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POINT BY POINT FEMTOSECOND LASER INSCRIPTION OF FIBRE AND WAVEGUIDE BRAGG GRATINGS FOR PHOTONIC DEVICE FABRICATION

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Abstract

We present a flexible and rapid method for the production of Bragg gratings in a range of optical waveguides such as optical fibres and direct laser-written waveguides in bulk media. Using a low repetition rate (1 kHz) femtosecond laser, Bragg grating structures can be written in a point-by-point fashion (where each laser pulse inscribes one period of the Bragg structure) in both passive and active media be they fibre (FBG) or waveguide (WBG) based. Furthermore it is possible to control parameters such as the amplitude and chirp of the Bragg periods to create arbitrary reflection and transmission profiles. This technique can be coupled with existing fibre, rib waveguide and direct write waveguide technologies to create a range of photonic devices such as channel splitters, frequency combs, and signal amplifiers and conditioners for all-optical photonic signal processing. In initial tests 3 frequencies filter combs and Bragg grating reflectors with -53 dB insertion loss were written at arbitrary wavelengths in non-sensitised single mode fibre (SMF-28e) with process times between 30 and 90 seconds. These gratings are highly stable and withstand annealing to 600°C.

Introduction

Fibre Bragg gratings form an essential component of modern communications networks and are used in a wide range of applications including signal routing and conditioning. Such gratings are created by exposing the photosensitive core of an optical fibre to a varying intensity profile commonly created by interferometric means with the aid of a phase mask. Femtosecond lasers and phase masks have recently been used to great effect for the production of FBGs in standard single-mode Ge-doped core optical fibre (Corning SMF-28e) using infrared [1] and harmonic generated ultraviolet wavelengths [2]. In this paper we investigate an alternative and highly flexible method of Bragg grating production based on the point-by-point method [3] which has been recently been applied to femtosecond-laser grating inscription [4]. In this scheme periods of the grating are written individually using a low repetition rate femtosecond laser which is spherically focused into the core of an optical fibre using a microscope objective. In practice these gratings are written 'on-the-fly' by continuously translating the laser focus with respect to the fibre core. The period of the grating is given simply by the ratio of the translation velocity to the laser repetition rate. Therefore it is possible to write gratings for any operating wavelength providing that the effective refractive index of the subject medium is known. There are several advantages to this method of grating production; optical fibres do not need to be hydrogenated before processing, processing times are extremely short and the pitch of the gratings produced is no longer dependant on an expensive and fixed period mask. In phase mask FBG inscription systems the long term stability of the writing laser (commonly excimer or frequency-doubled argon-ion based systems) can influence the performance of the gratings produced. The very short process times of the point-by-point method and excellent stability of the femtosecond laser allow long and highly uniform gratings to be produced.

Experiment

The laser used in this study was a commercially available Hurricane from Spectra Physics that produced 800 nm wavelength 120 fs pulses at a repetition rate of 1.00 kHz. The output from the laser was attenuated using a polarisation based attenuator and focused into the core of the optical fibre using an oil-immersion 20× 0.80 NA apochromatic microscope objective. The optical fibre

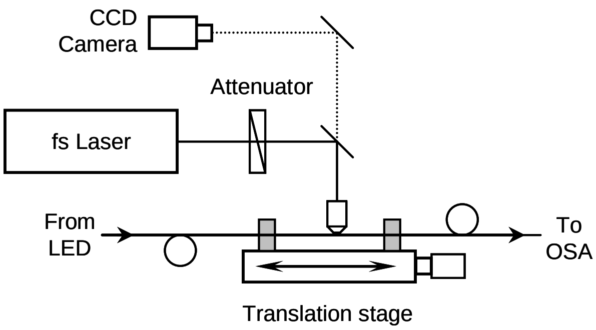

Fig. 1. Experimental layout. For clarity only the principle translation stage is shown.

was mechanically stripped of its polymer jacket and mounted on an orthogonal three-axis computer controlled translation stage system. A vision system was used to aid alignment of the laser focus and optical fibre core. The characteristics of the FBG produced were monitored during the inscription process using an edge-emitting LED (EE-LED) light source and optical spectrum analyser (OSA). For higher resolution and dynamic range measurements the FBGs produced were studied using a scanning laser based swept wavelength system (SWS) from JDS Uniphase. The principle components of the experimental setup are shown in Fig. 1.

Second and third order gratings with design wavelengths between 1040 and 1550 nm, and lengths up to 55 mm were written in unsensitised (non-hydrogenated) single-mode fibres (Corning Hi-980 and SMF-28e) and active laser fibres. Pulse energies of 100 – 400 nJ per period

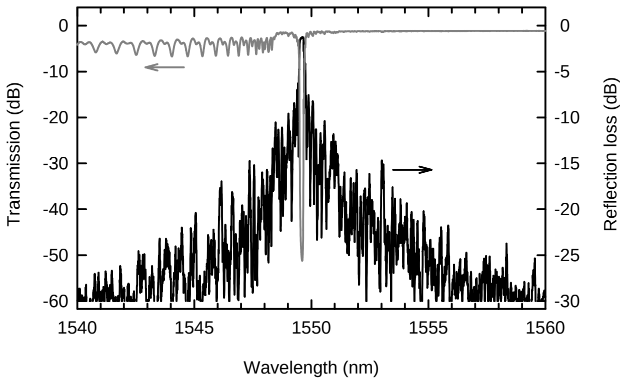

Fig. 2. Transmission (grey curve) and reflection (black curve) spectra of a second order, 30 mm long point-by-point inscribed FBG in SMF-28e optical fibre.

were used depending on the optical fibre type. It was found that the writing pulse energy had to be carefully selected so as to write highly reflective gratings that did not exhibit significant out-of-resonance transmission losses.

Results

Individually written second order FBG gratings with up to -53 dB measured insertion loss were written in SMF-28e. The transmission and reflection spectra of a typical point-by-point grating written in SMF-28e and

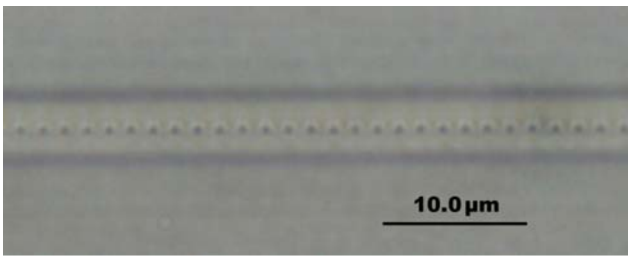

Fig. 3. Optical microscope image of the core of a Ytterbium doped fibre laser (central band) showing the individually inscribed grating periods of a third order grating for operation at 1064 nm.

measured using the SWS is shown in Fig. 2. The grating length was 30 mm, the pitch was 1070.21 nm and the pulse energy used during inscription was 0.37 μJ. The grating writing process took 28 seconds. Under these conditions the peak intensity at the laser focus was approximately 4×10^{14} Wcm^{-2}. The full-width half

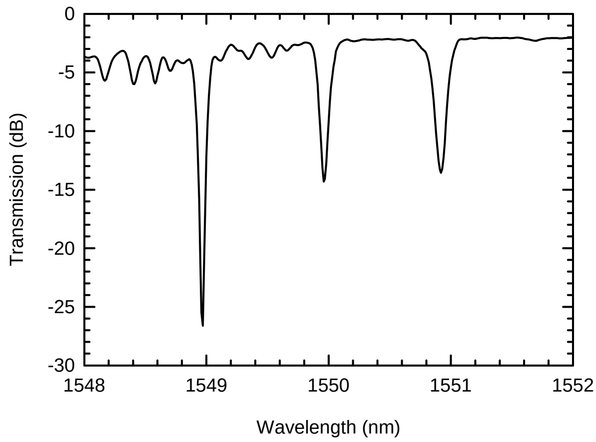

Fig. 4. Transmission spectrum of three FBGs written sequentially in a single scan.

minimum (FWHM) linewidth of the grating is 150 pm and its out-of-resonance loss is 1.1 dB. The grating exhibits strong cladding modes in transmission that extend on the short wavelength side of the principle spectral feature.

Microscopic analysis (Fig. 3) of point-by-point gratings reveal that the laser pulses write cylindrical regions of refractive index change approximately 1 µm in diameter in a region that is confined to the fibre core.

To further exemplify the flexibility of this grating writing method a varying reflectivity three wavelength comb grating with was written in a single piece of fibre. The spectral response of this grating observed using an OSA is shown in Fig. 4. Each grating was written sequentially in the fibre in a continuous process. The strength of the individual gratings was controlled by varying the length of written region. The design wavelengths for these gratings were 1549, 1550 and 1551 nm. The small offset (0.04 nm) between the design and actual wavelengths of the gratings in Fig. 3 is due to relaxation of tension in the fibre that is induced when the fibre is mounted prior to grating inscription.

The thermal stability of the gratings was investigated by annealing FBGs of -30 dB depth in a tube furnace capable of operation up to 600°C. It was typical to observe a decrease in the strength of the gratings by approximately 3 dB after an isochronal annealing cycle (30 minutes per 50°C step) with a peak temperature of 600°C.

Summary

Using the point-by-point method of FBG inscription deep gratings have been written in a range of optical fibres at arbitrary wavelengths. The process is quick and extremely flexible and we have demonstrated that it can be used to write gratings with periods of approximately 1 μm and above in a range of optical fibres.

This method has a number of key applications in writing gratings in both active and passive media such as active and passive optical fibres, and rib and direct laser written waveguides (in both passive and active media). In preliminary studies we have demonstrated that these gratings can indeed be written in active fibre laser materials with cores diameters as small as 4.4 μm. It is our intention to develop fibre laser sources based on these gratings as either output couplers, high reflectors or both. Furthermore we are seeking to write grating structures in direct laser written waveguides such as those in reference [5]. We will present the results of these studies at PICALO 2006.

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