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Simultaneous measurement of curvature and strain based on fiber Bragg grating in two-dimensional waveguide array fiber

Zhifang Wu,^{1,2,3} Yan-Ge Liu,^{1,*} Zhi Wang,¹ Meng Jiang,⁴ Wenbin Ji,² Tingting Han,¹ Shuo Li,¹ Xuguang Shao,² Xuan Quyen Dinh,^{3,5} Swee Chuan Tjin,² and Perry Ping Shum^{2,3}

¹Key Laboratory of Optical Information and Technology, Ministry of Education, and Institute of Modern Optics, Nankai University, Tianjin 300071, China

²School of Electrical and Electronics Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

³CINTRA CNRS/NTU/THALES, UMI 3288, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553

⁴Applied Physics Department, College of Science, Donghua University, Shanghai 201620, China

⁵Thales Solutions Asia Pte. Ltd., R&T Department, 28 Changi North Rise, Singapore 498755

*Corresponding author: ygliu@nankai.edu.cn

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We report on the fabrication of a fiber Bragg grating (FBG) with multiple resonances in a two-dimensional waveguide array microstructured optical fiber containing 91 cores. Theoretical investigation reveals that these resonances originate from the identical and nonidentical mode couplings between forward-propagating and backward-propagating LP_{0m} -like ($m = 1, 2, 3$; LP refers to linearly polarized) supermodes. Since both the central wavelength and minimum transmission of these resonant dips respond differently to curvature and axial strain, this FBG can be applied in the simultaneous measurement of curvature and axial strain. © 2013 Optical Society of America

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In the past few years, a new type of multicore fiber named waveguide array microstructured optical fiber (WAMOF), has been proposed and fabricated with similar manufacturing technologies of photonic crystal fibers. WAMOF has attracted increasing attention for its greatly promising applications in discrete optics [1–3]. Compared with the waveguide arrays in bulky materials usually based on photorefractive effects [4] or femtosecond-laser-written techniques [5], the fiber-based waveguide arrays show some special advantages, such as incomparably long interaction length, high damage threshold, and engineerable dispersion properties, which are considered as important factors for the formation of three-dimensional light bullets (spatialtemporal solitons) [6]. Moreover, in combination with well-developed fiber postprocessing techniques, WAMOFs provide high flexibility to control or shape the light beam in discrete systems [7,8].

Another specific property of WAMOFs is that their guiding modes are characterized as phase-locked states called supermodes [3,9], which are demonstrated useful applications in multicore fiber lasers for the mode selection [10]. Furthermore, WAMOFs are often multimode waveguides because of their quite large equivalent core diameters. Using this multimode property, an intermodal interferometer based on a kind of WAMOF has been proposed and applied as a curvature sensor by simply splicing a section of WAMOF with single-mode fibers (SMFs) at both ends [11].

Since the cores of WAMOFs are often made from Ge-doped silica, these WAMOFs find some valuable applications by inscribing fiber Bragg gratings (FBGs). A curvature sensor and an accelerometer have been demonstrated using FBGs in 4-core fibers [12,13].

Another 19-core WAMOF has also been employed to fabricate an FBG and then applied in background-free Raman sensing [14]. In this Letter, we report the fabrication of an FBG with multiple resonance dips in a two-dimensional (2-D) WAMOF containing 91 cores. Theoretical investigation reveals that these resonances are corresponding to the mode couplings between forward-propagating and backward-propagating LP_{0m} -like ($m = 1, 2, 3$) supermodes, respectively. Since both the central wavelength and minimum transmission of these resonance dips respond differently to curvature and axial strain, this FBG finds a useful application in the simultaneous measurement of curvature and axial strain.

The 2-D WAMOF in our experiments is manufactured by Yangtze Optical Fiber & Cable Company and its cross section is shown in Fig. 1, which is the same as that in [11]. It consists of a triangular array of 91 identical Ge-doped rods embedded in the pure silica background. The diameters of each single Ge-doped rod and the whole fiber are about 1.40 and 125 μm , respectively. The pitch of two adjacent rods is about 4.54 μm . The refractive indices

Fig. 1. Cross section of 2-D WAMOF.

Fig. 2. Electric field distributions of LP_{01} -, LP_{11} -, LP_{21} -, LP_{02} -, and LP_{03} -like supermodes.

of the Ge-doped rods and the silica background are about 1.474 and 1.444, respectively.

Using the full-vector finite-elements method and the structural parameters of the WAMOF, some representative modes guided in this fiber, as shown in Fig. 2, are theoretically investigated. Since the distance between two adjacent Ge-doped rods is quite small, the light cannot be confined within each rod but is strongly coupled to adjacent rods, resulting in the formation of a series of supermodes. These supermodes are noted as LP_{nm} -like (m, n are integers and “-like” will be omitted in the following text) supermodes by borrowing the denomination of modes in step-index fibers. Assuming a perfect axial alignment between the cores of SMF and the WAMOF, only LP_{0m} supermodes can be effectively excited and the excitation coefficients of LP_{01} , LP_{02} , and LP_{03} supermodes are much higher than those of other supermodes [11]. Then, the effective refractive indices (n_{eff}) curves of the LP_{01} , LP_{02} , and LP_{03} supermodes are calculated and shown in the inset of Fig. 3. According to the phase-matching condition of the FBG, $\lambda_{\text{res}} = (n_{\text{eff},1} + n_{\text{eff},2}) \cdot \Lambda$, the corresponding grating pitches of different resonance couplings are derived and plotted in Fig. 3. Here, λ_{res} is the Bragg resonance wavelength, $n_{\text{eff},1}$ and $n_{\text{eff},2}$ are the effective refractive indices of two modes involved in the resonance coupling, superscripts “+” and “-” represent, respectively, the forward-propagating and backward-propagating modes, and Λ is the grating pitch. As shown in Fig. 3, the six lines from right to left are corresponding to the resonance couplings between the LP_{01}^+ supermode and LP_{01}^- supermode, LP_{01}^+ supermode and LP_{02}^- supermode, LP_{02}^+ supermode and LP_{02}^- supermode, LP_{02}^+ supermode and LP_{03}^- supermode, LP_{03}^+ supermode and LP_{03}^- supermode, LP_{02}^+

Fig. 3. Grating pitches against wavelength for different mode couplings. The inset is the effective refractive indices of LP_{0m} -like ($m = 1, 2, 3$) supermodes. “+” and “-” represent the forward-propagating and backward-propagating modes, respectively.

Table 1. Resonant Wavelengths of the FBG

Mode Couplings	Theoretical Resonance Wavelengths (nm)	Experimental Resonance Wavelengths (nm)
$LP_{01}^+ - LP_{01}^-$	1548.58	1550.07
$LP_{01}^+ - LP_{02}^-$	1548.31	1549.57
$LP_{02}^+ - LP_{02}^-$	1548.06	1549.10
$LP_{01}^+ - LP_{03}^-$	1547.63	1548.76
$LP_{02}^+ - LP_{03}^-$	1547.37	1548.32
$LP_{03}^+ - LP_{03}^-$	1546.67	1547.53

supermode and LP_{03}^- supermode, and LP_{03}^+ supermode and LP_{03}^- supermode, respectively. For a given grating pitch, for example 535.1 nm, the theoretical Bragg resonance wavelengths are calculated and listed in the second column of Table 1.

Before the FBG fabrication, the WAMOF was photo-sensitized via hydrogen loading at 12 Mpa for one week. A ~5 cm long hydrogen-loaded WAMOF was spliced with two SMFs very carefully to prevent the core offset. After splicing, an obvious interference spectrum can be observed due to the multimode property of this WAMOF [11]. Then, a Bragg grating was inscribed by using a CW 244 nm frequency-doubled Argon laser and a phase mask with the pitch of 1070.2 nm. The length of the FBG was about 1 cm.

The reflection and transmission spectra of the WAMOF after the FBG fabrication are measured and shown in Fig. 4. There are six obvious dips labeled with A–F in the transmission spectrum and corresponding to the six reflection peaks with relatively high reflectivity, respectively. Similar with the aforementioned mode excitation from the SMF to the WAMOF, only LP_{0m} ($m = 1, 2, 3$) supermodes reflected by the FBG can be effectively coupled back into the SMF if the core offset between the SMF and the WAMOF is almost zero [15]. It indicates that these six marked reflection peaks relate most likely to LP_{0m} ($m = 1, 2, 3$) supermodes. The wavelengths of transmission dips A–F are measured and listed in the third column of Table 1. Although the experimental resonance wavelengths are not exactly equal to the theoretical ones, the deviation between each pair of values is similar. In addition, the amplitudes of dip A, C, and F

Fig. 4. Transmission (black) and reflection (red) spectra of the FBG in WAMOF. The inset is the transmission spectrum of the WAMOF with FBG over the wavelength range 1450–1600 nm.

Fig. 5. Spectral shift of dip C with varying strain.

are relatively larger than those of other dips in the transmission spectrum. The reason is that dip A, C, and F are originated from the identical-mode couplings of LP_{0m} ($m = 1, 2, 3$) modes and the overlap integral of identical-mode coupling is usually larger than those of non-identical ones [16]. Therefore, the experimental result still matches well with the theoretical result, considering the inevitable difference between the calculation model and the real fiber.

For axial strain characterization, the fiber with FBGs was clamped on two translation stages. One stage was fixed, and the other one was driven by a micrometer to stretch fiber. When the axial strain increases from 0 to 1220.6 $\mu\epsilon$, all resonant dips shift to longer wavelengths, as shown in Fig. 5. Meanwhile, the minimum transmissions of resonant dips descend almost linearly. We use the response of dip C to quantify the strain performance of the FBG we fabricated. As shown in Fig. 6, the strain sensitivities of central wavelength and minimum transmission are measured about 1.16 pm/ $\mu\epsilon$ and -3.73×10^{-3} dB/ $\mu\epsilon$, respectively.

Then, the curvature response of dip C was measured using the same setup and method mentioned in [17]. When the curvature increases from 0 to 1.2178 m^{-1} step by step, the central wavelength of dip C shifts very slightly to shorter wavelength, whereas the minimum transmission of dip C descends obviously, as illustrated in Fig. 7. The corresponding sensitivities of the central wavelength and minimum transmission to

Fig. 6. Axial strain responses of the central wavelength and minimum transmission of dip C.

Fig. 7. Spectral shift of dip C with varying curvature.

curvature are shown in Fig. 8 and measured at about -0.04498 pm/ m^{-1} and -1.851 dB/ m^{-1} , respectively.

The responses of the minimum transmission of dip C to strain and curvature are mainly attributed to the blue shifting of the whole interference spectrum, because the interference spectrum is highly sensitive to curvature and strain as mentioned in [11]. Moreover, the resonant dips of the FBG is located in the quasi-linear region of the interference spectrum, as shown as the inset in Fig. 4, resulting in the approximately linear shifting with varying curvature or axial strain.

Since both the central wavelength and minimum transmission of dip C respond linearly and differently to axial strain and curvature, this FBG can be applied to measure strain and curvature simultaneously by using the following relation [17,18]:

$$\begin{bmatrix} \Delta\epsilon \\ \Delta C \end{bmatrix} = \begin{bmatrix} S_{\epsilon,\lambda} & S_{C,\lambda} \\ S_{\epsilon,A} & S_{C,A} \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda \\ \Delta A \end{bmatrix} = \begin{bmatrix} 1.16 \times 10^{-3} & -4.498 \times 10^{-4} \\ -3.73 \times 10^{-3} & -1.851 \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda \\ \Delta A \end{bmatrix}, \quad (1)$$

where $\Delta\epsilon$, ΔC , $\Delta\lambda$, and ΔA are the strain, curvature, central wavelength, and minimum transmission variations and $S_{\epsilon,\lambda}$, $S_{C,\lambda}$, $S_{\epsilon,A}$, and $S_{C,A}$ are the strain and curvature sensitivities of the central wavelength and minimum transmission of dip C, respectively.

Fig. 8. Curvature responses of the central wavelength and minimum transmission of dip C.

In conclusion, we have reported the fabrication of an FBG with multiple resonance couplings in a 2-D waveguide-array microstructured optical fiber. The multiple resonances are corresponding to a series of mode couplings between forward-propagating and backward-propagating LP_{0m} -like ($m = 1, 2, 3$) supermodes, respectively, which are excited when the WAMOF is spliced with SMFs without any core offset. One resonance dip, labeled C in Fig. 4, is applied in a simultaneous measurement of axial strain and curvature, thanks to the quite different strain and curvature sensitivities of both the central wavelength and minimum transmission. The FBG in this WAMOF may also find a potential application in multiwavelength fiber laser.

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