1592

5.3 Fibre gratings in silica optical fibre

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A INTRODUCTION

Photorefractive fibre gratings are devices that are rapidly being taken up by the telecommunications and fibre sensor industries due to their wide range of uses. They can be thought of as one-dimensional holograms written directly into the core of a conventional optical fibre which have the capability of reflecting light of a specific wavelength back along the fibre. Like holograms, they are essentially permanent and are written using specialised lasers. They rely on the fact that the refractive index of the germania-doped silica fibre core can be changed by exposure to intense ultraviolet (UV) light, however the exact nature of the photorefractive change is not yet fully understood. In general, it is possible to produce an absolute refractive index change of 10^{-6} - 10” in most fibres, though it is necessary to use specially designed fibres in order to achieve the highest index change.

B GRATING MANUFACTURING TECHNIQUES

Fibre gratings were first ‘discovered’ when it was found that light from an Ar^+-ion laser at λ=514.5nm launched into a germania doped silica optical fibre was, after a period of time, being reflected back from the fibre end with high efficiency [1]. The light was being reflected from a region of the core containing a periodic modulation in the refractive index created by the standing wave interference between the incoming beam and the Fresnel reflection (- 4%) from the end of the fibre. This effect was weak and difficult to reproduce in a range of different fibre types, and furthermore produced a fibre grating that only worked at the wavelength with which it was written. It was later realised that the photorefractive effect responsible for the grating was a two-photon process centred on an absorption band around λ=240nm [2], and a much higher index change could be generated by writing directly at this wavelength. This required the adoption of a two-beam interference process external to the fibre [3] which had the additional benefit of allowing a much wider range of fibre gratings at different wavelengths to be fabricated (see Figure 1). In general, frequency doubled dye lasers, excimer lasers or frequency doubled Ar^+-ion lasers are used. The angle between the two writing beams is chosen to produce a grating with a pitch, A, which satisfies the following condition:

$$\lambda_{Bragg} = 2 \cdot n_{eff} \cdot \Lambda$$

where λ_{Bragg} is the centre wavelength of the grating and n_{eff} is the effective refractive index of the mode. Usually, this gives a pitch of 300-600nm for most gratings required in telecommunication and sensor systems.

INSERT FIGURE HERE

Figure 1: Interference fringes created by intersecting UV laser beams create the grating in the core of the fibre.

More recently, silica phase masks have been used to make fibre gratings [4,5]. These phase masks consist of a polished piece of UV-grade silica which have a diffraction grating etched into the surface, the depth and profile of which is designed to maximise coupling into the first order diffracted beams, while minimising the zero-order throughput. The pitch of the phase mask is twice the required pitch of the grating in the fibre. When a fibre is placed in contact with such a grating and illuminated through the mask with UV light, a photorefractive grating will be formed in the core of the fibre. This technique has the advantage that the uniformity of any fibre grating made this way is not limited by the spatial profile or coherence of the writing laser, which can be scanned over the phase mask. This advantage is gained at the expense of tunability, the wavelength being fixed at the design stage. Phase masks can routinely be made which have a length of several centimetres, so that it is possible to make long fibre gratings using a relatively simple experimental set-up.

In addition to making gratings in off-the-shelf fibre, it is also possible to write gratings in the fibre as it is being drawn [6]. This has the considerable advantage that the polymer coating which normally protects the fibre does not have to be removed and replaced, improving the physical strength of the grating. The main use however is in fabricating long arrays of gratings for use in multiplexed fibre sensor systems. By using a writing interferometer that can be tuned in wavelength as the fibre is being drawn, the wavelength of each grating in the array can also be selected [7]. A short pulse device such as an excimer laser must be used to write the gratings, and only low reflectivity gratings may be obtained due to the single-shot nature of the writing process.

An alternative method which avoids removal of the coating is to use a polymer which is transparent at the writing wavelength. This can be done either by using a proprietary coating which has low loss at near-conventional writing wavelengths [8] or by using a longer wavelength to write the grating through a standard coating [9]. Both techniques offer solutions to the problems of automated grating fabrication and production of robust grating arrays for fibre sensors.

C FIBRE SENSITISATION

It is not usually possible to obtain a high refractive index change in conventional telecommunication grade fibre. This is partly due to the relatively low germania content, but also to the addition of other dopants such as phosphorous, which weakens the photorefractive effect. One possible way to improve the index change is to increase the UV absorption of the core by the addition of extra germania. Unfortunately, this raises the index to such an extent that the fibre becomes incompatible with conventional fibre, a high splice loss being obtained due to the difference in the modal spot size. It was found that the addition of boron to the core of the fibre not only lowered the refractive index, as was well known, but also greatly improved the photosensitivity [10]. The boron/germania codoped silica fibre remains one of the most intrinsically photosensitive fibres to date. This led to a flurry of activity in the search for suitable codopants, with varying success. Those tried so far include: europium [11], cerium [12], tantalum [13], aluminium [14] and tin [15]. By far the most successful is tin, which has similar photosensitivity to boron codoped germania, but can be taken to much higher temperature before grating degradation becomes a problem.

The highest index changes are achieved by diffusing molecular hydrogen into the fibre core at high pressure (several hundred atmospheres) prior to writing the grating. Using this technique, refractive index changes of $\Delta n > 10^{-2}$ have been obtained [16]. Part of this index change however can be related to defect centres which have a relatively low activation energy and are not stable at typical industrial operating temperatures. In order to improve the reliability of such gratings, it is necessary to anneal them at elevated temperature, typically ~150°C. In addition, the fibre loss in the wavelength region $\lambda < 1\mu m$ is increased significantly, with possible repercussions in the field of rare-earth doped fibre lasers.

D TYPES OF GRATINGS

The conventional photorefractive effect as discussed above consists of an increase in the refractive index of the fibre core with increasing UV fluence - this mechanism is known as Type 1 and is the most commonly observed. Typically, such gratings are stable up to temperatures in the range 200°C - 300°C. Two other grating formation mechanisms are possible, usually referred to as Types 2 and 2A. Type 2A gratings are also photorefractive in nature, the primary difference being that the observed change in the refractive index is negative, not positive. In addition, such gratings are considerably more stable than those of Type 1. This type of grating may be obtained by 'over-exposing' a Type 1 grating, however the process can be very slow if carried out using a laser operating near 240nm. By writing the grating using an ArF excimer laser operating at $\lambda = 193nm$, Type 2A gratings may be written in a few minutes, greatly reducing the exposure time.

Type 2 gratings are not photorefractive in nature - rather they are formed when an intense UV laser pulse interacts with a highly absorbing fibre core, creating damage regions along the core/cladding interface [17]. Such gratings have been observed in germania and tin doped fibres. Very high index changes ($\Delta n > 10^{-3}$) can be obtained using this technique using only a single 25ns pulse from an excimer laser. In addition, due to the nature of the damage mechanism, such gratings are very robust, surviving at temperatures in excess of 800°C. There is however usually a small loss penalty associated with such gratings, rendering them unsuitable for use in multiple grating arrays.

E SPECIALISED GRATINGS AND APPLICATIONS

Fibre gratings are normally designed to reflect light of a specific wavelength propagating in the fundamental mode back along the core of the fibre. By increasing the pitch of the grating to several hundred microns however, the propagation constant of the core and cladding can be matched at various specific wavelengths [18]. This causes light to be coupled into the cladding and ultimately the polymer coating where it is lost. In this manner, efficient bandstop filters can be fabricated which do not couple light into the backward propagating mode, potentially causing problems in optically amplified telecommunication systems. Such gratings are fabricated either using point-by-point exposure of each individual element, or through a dedicated amplitude mask. The resulting gratings find use as gain equalisers in erbium doped fibre amplifiers for high bit-rate communication links [19].

Using the phase mask production technique, it is possible to fabricate long fibre gratings with properties which vary along the length of the grating. The index profile of the grating may be tapered, or apodised, in order to reduce the sidelobe reflections in the wings of the spectrum. Also, the pitch of the grating may be varied along the length, creating a wavelength chirp in the reflection profile. By combining both of these techniques, it is possible to fabricate a grating which can compensate for the dispersion of a 1.55μm telecommunications signal transmitted over standard 1.3μm zero-dispersion fibre [20]. Narrowband gratings can also be used as filters and add/drop multiplexers in multichannel wavelength division multiplexed (WDM) fibre links. Other telecommunication uses include using gratings as stable wavelength selective feedback elements for semiconductor diode and rare-earth doped fibre lasers [21].

Perhaps the most widespread use of fibre gratings to date has been in the area of fibre sensors, where they may be used for sensing strain, temperature, pressure and any other measurand for which the grating can be sensitised [22]. Most commonly they may be configured as strain sensors by using the simple principle that the grating pitch will increase when the fibre is placed under tension, moving the operating point to longer wavelength. Distributed arrays of such gratings in a single length of fibre may be embedded in a composite material for use in 'smart structures' such as an aeroplane fuselage.

F CONCLUSION

Photorefractive gratings in silica optical fibre are finding many uses as stable, robust optical elements in long haul fibre telecommunication and sensor systems. There is still some debate over the exact nature of the photorefractive mechanism in silica, however the physical characteristics of most types of fibre gratings are well enough understood for the vast majority of applications.

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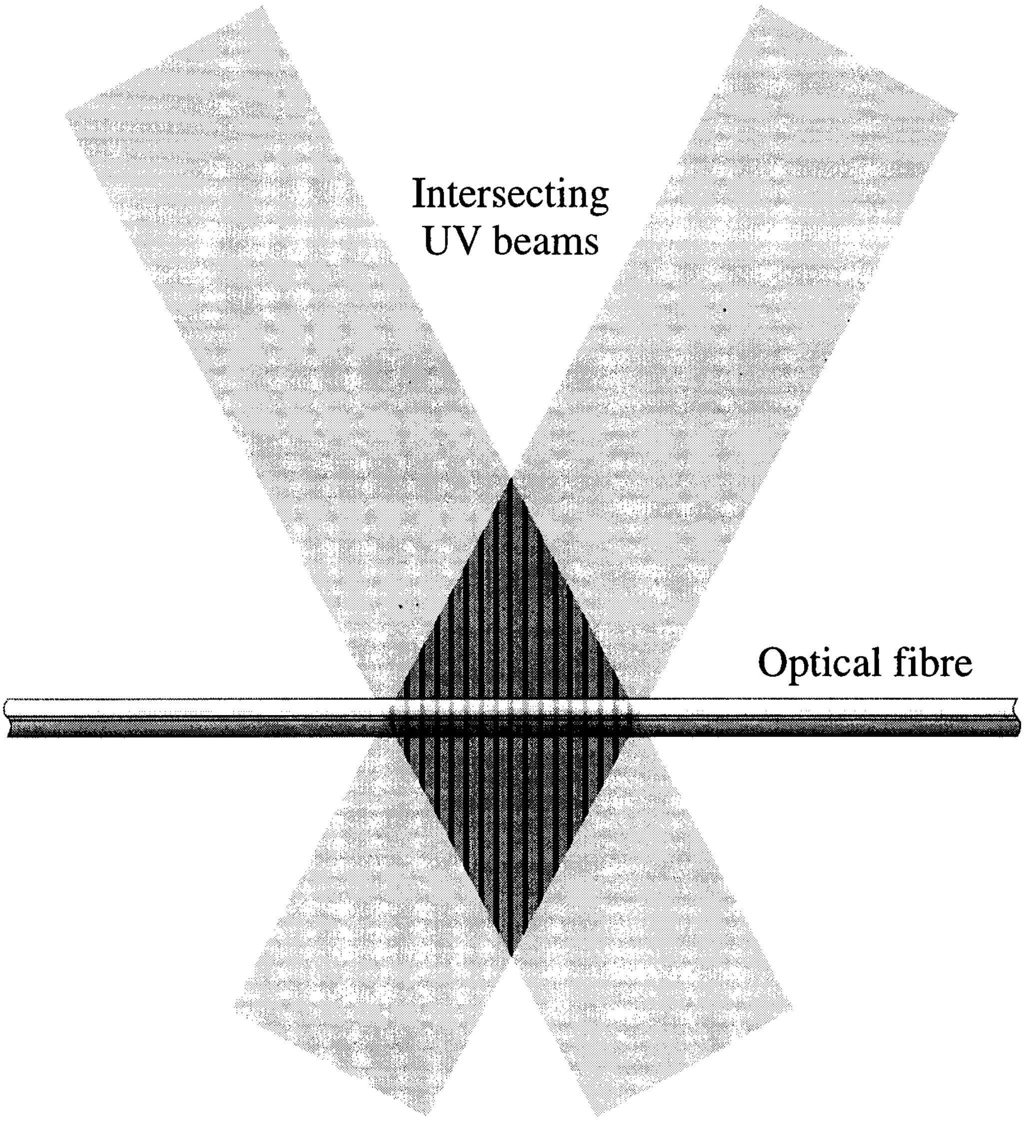
Intersecting
UV beams
Optical fibre