Fiber comb filters based on UV-writing Bragg gratings in graded-index multimode fibers

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Abstract: We report a new kind of comb filters based on fiber Bragg gratings in graded-index multimode fibers. It produces two groups of spectra with a total of 36 reflection peaks that correspond to 18 principal modes and cross coupled modes. The mode indices and wavelength spacings have been investigated theoretically and experimentally. This kind of comb filters may be used to construct multi-wavelength light sources for sensing, optical communications, and instrumentations.

OCIS codes: (230.1480) Bragg reflectors, (120.2440) Filters

References and links

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1. Introduction

Fiber Bragg gratings (FBGs) in single mode fibers are increasingly becoming important devices in optical communications, signal processing and optical sensing [1]. Bragg gratings in multimode fibers have also received attention for sensing, local communications and mode converters [2-5]. Mizunami et al. [3] experimentally reported their multimode fiber Bragg gratings (MFBGs) and analysed the spectral properties. However, they did not observe any cross coupled modes. Yang et al. [2] reported slanted MFBGs with enhanced coupling between fundamental core mode and higher order modes in the condition that not all modes were excited. In general, the spectral profiles of MFBGs reported vary depending on light sources, the mode coupling and the optical spectrum analyser used and therefore lack the consistency. By utilizing a multimode coupler, a single mode ASE source, and a free-space

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coupled optical spectrum analyser, we were able to excite all MFBG modes and have observed cross-coupled modes. Two groups of reflection modes with a total of 36 peaks, composing a kind of comb filters, correspond to the Bragg resonances of 18 principal modes and neighbouring cross coupled modes. Analytical expressions for the principal mode indices and wavelength spacings have been derived, which are in good agreement with experimental results. The comb filters of this kind can be used in wavelength standard when athermally packaged, or in fiber optic sensing and instrumentations. The spacing between two neighbouring peaks coincides with channel spacing of 100 GHz in optical communications, which would have some new applications such as wavelength locker.

2. Experiments and discussions

Fiber Bragg gratings were fabricated by exposing a multimode fiber with a KrF excimer laser through a phase mask. The typical energy density per pulse was 70 mJ/cm^2. The laser pulse rate was 10~20 Hz, while the exposure time was about 2~3 minutes. The exposure fiber length was 20 mm long. The spectra of the gratings were examined with an ASE light produced by a 980 nm laser diode pumped erbium doped fiber (EDF). Optical spectrum analyser Ando AQ-6310B with a resolution of 0.05 nm was used for the measurements. Graded-index multimode fibers (MMFs) with a diameter of 62.5 μm and numerical aperture of 0.275 (Corning, 62.5/125 CPC6) were used in the experiments. The fibers were hydrogen loaded for two weeks under a pressure of 150 atmospheres at room temperatures to enhance their photosensitivity.

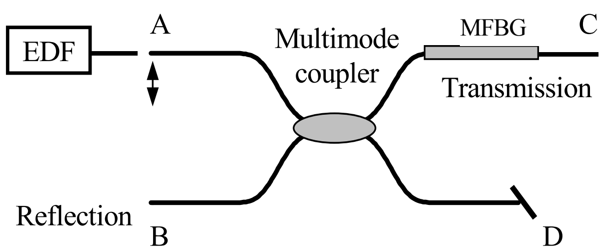

Fig. 1. Experimental measurement of multimode fiber gratings

The configuration of the experimental setup is shown in Fig. 1. In order to manually control the number of excited modes in the multimode fiber, we used an Erisson 975 fusion splicer to manually couple the light into a multimode fiber coupler at port A, as shown in Fig. 1. When the single mode ASE and the multimode fiber were aligned, the fundamental mode was excited dominantly. By offsetting the center of the multimode fiber with respect to the single mode ASE source, more modes could be excited in the multimode fiber. The coupling loss due to the offsetting was very small because the core diameter of the single mode fiber is much smaller than that of the multimode fiber.

The spectra were measured at port B and port C. Port D was angle cleaved and immersed in an index matching liquid to reduce the reflection. The OSA we used could accept multi modes because the light had an air path inside the OSA. However, some OSAs could only measure the fundamental modes if they use a section of single mode fiber to transmit the light inside the OSAs. In order to measure the fundamental modes of MFBGs using the Ando AQ-6310B, we spliced a piece of single mode fiber (SMF~2m) to the multimode fibers to filter out the high order modes.

The reflection and transmission of MFBGs were first measured during grating fabrication when the single mode ASE source was well connected to a multimode coupler. As the fiber was exposed to the UV radiation, the transmission dip initially deepened while it reached a saturation level simultaneously the linewidth widened as shown in Fig. 2. This was because

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the power was dominantly distributed in the fundamental mode when a single mode ASE source well connected to a multimode fiber. However, a small portion of the power still propagated as high order modes and passed the MFBGs at the transmission output at the Bragg wavelength of the fundamental mode. The saturation level of 14 dB dip in transmission indicates that a 4.0 % of the input power propagates in higher order modes. As shown in Fig. 2, the FWHM of the fundamental mode reflection is 0.211 nm. For a 20 mm long uniform grating, simulation shows that this linewidth corresponds to FBG stop band of -57 dB.

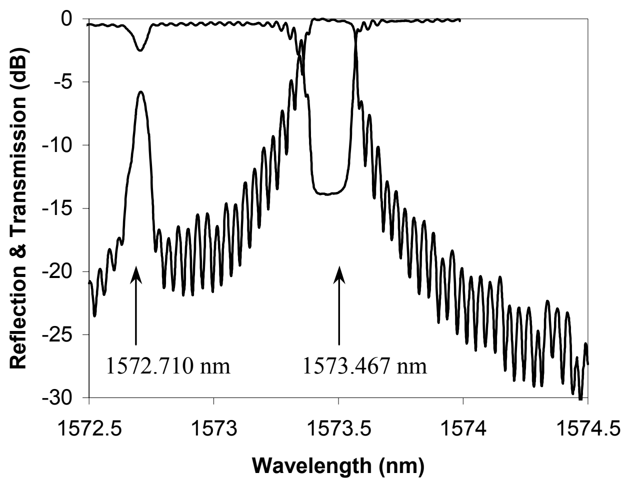

Fig. 2. The transmission and reflection of a 20 mm long multimode fiber grating

The resonance peak at the shorter wavelength side results from the cross-mode coupling between the forward fundamental mode and the second backward higher order mode. Note that cross-mode coupling is prohibited for ideal gratings. However, by exposing a fiber with the UV from the side of a fiber will introduce an asymmetric photo-induced refractive index change; this will results in a certain level of cross-mode coupling.

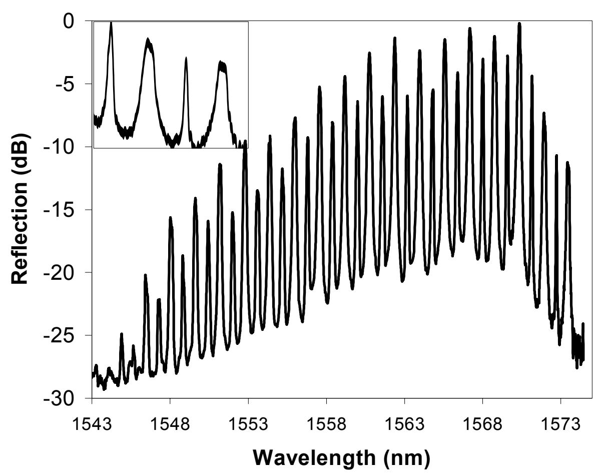

Fig. 3. The reflection spectrum of a 20 mm long MFBG. Two groups of reflections correspond to 18 principal modes (strong) and neighbouring cross coupled modes (weak).

We used a fusion splicer to manually couple light into a multimode fiber coupler from a single mode ASE source. When the two fibers are aligned with no offset, the reflection and transmission are shown in Fig. 2. When the offset increases, the fundamental mode weakens while the higher order modes gradually appear. When the offset is about 20 μm, the reflection spectrum is shown in Fig. 3. Clearly, there are two groups of reflection modes with a total of 36 reflection peaks that correspond to the 18 Bragg resonance modes and 18 neighbouring cross coupled modes. The wavelength spacings are 1.590 nm for both reflection groups. The shape of the spectrum varies depending on the mode excitation condition. For a certain mode excitation, it is possible to flatten the spectrum by employing a gain flattening filters (GFFs).

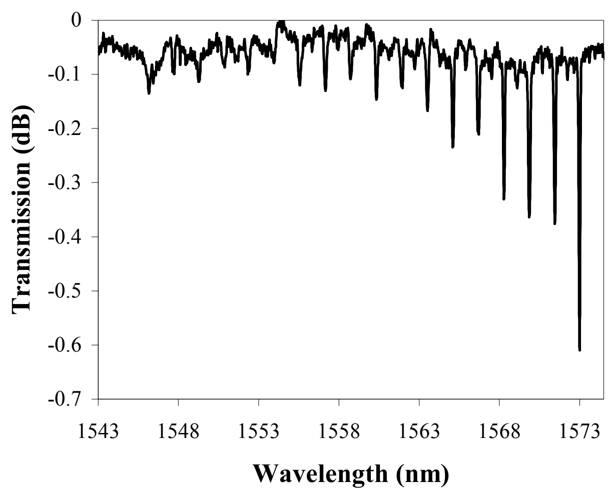

Fig. 4 The transmission of a 20 mm long MFBGs shows the principal modes coupling.

The transmission spectrum is shown in Fig. 4. The dips due to cross coupled modes can barely be recognized between the dips of two principal modes. The transmission dips are weak due to the fact that a very small portion of the power propagates in specific principal mode. Suppose there are N modes being equally excited, every mode should have 1/N of the total power. If every mode is completely rejected at its resonance, the maximum reflectivity is given by 10*log(1/N). For N=20, the measured strength is thus only 0.22 dB though the coupling strength of the gratings is very strong. The transmission spectrum as shown in Fig. 4 is typical in multimode fiber gratings [3]. However, by employing a single mode ASE source, a multimode coupler and a free-space coupled optical spectrum analyser, we observed up to 18 order principal modes with a total of 36 peaks in reflection spectrum.

3. Analysis

For a graded index multimode fiber with refractive index profile given by

$$n(r) = \begin{cases} n_0\sqrt{1-2\Delta(r/a)^2} & (0 < r < a) \\ n_0\sqrt{1-2\Delta} = n_a & (r \geq a) \end{cases} \tag{1}$$

where n_0 and n_a are respectively the indices at $r = 0$ and $r = a$, the normalized frequency V is defined as

$$V = 2\pi \cdot a \cdot NA / \lambda \tag{2}$$

where $NA = \sqrt{n_0^{\ 2} - n_a^{\ 2}}$ is the numerical aperture of the fiber. By using Eq. (1), the numerical aperture can be expressed as

$$NA = n_0 \sqrt{2\Delta} \tag{3}$$

For a graded-index multimode fiber, the number of supported modes is approximately given by $V^2/4$, specified by a pair of numbers (μ, ν), which, respectively, count the resonances in the radial and azimuthal directions [6]. In the case of step index and parabolic index fibers, there is an approximate set of degeneracies classified by a set of principal modes *m*=1, 2,.., *M*. The total principal modes for a parabolic graded-index fiber is given by [7-8]

$$M = V/2 \tag{4}$$

For the *m-th* principal mode, the propagation constant is defined by $\beta_m = 2\pi \cdot n_m / \lambda$, then, the mode index n_m is given as [7]

$$n_m = n_0 \sqrt{1 - 4\Delta \cdot m / V} \tag{5}$$

where *m*=1, 2,.., *M* are the orders of principal modes. Note that the first principal mode is simply the fundamental mode. Since $4\Delta \cdot m / V << 1$, by using Eqs. (2) and (3) and taking the first order approximation, Eq. (5) maybe reduce to

$$n_m = n_0 - m \cdot \frac{\lambda_0 \cdot NA}{2\pi \cdot a \cdot n_0} \tag{6}$$

where λ_0 is the central wavelength of the spectrum. The main coupling is between the forward and backward principal modes. However, any asymmetric structure, especially when the refractive index fringes of gratings are slanted relative to the fiber axis, cross-mode coupling will be significantly enhanced [2]. For a grating with a slight asymmetry, cross-mode coupling may be limited to neighbouring principal modes only. The Bragg resonances for the *m-th* principal mode and *m-th* neighbouring cross coupled mode are thus

$$\begin{cases} \lambda_m = 2 n_m \Lambda \\ \lambda_m^{cross} = (n_m + n_{m+1}) \Lambda \end{cases} \tag{7}$$

Clearly, between two principal modes, *m-th* and (*m+1)-th*, there is one cross coupled mode. Note that the linewidth of the cross coupled modes is significantly narrower than the principal modes (see the insert in Fig. 3). This maybe results from the superposition of the two couplings - the coupling between forward *m-th* and backward *(m+1)-th* modes, forward *(m+1)-th* and backward *m-th* modes. Using Eq. (6) and (7), the wavelength spacing between two reflection peaks for both groups of modes is obtained as

$$\Delta\lambda = \frac{\lambda_0^{\ 2} \cdot NA}{2\pi \cdot a \cdot n_0^{\ 2}} \tag{8}$$

For a fiber with parameters *NA*=0.275, 2a=62.5 μm, λ_0=1560 nm, Eq. (2) gives $V = 34.8$. The total number of principal modes given by Eq. (4) is thus 17.4. This is in a good agreement with the 18 principal modes observed in experiment. The wavelength spacing is given by Eq. (8) as 1.577 nm, which also agrees with the experimental result of 1.590 nm.

4. Conclusions

A comb filter was realized based on Bragg gratings in graded-index fibers. Two groups of reflections with a total of 36 reflection peaks that correspond to the Bragg resonances of 18 principal modes and neighboring cross coupled modes was reported for the first time. Analytical expressions to calculate the principal mode indices and the wavelength spacings were also provided, which shows in good agreement with the experimental results. This kind of comb filters may be used to construct multi-wavelength light sources for sensing and

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instrumentations. The spacing between two neighbouring peaks is about 0.8 nm, which coincides with the ITU channel spacing standard of 100 GHz, may have applications in optical communications.

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