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Multi-resonance peaks fiber Bragg gratings based on largely-chirped structure

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A B S T R A C T

A composite fiber Bragg grating (FBG) with multi-resonance peaks (MRPs) has been realized by using femtosecond (fs) laser point-by-point inscription in single-mode fiber. This device contains a segment of largely-chirped gratings with the ultrahigh chirp coefficients and a segment of uniform high-order gratings. The observed MRPs are distributed in an ultra-broadband wavelength range from 1200 nm to 1700 nm in the form of quasi-period or multi-peak-group. For the 8th-order MRPs-FBG, we studied the axial strain and high-temperature sensing characteristics of different resonance peaks experimentally. Moreover, we have demonstrated a multi-wavelength fiber lasers with three-wavelength stable output by using a 9th-order MRPs-FBG as the wavelength selector. This work is significant for the fabrication and functionalization of FBGs with complicated spectra characteristics.

1. Introduction

Fiber Bragg grating (FBG) has narrow band filtering characteristics at certain wavelength, which becomes important devices for fiber sensing [1], fiber laser [2–4] and fiber communication [5]. Aiming at the demands in special fields of multi-parameter sensing and wavelength division multiplexing, the researchers have developed multiple FBGs with multi-resonance peaks (MRPs), such as superimposed-[6], superstructure-[7], cascaded-[8] and multi-core-[9] FBG. As for these grating structure, the conventional UV laser writing technique has some drawbacks, such as, the fiber needs to load hydrogen, Bragg resonance wavelength highly depends on the phase mask period, and it is difficult to fabricate large period (high order) Bragg grating. These problems make the fabrication process of the UV-FBG lack of flexibility, which is challenging to realize complex grating structures and expand their functions. In recent years, femtosecond laser directing writing (FsLDW) technique demonstrates obvious advantages in fabrication of FBG [10–16]. The fs laser interacts with dielectric material through high nonlinear photoionization mechanism, leading to the modification which is not related to the photosensitivity of material [12–14]. If we combine this technique with point-by-point (PbP) method, we can control the location of the refractive index (RI) modification in the fiber precisely and flexibly through the fabrication program [14,17–22]. Therefore, fs laser point by point writing technique can fabricate any complex grating structures in principle, which is very important for achieving the FBG with unique spectrum characteristics and functionalities [20].

In this manuscript, we utilize the flexible fs laser PbP writing method and fabricate a kind of composite FBG with MRPs. This composite grating contains a segment of largely-chirped grating with ultra-high chirped coefficient and a segment uniform high-order grating, which is realized through designing the axial location of the RI modulation in the fiber core. In the experiment, we fabricate two kinds of MRPs-FBG, which own multiple narrow band resonances distributed in the forms of quasi-period or multi-peak-group. For the former, we studied the high temperature and axial strain sensing characteristics of the multi-resonances peaks. For the latter, we demonstrate a kind of three wavelength fiber laser utilizing the multiple wavelength selectivity.

2. Experiments

The schematic diagram of the setup for FBG inscription by PbP method with fs laser is shown in Fig. 1(a). Experimentally, a Ti: sapphire regenerative amplifier laser system (Spectra Physics) with the operation wavelength of 800 nm and pulse duration of 100 fs was adopted. The chosen laser repetition (f) and pulse energy are 100 Hz and 75 nJ/pulse,

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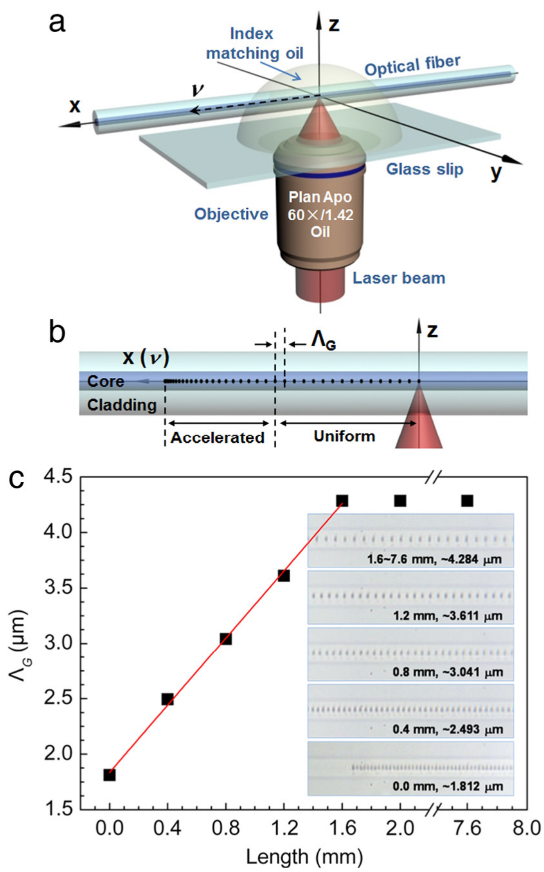

Fig. 1. (a) Schematic diagram of the setup for FBG inscription by PbP method with fs laser. (b) Sketch of the fs-written RI modification array. (c) The gratings period changes with the grating length. Insets: the microscopic grating structures are corresponding to the different locations.

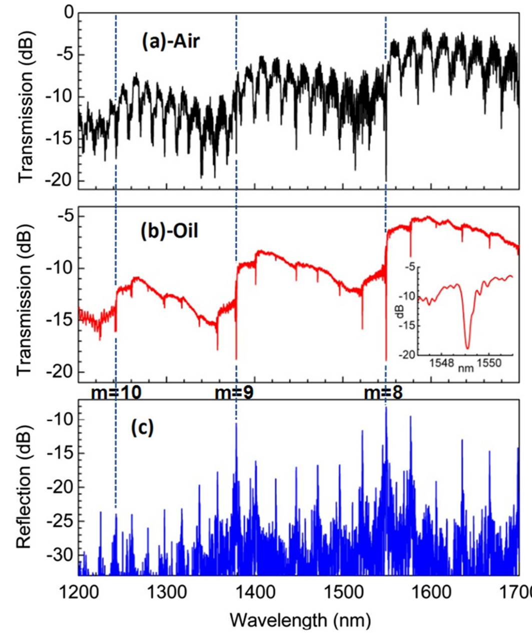

Fig. 2. Spectra of the 8th-order MRPs-FBGs. (a) Transmission spectrum in air. (b) Transmission spectrum in RI matching oil. (c) Reflection spectrum, the inset shows the close-up of the 8th-order major Bragg resonance.

respectively. In order to control the RI modification profiles precisely, the laser beam was firstly filtered through a pin-hole to get rid of noise and form a smooth Gaussian beam with the diameter adjusted to 4 mm. And then, the laser beam was tightly focused into the fiber (Corning SMF-28) in a tiny volume through a high numerical aperture (N.A. = 1.42) 60 × oil-immersion objective to increase the RI modulation. The fiber sample was not photosensitized and was fixed to a high-precision three dimensional translation stage. In order to avoid the focus distortion caused by the fiber cylindrical lens effect, the fiber is immersed in the pine tar with the RI of 1.515 [19–21].

Fig. 1(b) shows the illustration of the fiber moving along X axis during the fabrication process, which contains an acceleration movement segment and a uniform velocity movement segment. In such MRPs-FBG, a segment of chirped grating with ultra-large coefficient (C) and a segment of uniform grating with high-order period (Λ_G) will be formed. In the chirped grating segment, the relationship between the period ($\Lambda(x)$) and the chirped coefficient can be expressed as $\Lambda(x) = \Lambda_0 + C \cdot x$, in which, Λ_0 is the initial period. The chirped coefficient can be achieved with the fiber acceleration, all the FBGs in this paper have the same acceleration value, i.e. 20 μm/s^2. In the uniform grating segment, the period can be expressed as $\Lambda_G = v_G/f$, in which, v_G is the inscription speed of the uniform grating. For the 8th- and 9th-order uniform gratings involved below, the speeds are 428.4 μm/s and 482.0 μm/s, respectively. The grating inscription is controlled by the fabrication program. The inscription program is programmed based on the period of the high order uniform grating and acceleration.

The largely-chirped structure in the composite FBG is comprised of a serial of short length and period increased uniform gratings. The resonance wavelength λ_B can be achieved with the phase matching condition $m\lambda_B(x) = 2n_{eff}(x)\Lambda(x)$, in which, m is the grating order, n_{eff} is the effective RI of the guiding mode. For the grating written by fs laser, when the induced RI modulation is large enough (larger than 10^{-3}), the grating can still produce strong Bragg resonance, even the grating length is only about hundreds of micrometers [23]. Therefore, we can predict that, the spectrum of this unique grating structure will not only show the major Bragg resonance that comes from the uniform grating section, but also present many additional Bragg resonances that result from the largely-chirped section. In experiment, we fabricate two kinds of MRPs-FBG, their multi-resonances are distributed in forms of quasi-period and multi-peak-group, respectively. We will give the representative device and characteristic spectrum in the following paragraph. A broadband light source (Superk Compact, NKT Photonics) and an optical spectrum analyzer (OSA, AQ6370B, Yokogawa) with a wavelength resolution of 0.02 nm are used for characteristic spectrum monitoring.

Fig. 1(c) gives the relationship of the fabricated 8th-order (Λ_G = 4.284 μm) composite grating period changes with the grating length. The inset shows the RI modulation microscope image at different locations. The length of the chirped segment is 1.6 mm, the initial and the final periods are 1.812 μm and 4.284 μm, respectively, and the chirped coefficient is 1545 nm/mm. The length of the uniform grating segment is 6.0 mm. It needs to be declared that the highly localized composite FBGs will excite a strong cladding mode resonance [24–26]. In addition, the Mie scattering derived from micro-void modifications will induce strong broadband scattering loss in the grating [27]. The above spectra characteristics are reflected in the transmission spectrum shown in Fig. 2(a), which is measured in air. The reflection spectrum corresponding to the 8th-order composite grating is shown in Fig. 2(c), as expected, there are other extra six resonance peaks distributed between the two adjacent major Bragg resonances in a quasi-period way, which result from the largely-chirped gratings section. To verify whether they result from the resonances among the fundamental modes of the largely-chirped gratings section, the whole composite grating is immersed in RI matching oil to check whether the extra resonance peaks have changes in intensity and wavelength. The experimental results show that none of the resonance peaks changes, and only the cladding modes in the transmission spectrum are converted to radiation modes. It makes the