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Short Note

Spectral Response of Fiber Bragg Gratings Connected in Series with Different Wavelengths

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When fiber Bragg gratings (FBG) with different reflection wavelengths are connected in series, the reflection spectrum may be affected by cladding modes depending on the order in which the FBGs are connected and on which side the signal light is incident. It is analyzed and experimentally demonstrated that, in order to obtain proper reflection signals from multiple FBGs, the FBGs must be connected in order from those with shorter wavelengths to those with longer wavelengths and signal light must be incident on the shortest wavelength FBG. [DOI: 10.1143/JJAP.42.6933]

KEYWORDS: fiber Bragg grating, optical circuit, optical fiber, cladding mode, fiber sensor, reflection spectrum

Because the fiber Bragg grating (FBG) has a very narrow-band sharp-reflection spectrum, it is well suited for applications that deal with narrow-band optical signals in its spectrum, such as optical filters in dense wavelength division multiplexing (WDM) systems, external reflectors of a fiber laser cavity and various types of fiber sensors. In these applications, the FBGs with different reflection wavelengths are often used by connecting them in series. For example, in order to detect temperatures or stresses at several different locations, FBGs with different reflection wavelengths are assigned to each location and are all connected in series so as to simultaneously measure parameters sensed at different locations from multiple spectra reflected through a single fiber. An FBG fabricated from a fiber that is commonly used in optical telecom systems normally has a so-called cladding mode.[1)] Depending on the order in which the FBGs are connected and also on which side the signal light is incident from, the overall reflection spectrum may become distorted by the cladding modes. Othonos[2)] has pointed out this effect in his review article by stating briefly that the cladding-mode problems become very serious at wavelengths shorter than the peak reflection wavelength. However, experimental demonstration has not been given. In this work, we analyze the conditions under which distortion occurs and we demonstrate them experimentally.

The cause of the cladding modes is as follows. The FBG is usually fabricated by inducing defects in the fiber core, which increases the refractive index. The defects are periodically induced along the fiber by exposing the fiber to periodically modulated UV laser light which is generated by interference of the UV laser light diffracted by a phase mask grating. The defect is induced in Ge chemical bonding in a silica glass network by its UV photosensitivity. This occurs only in the fiber core where Ge is doped. The cladding of the fiber is not affected by the UV laser light because Ge is not doped there. Light transmitted in a single-mode fiber has its intensity concentrated mostly near the center of the fiber core with a distribution slightly smeared out into the fiber cladding around the core. The grating of the FBG reflects light of a particular wavelength defined by the grating pitch in the fiber core, and the light smeared out in the fiber cladding is not reflected by the FBG. This results in partial mode conversion of the fundamental mode into higher order modes, which are called cladding modes. Since a higher order mode cannot propagate in a single-mode fiber, the cladding modes are lost and cause attenuation of the fundamental mode. The cladding modes usually show up at wavelengths in the range from approximately 1 nm to 10 nm shorter than the FBG central wavelength. This cladding mode can be suppressed by using a special fiber with Ge doping in the cladding around the core, which needs additional doping such as fluorine to compensate for the refractive index there. Such a fiber is for a special purpose and is expensive with limited availability. Standard telecom fibers, for example Corning SMF-28, are commonly used to fabricate FBGs.

When two FBGs are connected in series having central wavelengths λ_1 (FBG#1) and λ_2 (FBG#2) with $\lambda_1 < \lambda_2$, and when light is incident on FBG#1, λ_1 is reflected by FBG#1 without being affected by FBG#2. Conversely, if light is incident on FBG#2, λ_1 goes through FBG#2, is reflected by FBG#1 and passes back through FBG#2 again. During the two passes through FBG#2, it may suffer cladding mode attenuation from FBG#2 because λ_1 may overlap with the cladding mode wavelengths of FBG#2.

In order to confirm the distortions discussed above we have fabricated two FBGs, whose central wavelengths are $\lambda_1 = 1552.9$ nm (FBG#1) and $\lambda_2 = 1555.9$ nm (FBG#2), using standard telecom single-mode fibers (Corning SMF-28) by exposing each fiber to a UV excimer laser through a phase mask grating. The length of the FBG section is 15 mm for both. The reflection and transmission spectrum of these FBGs, measured individually, are shown in Fig. 1(a) for FBG#1 and (b) for FBG#2. Narrow-band sharp-reflection spectra are seen with nearly 100% reflectivity, and cladding modes are clearly visible in the transmission spectra at wavelengths shorter than the central wavelength by approximately 1 nm to 10 nm. The cladding mode signals are simply lost and appear as an attenuation of the transmission spectra.

When these two FBGs are connected in series by fusion splicing, the transmission and reflection spectra become like those shown in Fig. 2(a) when broad-band light is incident

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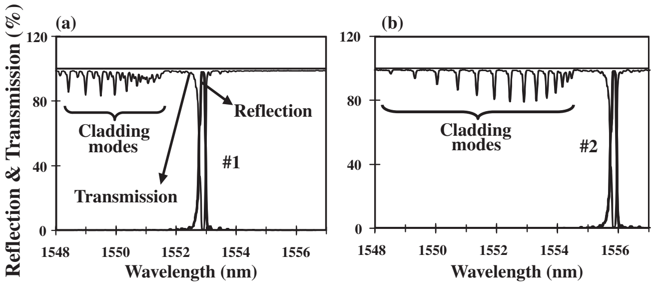

Fig. 1. Reflection and transmission spectra of two FBGs #1 and #2. The spectra are taken individually.

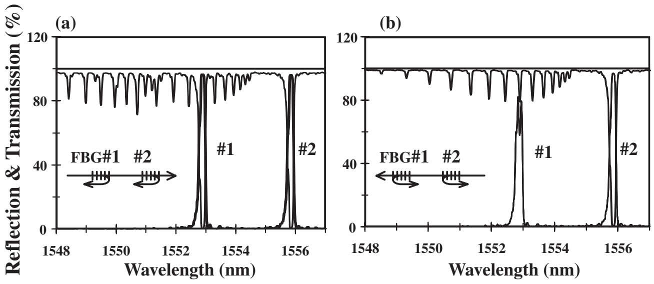

Fig. 2. Reflection and transmission spectra of two FBGs #1 and #2 connected in series. Signal light is incident on FBG#1 first in (a) and on FBG#2 first in (b).

on FBG#1 first. Both wavelengths λ_1 and λ_2 are reflected with little attenuation and with nearly identical spectra as those in Figs. 1(a) and 1(b), respectively. Conversely, when light is incident on FBG#2 first, the reflection spectrum of λ_1 is attenuated by approximately 30% as seen in Fig. 2(b). The reason for this attenuation is because λ_1 goes through FBG#2 twice in its round trip and is affected by the cladding mode of FBG#2 as explained above.

The effect on the reflected light signal of how the FBGs are connected and in which direction the signal light is incident also applies to multiply connected FBGs with different reflection wavelengths. This is demonstrated in Fig. 3, where five FBGs are connected in series. The FBGs are fabricated in the same way as those of Fig. 1. But for these, one single-phase mask grating is used and different tension has been applied to the fiber. Releasing the tension

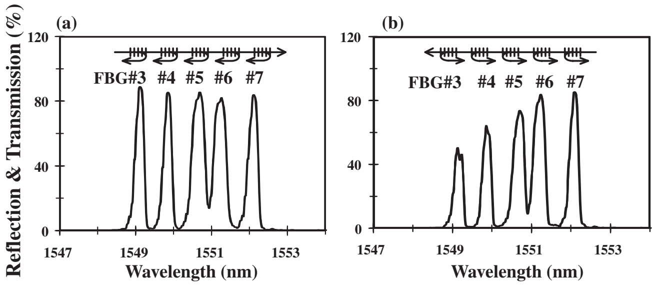

Fig. 3. Reflection spectra of five FBGs #3–# 7 connected in series. Signal light is incident on FBG#3 first in (a) and on FBG#7 first in (b).

after imprinting the FBG shifts the central wavelength.[3] Five FBGs (FBG#3∼#7) with $\lambda_3 = 1549.1$ nm, $\lambda_4 = 1549.8$ nm, $\lambda_5 = 1550.7$ nm, $\lambda_6 = 1551.2$ nm and $\lambda_7 = 1552.1$ nm are consecutively fabricated in one fiber with a 20 mm separation between each. Reflection spectra are shown in Fig. 3 with a broad band incident first on (a) FBG#3 and on (b) FBG#7. When the light is incident first on the short wavelength FBG, it is reflected with little attenuation and without being affected by the cladding modes of other FBGs as seen in Fig. 3(a). However, when it is incident first on the longer wavelength FBG, all but the first wavelength, that is λ_7, suffer attenuation from the other FBG cladding modes. That is, λ_7 is reflected immediately by FBG#7 but λ_3 is attenuated by the cladding modes of FBG#4–#7 and λ_4 by the cladding modes of FBG#5–#7 as seen in Fig. 3(b).

From these results, in order to obtain proper reflection signals from multiple FBGs connected in series without attenuation by cladding modes, it can be concluded that they must be connected in order from the shortest wavelength FBG to the longest wavelength FBG and the signal light must be incident first on the shortest wavelength FBG.

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