TILTED FIBRE GRATINGS FOR SIDEWAYS LIGHT DELIVERY

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Abstract

We investigate the properties of tilted fibre gratings written using two techniques - namely UV laser with phase mask inscription in hydrogenated fibre, and point-by-point femtosecond IR inscription in non-photosensitised fibre. The intended application of this work is for laser light delivery from the side of an intravenous optical fibre for cauterising biological tissue in surgical procedures. Consequently, broad bandwidth gratings capable of withstanding temperatures of 100’s of degrees celsius are required. With an efficient and rapid writing process (exposure times of a few seconds to minutes are typical), we have produced phase-mask- inscribed gratings using tilt angles of up to 8° and point-by-point inscribed tilted gratings. The latter have the advantage of being highly thermally stable (up to 600° C) and offer the prospect of suitable bandwidths through careful design of the grating. We present an investigation of these two grating structures.

Introduction

Optical fibre gratings are useful as wavelength-sensitive filters and reflectors in optical fibre systems, for telecommunications and sensing applications for example [1]. These gratings are normally fabricated in the germanium-doped core of single mode optical fibre by exposure of the fibre to a modulated UV light source, such as is obtained by irradiation of the fibre through a phase mask [2]. To improve the speed and efficiency of the fabrication process, the photosensitivity of the optical fibre core may be enhanced by high pressure loading with hydrogen gas [3], for example. More recently, focussed sub-picosecond lasers have been used to produce gratings [4,5], either by irradiating the fibre through a phase mask, or point-by-point. This latter approach has been shown to produce robust and highly reflective gratings in optical fibres, and it has the advantage of being effective for pure silica fibre [6]. A less well-known feature of optical fibre gratings is their ability to couple light into cladding or radiation modes, for example, by tilting the grating planes [7,8]. This effect may be explained by considering the grating as both a reflector and a diffractor. Both optical effects arise due to the grating, and the grating parameters may thus be optimised. We are interested in applying tilted optical fibre gratings in surgical applications for which laser light must be delivered sideways from an intravenous optical fibre. Such requirements arise in some types of “keyhole” surgery where intravenous delivery of laser light via optical fibre is needed to treat internal organs. In a proposed treatment of cardiac arrhythmias, for example, laser light of substantial average power, ~20 W, must be directed sideways in a continuous line of 5-10 mm in length from the side of a multimode optical fibre introduced inside the heart, in order to cause deep lesions at specific positions in the heart muscle [9].

Because the length, reflectivity pattern and beam direction angle of tilted fibre gratings can be controlled, these devices appear suitable for this and similar surgical applications. Previous research has indicated that standard fibre grating fabrication techniques are not suitable for producing tilted gratings due to the effects of jitter on the writing beam during the long irradiation times required for strong reflective gratings [10]. Although our intended application requires multimode optical fibre for delivery of high average power laser light, we here report preliminary experiments on grating fabrication and characterisation using single mode fibre.

Design of gratings

A comprehensive study of tilted gratings requires coupled mode analysis, and knowledge of the cladding and radiation mode characteristics of the specific optical fibre to be used [7,8]. However, simple design criteria for tilted gratings in single mode fibre can be understood with a more intuitive approach (similar to that of Ref. 8) as follows. The diffraction angle of the light at the desired wavelength $\lambda$ is matched to the angle of the light reflected off each plane of the grating, for the most efficient, namely phase-matched, operation. This is evaluated by considering the effective propagation constant of the fundamental mode of the optical fibre, $\beta$, and using momentum conservation. For a light diffraction angle of $\theta$ from the fibre, the grating period $\Lambda$ must satisfy

$$\frac{\beta}{\lambda} = \frac{2\pi}{\Lambda} \sin \theta \leq \frac{2\pi}{\Lambda}.$$
Since the grating essentially acts as a blazed diffraction grating, its operation can also be understood in terms of the optics of blazed gratings. By adjusting the blaze angle of the grating, the angle for specular reflection can be matched to the peak of the diffraction pattern for a specific wavelength. The out-coupling of the light is thus optimised by choosing the tilt angle of the grating planes (the blaze angle) to be half of the diffracted angle, i.e., by $\theta/2$. For example, at a wavelength of 1.55 $\mu$m, with a first order grating pitch of 1.1 $\mu$m, a fibre grating tilt angle of 4° is required.

Experimental Methods and Techniques

Standard single mode Corning SMF-28 fibre was used. For the phase mask experiments, it was hydrogen loaded at 18 MPa at room temperature for a week to increase its photosensitivity to UV light. For the point-by-point experiments it was not hydrogenated. The acrylate coating was mechanically stripped and the fibre cleaned with isopropanol before grating fabrication.

The laser used for the point-by-point inscription was a Spectra-Physics Hurricane Ti:sapphire regeneratively amplified laser with typical operating parameters of 200 nJ per pulse, 1 kHz repetition rate and wavelength of 800 nm. The laser was focussed using an oil immersion objective (20 x, 0.80 N.A.) and the grating was written by translating and irradiating the fibre at each position with a single laser pulse. Because the laser beam under-filled the microscope objective, illumination of the microscope objective off-centre tilted the focussed laser beam, though the imaging characteristic of the lens was maintained. The dimensions of the individual laser damage spots within the fibre core allowed second and third order gratings to be fabricated.

The same laser was frequency tripled for the phase mask grating fabrication with typical operating parameters of 120 fs pulsewidth and 150 mW average power at 1 kHz pulse repetition rate and 266 nm wavelength. The UV laser beam was focussed using a cylindrical lens onto a phase mask with a pitch of 1068.60 nm, which was positioned close to the fibre, and the phase mask was rotated up to 8° in the plane of the mask to write tilted gratings. Because of the lensing effect of the fibre itself, the tilt of the incident UV interference pattern is reduced in the actual fibre core [11].

The gratings were monitored in transmission during the inscription process using a light source and an optical spectrum analyser. The third order gratings were observed using an optical microscope with a 50 x objective. After the writing process, the reflection and transmission characteristics of the resultant gratings were recorded using a C-band swept wavelength system and 3-port circulator.

Results

Normal (zero degrees angle) gratings were initially fabricated and gratings of 5-20 dB peak reflectivity were obtained. Tilted gratings were fabricated in third order by the point-by-point method and in first order by the phase mask method, while monitoring the grating transmission spectra in each case. There is a strong peak at the Bragg wavelength (1550 or 1560 nm) in each spectrum, and coupling into cladding modes to shorter wavelengths is seen. Optical micrographs of the point-by-point gratings show the tilted planes within the fibre core. See Figure 1.

Figure 1 Optical micrograph of the point-by-point tilted fibre Bragg grating, with tilt angle of 5°. The grating pitch is 1.6 $\mu$m.

Comparison of transmission and reflection spectra for the two types of gratings shows the characteristic cladding mode signature typical of tilted gratings, for wavelengths shorter than the Bragg wavelength peak. By immersing the fibre in index-matching oil, it is possible to couple the light from the cladding modes out of the fibre grating in each case. This effect is shown for a point-by-point tilted grating in Figure 2. Spectra showing insertion loss for two phase mask-written untilted and tilted gratings are shown in Figure 3. The narrow feature at the Bragg wavelength indicates the regularity of the grating structure.

Although these are preliminary results, and we have not yet optimised the point-by-point writing process for tilted gratings, it is evident that we can achieve relatively large tilt angles using the large numerical aperture of the microscope objective, and the high degree of positioning control afforded by the translation stage allows extremely regular grating structures.

Isochronal annealing studies of the fibre gratings, heating in stages up to a temperature of 600 °C, show that the point-by-point gratings are robust with relatively small changes to the spectrum. By contrast, the phase-mask-inscribed gratings are not robust to this temperature.
Figure 2. Insertion loss of 5° tilted point-by-point grating showing out-coupling of light due to cladding modes when grating is immersed in oil.

Figure 3. Normalised insertion loss spectra for the phase mask written gratings written with phase mask tilt angles of 0 (navy) and 2 (cyan) degrees.

Conclusions

We believe that the point-by-point inscription of tilted Bragg gratings in optical fibre has promise. The technique of offsetting the focusing lens to tilt the writing beam allows some flexibility in the resulting tilt angle. With appropriate motion control, the point-by-point technique offers excellent feature regularity.

The phase mask technique for UV- inscription of tilted fibre gratings was also successful, leading to strong gratings with tilt angles up to 8°.

References


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