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MECHANISMS OF GRATING FORMATION IN OPTICAL WAVEGUIDES

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Summary

Despite the proliferation of materials in which waveguides may be formed, the vast majority of grating work is still carried out using silica-based optical fibres. This work is being driven by the fibre telecommunications and sensor markets, where there are requirements for low-loss, low-cost filters which are robust and easy to manufacture. There has yet to be serious interest in fibre gratings in other materials, although some devices are starting to appear. A full understanding of the underlying process to grating formation is not yet available.

Abbreviations

UV ultraviolet
CW continuous wave
AFM atomic force microscope
ZBLAN zirconium/barium/lanthanum/aluminium/sodium
WDM wavelength division multiplexing

Introduction

The fields of optical fibre telecommunications, fibre sensors, rare-earth doped fibre lasers and optical amplifiers have created a need for devices such as switches, modulators, and filters which use the fibre itself as the active medium. Such devices dispense with the unwanted requirement of removing light from the fibre in order to perform some signal processing function, incurring unnecessary losses at the same time. The erbium-doped fibre amplifier is perhaps the best known example of such a device, in which the optical signal in a fibre telecommunications link is boosted without ever leaving the fibre. The Bragg grating is another successful example of such a device.

It is possible to permanently modify the refractive index of some types of glass by illuminating with intense light, the preferred source being a UV laser, either cw or pulsed. The core of telecommunication-grade silica-clad optical fibre is doped with germania which has a strong absorption of approximately 0.1-1dB/μm near λ=240nm, dependent on the dopant concentration. If the fibre is illuminated with laser light of this wavelength, the refractive index of the core may be increased in the illuminated region by approximately 10^{-5}. Furthermore, if the core is exposed to an interference pattern created using two mutually coherent UV laser beams, a periodic modulation in the refractive index may be achieved, resulting in a Bragg fibre grating. On resonance, the grating will reflect some fraction of the incident light back along the fibre. Even though the index modulation is small, the grating length can exceed several centimetres, and so the reflectivity of the grating can readily approach 100%. The temperature stability of these gratings is such that they are essentially permanent at room temperature.

Such gratings are finding many uses as filters and sensing elements in areas which already use optical fibres, as well as being employed as wavelength-selective mirrors in fibre lasers. The small index change obtainable with telecommunication fibre however has been a limitation which it was necessary to overcome if certain devices requiring 'strong' gratings were to be fabricated. This review will examine the progress which has been made in searching for new materials which show enhanced photosensitivity and also the merits of using different types of laser for the inscription process. The holographic process which is used to fabricate the gratings and the applications for which they are used will not be discussed here in any detail.

In addition to the work being carried out on silica fibre, there is a growing body of work using other types of glass in both fibre and planar form. These fields will also be briefly covered.

Silica fibre

There is a large body of literature on the photorefractive effect in glass dating back for many years, and much of this work relates to silica given that this glass has reasonable transparency in the near UV. This area has been revived in recent years due to the intense interest generated by fibre gratings. However, despite the progress which has been made into fabricating new types of gratings and improving the photosensitivity of the fibre, there are still many unanswered question about the fundamental nature of the photorefractive process itself. This has created problems for researchers who are attempting to optimise the photorefractive properties of the fibre, leading to a 'suck-it-and-see' approach. In addition, there are several types of fibre grating to be considered: Type 1 (the most commonly fabricated photorefractive grating, characterised by a net positive index change), Type 2A (also photorefractive, with a negative index change) and Type 2 (positive index change, caused by UV-induced damage of the core-cladding interface).

Three schools of thought exist as to the fundamental nature of the Type 1 photorefractive process in optical fibres: the Kramers-Kronig model [1] which relates the observed refractive index change to optically-induced changes in the UV defect centre absorption bands, the compaction model [2,3*4] and the stress model [5,6]. Glass compaction had been observed previously in bulk glass samples and fibre preform plates [7], however it was shown for the first time in [3*] that UV-induced compaction of the core glass also took place within an optical fibre. This was done by etching away the fibre cladding adjacent to a previously written Bragg grating and examining the exposed core with an AFM. A relief grating was observed in both the core and adjacent cladding region, clearly indicative of some structural or chemical change in the glass structure. There was a dephasing of π between the gratings in the two regions.

Non-destructive optical stress measurements made on UV-irradiated fibres [6] have shown that tensile stress in the fibre core is actually increased after irradiation, contrary to previous reports which suggested stress relief as a grating formation mechanism [5]. This stress increase leads to a localised decrease of the refractive index in the illuminated region. Taking compaction and structural deformation of the glass matrix into account however, an overall positive change in the average refractive index as observed experimentally is accounted for.

Type 2A gratings are a much more recent invention [8], and consequently they are not as well understood as Type 1 gratings. They are fabricated by over-exposing Type 1 gratings and are generally characterised by a negative overall change in the refractive index of the core region and improved temperature stability when compared to Type 1 gratings made in the same fibre and at the same optical power level. Interestingly, Xie *et.al.* found that it was not possible to fabricate bulk Type 2A gratings in fibre preforms from which fibre capable of taking such gratings had been drawn, suggesting that the fibre structure or the pulling procedure played a large part in the overall grating formation process[9].

For some time, the preferred wavelength for writing Bragg gratings has been in the region of 240-250nm. More recently, it has been shown that the ArF excimer laser which operates at 193nm has distinct advantages when writing gratings in certain types of fibre. Gratings having index modulations in excess of 10^{-3} were written in standard telecommunications fibre [10], an order of magnitude improvement over previous results obtained using the same fibre with longer wavelength writing and no hydrogen loading. It was also shown that a two-photon mechanism was responsible for grating formation in low Ge-concentration fibres at 193nm, as opposed to a single-photon process in fibres with high Ge-doping [11]. A three-level model has been proposed to explain the growth mechanism of Type 2A gratings in boron co-doped germania fibres [12,13], although a more detailed understanding of the physical nature of the mechanism has yet to be obtained.

In order to improve the photosensitivity of the fibre, boron co-doping [14] and hydrogen loading [15] remain the favoured options. Boron however introduces loss in the crucial 1.5μm region of the spectrum, whereas hydrogen loading introduces losses in the visible and near infrared regions. Furthermore, gratings in boron co-doped fibre are not stable at high temperature. One solution is to co-dope the fibre with tin rather than boron. Tin is a logical choice as co-dopant, occupying the same column of the periodic table as silicon and germanium. Both germania-free phosphosilicate [16*] and germanosilicate [17] fibres have been doped with tin to enhance the photorefractive effect. Index modulations of 1.2×10^{-3} and 1.4×10^{-3} respectively were obtained using a KrF excimer laser at 248nm, approaching the performance of boron co-doped fibre. In addition, the temperature stability of the tin-doped germanosilicate fibre was substantially better than boron co-doped fibre, and even better than standard germanosilicate fibre, with no significant additional intrinsic loss at 1.5μm. Single pulse, high reflectivity Type 2 gratings were also written in the tin-doped phosphosilicate fibre, the first time that such gratings have been observed in germania-free fibre. Tantalum co-doping has also been tried [18], with less successful results.

Long period fibre gratings are becoming increasingly useful as non-reflective filters in telecommunication systems and fibre amplifiers [19,20]. Unfortunately, they suffer from poor temperature stability when compared to conventional fibre Bragg gratings. Judkins *et.al.* [21] showed that this problem could be eliminated by tailoring the refractive index profile in order to balance the waveguiding properties of the fibre with the material properties. An order of magnitude improvement was obtained in a preliminary experiment. In another paper [22], the temperature sensitivity of these gratings was used to discriminate between strain and temperature by fabricating a fibre sensor which combined both long period and Bragg gratings.

'Soft glass' fibre

Silica fibres remain the most popular for device applications. It is sometimes necessary however to exploit the properties of other types of fibre in order to perform certain tasks. Low phonon energy materials such as chalcogenide and ZBLAN-based fluoride glasses can be doped with rare-earths and made into fibres to be used as lasers and amplifiers at wavelengths not accessible to silica. Strong, robust fibre gratings would be a useful addition to such devices. Photosensitivity in chalcogenide glasses has been known about for many years, however it is difficult to fabricate single-mode fibre from such material. A preliminary experiment [23] showed that gratings could be written in a highly multi-mode As_2S_3 glass fibre using only 5mW of power launched axially from a HeNe laser at λ=633nm. More usefully, a grating operating at λ=1.54µm was written in a single-mode As_2S_3 fibre using the transverse holographic method which allows the resonance wavelength of the grating to be chosen [24]. An index change of 4.6×10^{-5} was estimated from the grating profile (reflectivity=90%) however this was probably limited by vibration within the interferometer. Optically induced index changes of 10^{-2} should be obtainable in such fibre.

Cerium co-doping has been used in silica fibres to enhance the photosensitivity. More recently, Ce^{3+}-doping has been used with ZBLAN fluoride fibres in order to allow gratings to be written [25,26]. UV pumping of the cerium transition near λ=245nm results in the creation of a permanent change in the refractive index of approximate to 2×10^{-5}.

Planar waveguides

Gratings are also useful in planar waveguide structures for filtering, WDM, laser mirrors, *etc*. The photorefractive effect in germanosilicate slab waveguides is sufficiently strong that single-mode waveguides can be directly written into the substrate by UV laser [27,28]. By writing into rare-earth doped glass, lasers and amplifiers can be manufactured [29]. Using techniques similar to those used with fibre, gratings can be manufactured into both optically induced and rib waveguides in planar form [30,31*]. Gratings having a reflectivity >99.9% were written in PECVD-grown germanosilicate rib waveguides without the aid of hydrogen loading [31*].

Conclusions

Bragg grating technology is still largely concerned with silica optical fibres, despite the growing interest in alternative glasses for use with rare-earth doped fibre lasers and amplifiers. The need for gratings is largely driven by the telecommunication and sensor markets, where they are used as filters, mirrors, channel separators, dispersion compensators and strain and temperature sensors. Despite the fact that almost two decades have passed since the first fibre gratings were made, there is still much to be learned about the photorefractive effect in glass. Some progress is being made in the search for fibres with better photosensitivity over a wider range of conditions, but the research is very much hit-and-miss. Gratings in planar structures are expected to become more popular as silica waveguide structures become integrated into future telecommunication systems.

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