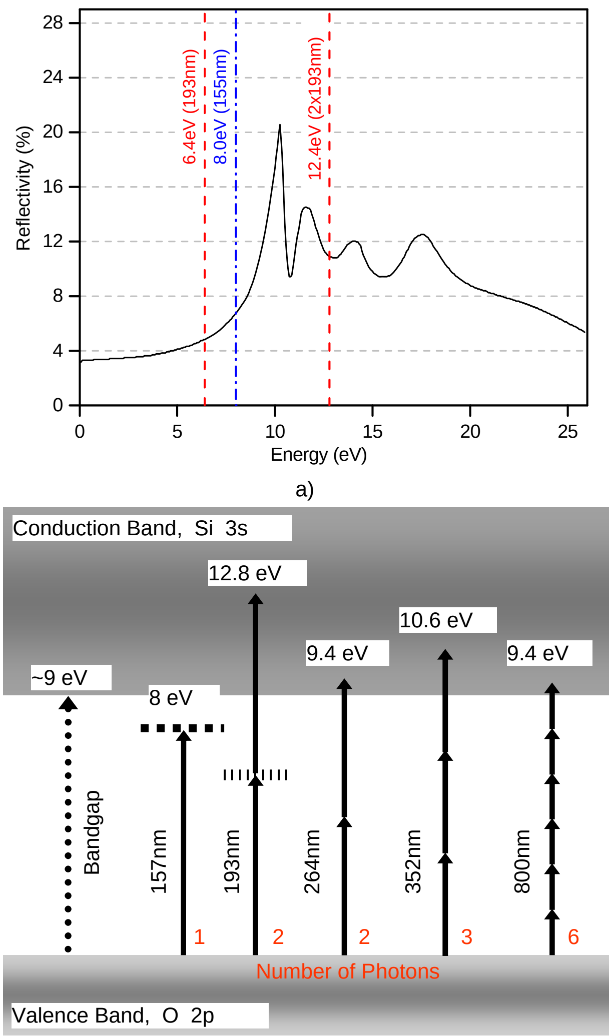

Figure 1. a) Reflectance from vitreous silica showing the absorption edge. Adapted from Philipp.8 b) Schematic diagram of the band gap of vitreous silica including the number of photons required by the respective wavelengths to excite into the conduction band.

Fabrication of air-silica structured fibre:

The ASSF was manufactured using the stack and draw method. Capillaries and rods are stacked forming a preform which is drawn into fibre using normal fabrication techniques. The stack and draw method allows a variety of patterns to be fabricated dependent on the sizes of capillaries and rods used. An alternative method involves drilling holes in a solid perform forming the desired pattern which is then drawn into fibre. However, the drilling process is time consuming and the length of the preform is limited. The ASSF used here comprised of four rings of holes in a hexagonal pattern surrounding a solid core.

Fibre Bragg Grating Writing:

Gratings were inscribed in the ASSF using an ArF exciplex laser operating at 40Hz with 193nm radiation (~15ns pulse width). The light was focused by a cylindrical lens to (1.0±0.1)cm in length along the fibre to induce two photon absorption. The pulse energy was ~(250-300±15)mJ.cm^{-2} leading to a cumulative fluence of ~(200±10)kJ.cm^{-2} producing gratings ~10-20dB in strength. Monitoring the grating growth during writing was done using the

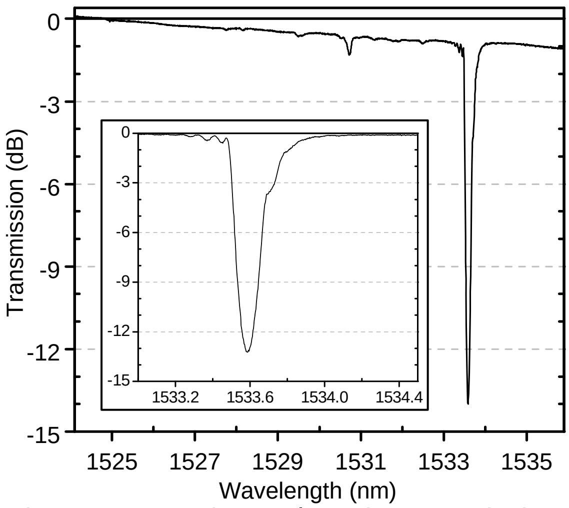

Figure 3. Broad wavelength transmission spectrum of FBG in ASSF. Inset: Narrow wavelength spectrum.

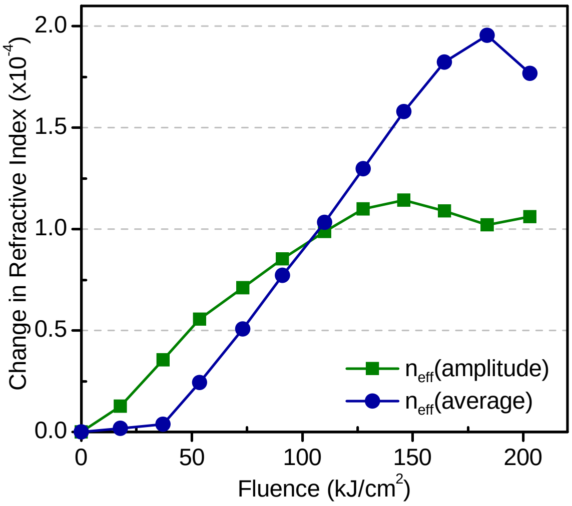

Figure 2. Growth characterisation for the ASSF.

amplified spontaneous emission from an erbium doped fibre amplifier and an optical spectrum analyser (resolution 0.05nm). Broad and narrow wavelength transmission spectra of a ~13dB grating are shown in Figure 2. The broad spectrum shows no cladding modes normally present in standard step index fibre because the ASSF is a single material and therefore the grating is written across the entire fibre. The 3dB bandwidth for the 1cm long grating was (0.23±0.05)nm.

Devices, such as, distributed Bragg reflector[13] (DBR) and distributed feedback[14] (DFB) fibre lasers were fabricated from gratings written in erbium/aluminosilicate doped core ASSF. Whilst high intensity was still required to write the gratings, a larger growth rate than pristine silica was observed.

FBG growth characteristics for ASSF are shown in Figure 3. The growth rate below ~125kJ/cm^{-2} shows a linear dependence, indicating a single process is occurring. After ~150kJ.cm^{-2} the gratings begin to saturate because the density of silica at the refractive index minima in the FBG begins to increase whilst the refractive index maxima remain unchanged. Thus the FBGs refractive index profile is washed out and the grating decreases in strength. The last data point was recorded when the fibre was no longer being irradiated and shows a slight increase in index amplitude with a decrease in average index. This is attributed to a number of factors, 1. the laser creates localised heating when operating at 40Hz repetition rate, and 2. the silica undergoes further relaxation.

High Temperature Annealing:

To explore the FBGs temperature stability the fibre was annealed isochronally up to 700°C (Figure 4). No decay in strength occurs until exceeding 300°C. The ASSF FBGs show a larger resistance to temperature when compared to type I gratings that have a large strength reduction for

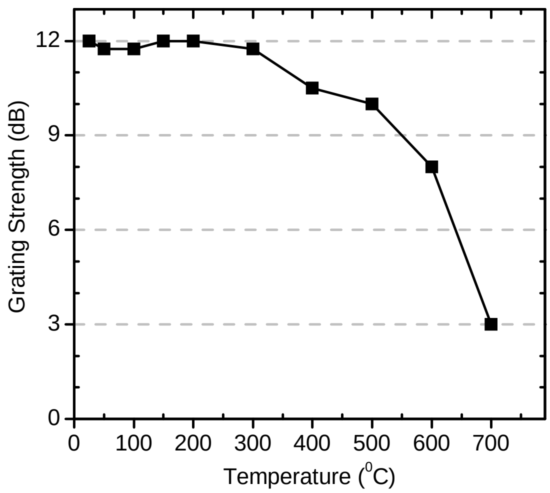

Figure 4. Isochronal annealing of the FBG in ASSF.

temperatures around 200-300ºC. In fact the grating remains >50% reflective up to 700ºC. High temperature resistance of this magnitude has been observed in type 2A[15, 16] and type IA gratings.[17] Since the ASSF gratings decay <800ºC, and there is no evidence of damage when visually inspected, they are not classified as damage gratings (type II) which show resistance up to ~900ºC.[18] The damage threshold for type II gratings is stress dependent[19] and therefore ASSF fibres are expected to be much higher than conventional fibres which have a different thermal expansion coefficient between core and cladding. The average index remained unchanged as the grating decayed indicating the maxima and minima of the refractive index modulation equilibrated from stress equalisation.

Conclusion:

FBGs were fabricated in ASSF by exploiting a multiphoton absorption process when exposed to high intensity UV laser radiation. The high intensity pulses are thought to cause the silica to momentarily melt allowing intrinsic stress relaxation, resulting in densification. FBGs as strong as 20dB have been written in ASSF. The UV scattering from the air-silica structure will lead to a decrease in grating writing efficiency which can be increased by inserting a material into the holes with a similar but lower refractive index to silica and low UV absorption. High temperature annealing indicates a semi-permanent material modification as the gratings show resistance to temperatures <400ºC and decay >600ºC.

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References:

1. P Kaiser, HW Astle, *Low-loss single material fibers made from pure fused silica,* Bell Sys. Tech. J. **53** (6), 1021 (1974)
2. JC Knight, TA Birks, PStJ Russell, DM Atkin, *All-silica single-mode optical fiber with photonic crystal cladding,* Opt. Lett. **21**(19), 1547 (1996)
3. J Canning, *Diffraction-free mode generation and propagation in optical waveguides,* Opt. Comm. **207** 35 (2002)
4. RF Cregan, BJ Mangan, JC Knight, TA Birks, PStJ Russell, PJ Roberts, DC Allan, *Single-Mode Photonic Band Gap Guidance of Light in Air,* Science **285**(5433), 1537 (1999)
5. BJ Eggleton, PS Westbrook, RS Windeler, S Spälter, TA Strasser, *Grating resonances in air-silica microstructured optical fibers,* Opt. Lett. **24**(21), 1460 (1999)
6. J Albert, M Fokine, W Margulis, *Grating formation in pure silica-core fibers,* Opt. Lett. **27**(10), 809 (2002)
7. N Groothoff, J Canning, E Buckley, K Lyttikainen, and J Zagari, *Bragg gratings in air–silica structured fibers,* Opt. Lett. **28**(4), 233 (2003)
8. HR Philipp, *Optical transitions in crystalline and fused quartz,* Sol. State Comm. **4**, 73 (1966)
9. A Dragonmir, JG McInerney, DN Nikogosyan, *Femtosecond measurements of two-photon absorption coefficients at λ=264nm in glasses, crystals, and liquids,* Appl. Opt. **41**(21) 4365 (2002)
10. CW Smelser, SJ Mihailov, D Grobnic, *Formation of typeI-IR and typeII-IR gratings with an ultafast IR laser and phase mask,* Opt. Exp. **13**(14), 5377 (2005)
11. NF Borrelli, C Smith, DC Allan, TP Seward III, *Densification of fused silica under 193-nm excitation,* J. Opt. Soc. Am. B **14**(7), 1606 (1997)
12. A Wootton, B Thomas, Peter Harrowell, *Radiation-induced densification in amorphous silica: A computer simulation study,* J. Chem. Phys. **115**(7), 3336 (2001)

13. J Canning, N Groothoff, E Buckley, T Ryan, K Lyytikainen, J Digweed, *All-fibre photonic crystal distributed Bragg reflector (PC-DBR) fibre laser,* Opt. Exp. **11**(17), 1995 (2003)
14. N Groothoff, J Canning, T Ryan, K Lyytikainen, H Inglis, *Distributed feedback photonic crystal fibre (DFB-PCF) laser*, Opt. Exp. **13**(8), 2924 (2005)
15. L Dong, WF Liu, L Reekie, *Negative-index gratings formed by a 193-nm excimer laser,* Opt. Lett. **21**(24), 2032 (1996)
16. N Groothoff, J Canning, *Enhanced type IIA gratings for high-temperature operation,* Opt. Lett. **29**(20), 2360 (2004)
17. Y Liu, JAR Williams, L Zhang, I Bennion, *Abnormal spectral evolution of fibre Bragg gratings in hydrogenated fibers,* Opt. Lett. **27**(8), 586 (2002)
18. JL Archambault, L Reekie, PStJ Russell *100% Reflectivity Bragg reflectors produced in optical fibres by single excimer laser pulses,* Elec. Lett. **29**(5), 453 (1993)
19. PC Hill, GR Atkins, J Canning, GC Cox, MG Sceats, *Writing and visualization of low-threshold type II Bragg gratings in stressed optical fibers,* Appl. Opt. **33**(33), 7689 (1995)