Fibre Bragg Gratings Inscribed in Homemade Microstructured Fibres *

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Fibre Bragg gratings (FBGs) are inscribed in homemade microstructured fibres by the standard phase mask method. Enhanced couplings between the forward fundamental mode and backward cladding modes are obtained. The mode coupling and spectral characteristics are investigated experimentally. The cladding mode resonances can be affected by filling active materials into the air holes, which will be useful for the implementation of tunable photonic devices in optical fibre communication and sensing systems.

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In more than 15 years, fibre Bragg grating technologies in step-index fibres have developed dramatically to perform an important role in fibre communication and optical fibre sensing.[1] In recent years, the introduction of microstructured optical fibres (MOFs) with a wide range of novel properties results in unique spectral characteristics of FBGs in these fibres.[2−9] The air/silica structure in the fibre cladding reconstructs the cladding mode distribution and produces enhanced cladding mode resonances in these fibre gratings.[2,3] Moreover, the air regions allow for the infusion of active materials, which leads to enhanced tenability.[4,5] Hence their potential applications in the design and fabrication of novel fibre Bragg gratings (FBG) based photonic devices, including comb filters, multiwavelength fibre lasers, fibre sensors for the measurement of directional bend, lateral stress and surrounding refractive index, are desirable. However, there have been some difficulties in FBG inscription into microstructured fibres. It has been demonstrated that the scattering of incident UV light by the air holes running along the fibre length will greatly reduce the inscription efficiency.[6] The periodically distributed air hole layers may even cause photonic-bandgap-like effect and prevent the entry of incident light. In addition, the orientation of fibre geometry with respect to the incident light will influence the inscription efficiency as well. So far only a few FBGs written in MOFs have been reported, by means of a complicated IR femtosecond laser inscription system with high output power,[7] or by reducing the number of air lattices. However, it is desirable to fabricate FBGs in MOFs by the mature, convenient and low-cost phase mask method. In this Letter, FBGs inscribed in homemade microstructured fibres by standard phase mask method are reported. Several attenuation bands are observed in their transmission spectra, owing to the existence of air holes incorporating in the fibre. Experimental investigations are carried out for the spectral characteristics and mode couplings of these FBGs.

The photosensitive microstructured fibre is fabricated by FibreHome Telecommunication Technologies Co Ltd., Wuhan, China. The optical microscope photograph for the cross section of the fibre is illustrated in Fig. 1. The MOF has an outside radius of 62.5 μm. Its core is highly doped with Ge^{3+} to obtain adequate photosensitivity to UV illumination, which has a radius of about 6 μm and a refractive index of 1.47267 ($\lambda = 633$ nm). The fibre core is surrounded by six large air holes, forming an inner cladding radius of 36 μm. The index difference is measured by $\Delta = (n_{\rm core} - n_{\rm clad})/n_{\rm core} = 1.06\%$. Based on the fibre parameters, the corresponding V is calculated to be 3.59 at $\lambda = 1.57\,\mu$m, which means that the fibre supports the guiding of LP_{01} and LP_{11}.

A 5-cm MOF is spliced with two sections of conventional single mode fibres. The fusion splicing parameters for the two kinds of fibre including the arc duration and strength are optimized and a total insertion loss of less than 1.5 dB is obtained. The fibre is H_2 loaded at 120 atm, 100°C for 72 h to enhance its photosensitivity.

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The FBG fabrication is performed by the standard phase mask method. The setup for the FBG inscription is illustrated in Fig. 2. The MOF is exposed through a phase mask at a fluence of pulses from a 248 nm KrF excimer laser. The phase mask has a period of 1074.67 nm, thus the grating period $\Lambda = 537.33$ nm. The fibre is placed vertically and attached to the phase mask. The average energy of the incident laser pulses is 50 mJ. The length of the grating region is 2 cm. The growth of the fibre grating is monitored via its transmission spectrum, which is recorded by an optical spectrum analyser with 0.1 nm resolution.

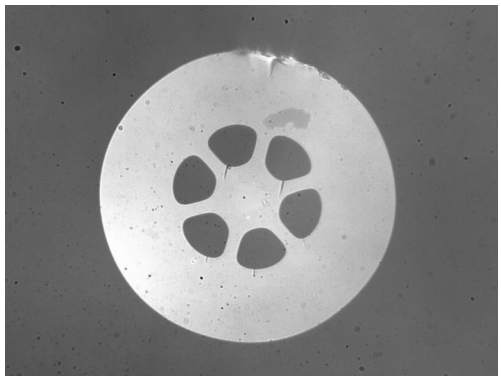

Fig. 1. Optical microscope photograph for the cross section of the microstructured fibre.

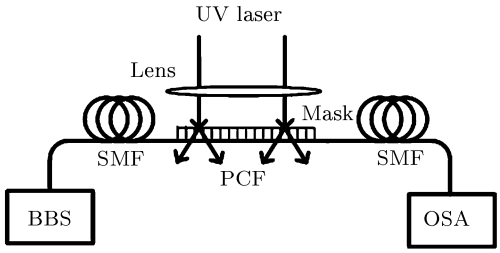

Fig. 2. Experimental setup for the FBG inscription in the MOF.

Figure 3(a) shows the transmission spectrum of the FBG, which is measured after annealed to remove H_2. Five dips are visible in the spectrum as labelled, located at $\lambda_1 = 1569.48$ nm, $\lambda_2 = 1567.80$ nm, $\lambda_3 = 1565.96$ nm, $\lambda_4 = 1563.44$ nm and $\lambda_5 = 1561.44$ nm, respectively. The resonance depths at λ_1 and λ_2 are 26.25 dB and 14.75 dB, respectively, much larger than those of the other three resonances. The evolutions of the resonance strengths versus exposure are plotted in Fig. 4. As can be seen, resonance at λ_1 becomes saturated at 1400 pulses, while the depth of dip2 is increasing until 1900 pulses. Note that all the resonances have a bit decrease when annealed. Figure 3(b) illustrates the corresponding reflection spectrum, which is obtained by using a three-port circulator to retrieve the reflective signal. The resonance at λ_1 presents a high reflectivity, which indicates that it arises from the coupling the forward to the backward fundamental mode; while the other resonances correspond to couplings from forward fundamental mode to backward higher order modes. The effective index of the fundamental mode of the fibre is 1.4604, according to the amplitude of λ_1. An effective index variation $\delta n = 0.0007$ is produced by the UV illumination.

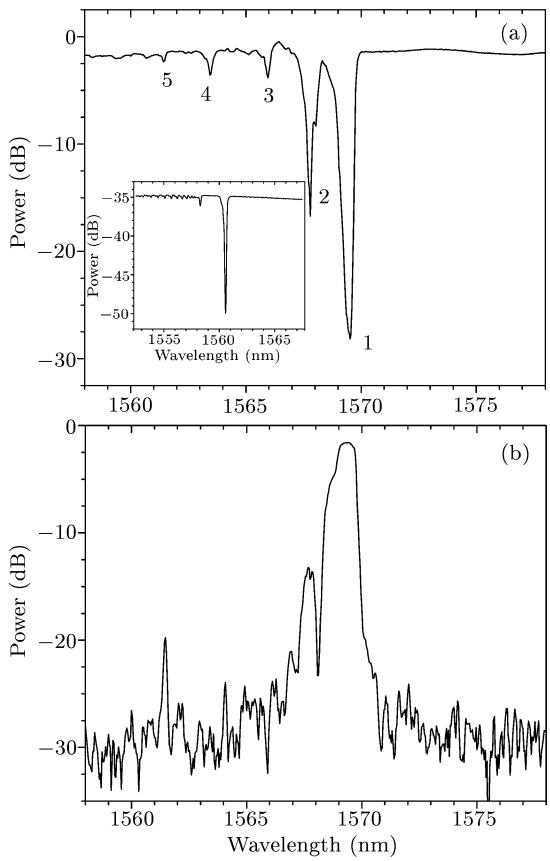

Fig. 3. Transmission (a) and reflective spectra (b) of the FBG inscribed in the microstructured fibre. The inset shows the contrasting transmission spectrum of an FBG in a conventional single mode fibre under the same inscription conditions.

Several experiments were further carried out for the investigation on mode couplings of the FBGs in the MOF.

(1) A tilted fibre grating is written into this microstructured fibre by rotating the phase mask in the plane of the fibre. The effective tilt angle is about 2°. The tilted index modulation in the fibre core actually causes an asymmetric index distribution over the fibre core cross section and strengthens the couplings to the higher order modes.[10] As can be seen from the corresponding transmission spectrum, enhanced cladding mode resonances are obtained, as shown in Fig. 5. The tilt index modulation also drives couplings to asymmetric cladding modes, which are not seen in Fig. 3(a).

We filled all the six air holes of the FBG with an index matching gel (IMG, $n = 1.49$) by a capillary action. The length of the FBG region covered by the IMG is about 8 mm. As observed in the transmission spectrum shown in Fig. 5, the attenuation bands at the short wavelength side are weakened, while the resonances at λ_1 and λ_2 are not affected. The result illustrates that the two guiding modes LP_{01} and LP_{11} are supported by the fibre, which are confined in the fibre core and unaffected by the index changes in the fibre cladding. Dips 1 and 2 correspond to the couplings from forward core modes to backward core modes, respectively. On the other hand, the multiple cladding resonances can be affected by the index change in the cladding air holes. If the IMG covers the whole fibre grating region, the cladding mode resonances will be eliminated.

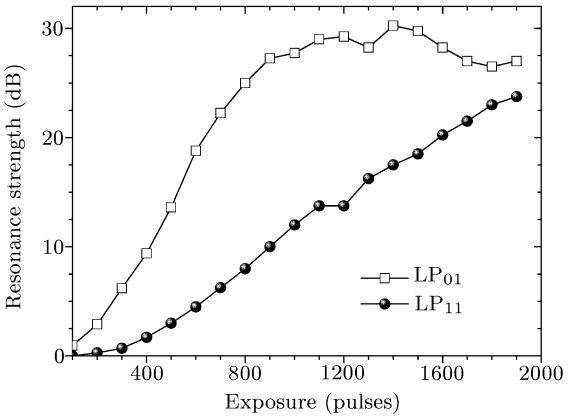

Fig. 4. Growths of the resonance bands versus exposure time.

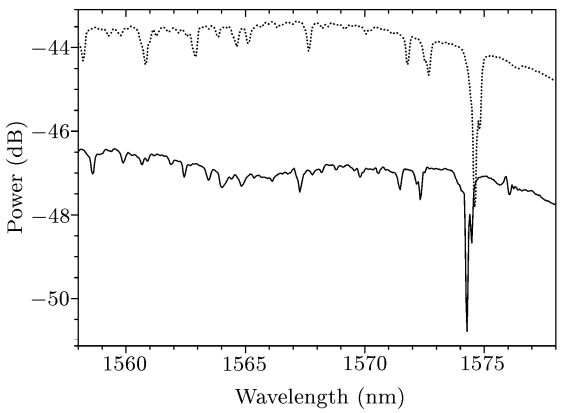

Fig. 5. Transmission spectra of a tilted FBG in an MOF before (upper) and after (lower) filling the index matching gel.

(2) We fabricated an FBG in step-index photosensitive single mode fibre (SMF) under the same inscription conditions. Its transmission spectrum is shown in the inset of Fig. 3(a). The measured cladding mode resonance depths are less than 0.5 dB when that of the fundamental mode reaches 15 dB. The difference in spectral characteristics between FBGs written in the conventional SMF and the MOF can be explained by the reduced size of effective fibre cladding in the MOF, which is caused by the introduction of the large air holes. The greatly confined in the MOF cladding modes have more fractions overlapped with the fundamental modes, resulting in enhanced coupling coefficient. Thus the measured cladding mode resonance depths are more than 3 dB.

In addition, the air/silica structure in the MOF cladding reconstructs the amplitudes of effective index of each order mode, which can be numerically obtained. The introduction of air holes reduces the effective inner cladding size of the MOF, which causes a more discrete distribution of the resonance dips in the transmission spectrum, as illustrate in Fig. 3(a).

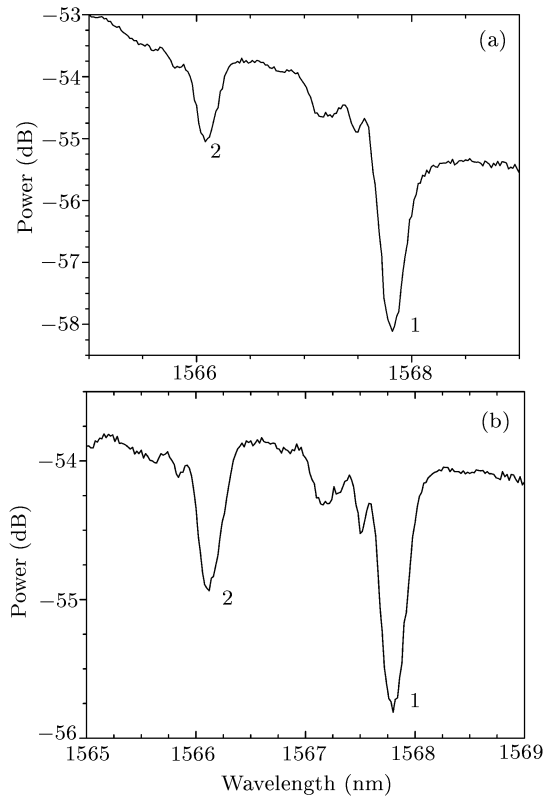

Fig. 6. Transmission spectra of an offset launched FBG in an MOF (a) before and (b) after applying lateral offset.

(3) We cleaved the fibre grating at its edge and the incident light from a single mode fibre is offset launched into it. The lateral offset between the single mode fibre and the fibre grating is controlled and monitored by a fusion splicer. When applying lateral offset, variations in resonance depths at λ_1 and λ_2 are observed, which indicates the MOF is multimode.[8,9] The offset launched field change the transverse field distribution in the fibre core and thus result in vari-

ation in coupling coefficients for each mode coupling. We inscribe FBG in another MOF of the same type with smaller fibre core size under the same condition and carried out the same experiment. We found that the changes in resonance depths are more sensitive. The comparison between its transmission spectra before and after applying lateral offset is shown in Fig. 6

In summary, fibre Bragg gratings are effectively inscribed in homemade photosensitive microstructured fibres. Enhanced couplings between forward fundamental mode and backward cladding modes are observed by the transmission spectrum. Experimental investigations are further carried out to obtain detailed information in its spectral characteristics and mode coupling features. The homemade MOF provides a platform for the design and realization of the next-generation FBG based photonic devices. By infusing active materials into the air holes incorporating in the fibre grating, spectral tunability or enhanced functionality can be obtained.

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