Two types of resonances in long-period gratings induced by arc discharges in boron/germanium co-doped fibers

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We demonstrate that under certain conditions it is possible to fabricate in a B/Ge co-doped fiber an arc-induced long-period grating whose spectrum contains a dual set of resonances. These two sets of resonances are formed by distinct mechanisms and are caused by coupling to cladding modes of different symmetries. They behave differently at high temperatures: the set produced by symmetric perturbation disappears during annealing at a temperature of 800°C, while the other set produced by an antisymmetric mechanism can withstand temperatures above 1000°C. © 2007 Optical Society of America

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Recently we showed that long-period gratings (LPGs) arc-induced in Corning SMF-28 fiber couple light to antisymmetric cladding modes, while gratings induced in B/Ge co-doped fiber, from Fibercore, couple to symmetric modes [1]. We attributed the inscription of the former gratings to microdeformations induced in the fiber core due to thermal gradients in the arc discharge [2]. The formation mechanism of the symmetric gratings was not identified. At the same time, the stress relaxation was indicated to be an important contribution to the formation mechanism of gratings in B/Ge co-doped fibers when the LPGs were inscribed by heating through exposure to CO_2 laser radiation [3]. Also, Grubsky and Feinberg noted that if the peak temperature reached by B/Ge fibers during the grating inscription was in the range ~700–1200°C the induced LPGs were erasable and rewritable and showed that the mechanism of grating formation is a reversible densification in the fiber core [4]. In a previous work studying arc-induced gratings in B/Ge co-doped fibers [5], we also revealed some similar characteristics. In particular, we observed that thermal annealing of such gratings at temperatures above 700–800°C leads to their erasure. Meanwhile we were intrigued by the absence of antisymmetric resonances in the spectra of the produced gratings. In this paper, we investigate the possibility to excite antisymmetric modes by arc-induced gratings in B/Ge co-doped fibers, analyze the behavior of the spectra of these gratings with temperature, and discuss the mechanisms of formation.

LPGs were induced in a B/Ge co-doped fiber (PS1250/1500 from Fibercore) using the setup described in detail in [6]. In this setup, an uncoated fiber is positioned between the electrodes of a fusion splicing machine. One end of the fiber is clamped in a fiber holder on top of a stage, whose translation is controlled with a precision of 0.1 μm. At the other end, a mass is attached to keep the fiber under a constant axial tension (1–40 g). A short section of fiber is exposed to an arc discharge with an electric current of 8.5–10.0 mA for 0.5–2.0 s. Then the fiber is moved by the grating period, typically 400–700 μm. A computer-controlled sequence of arc discharges and fiber displacements is repeated 15–100 times until a required grating is produced.

In earlier experiments where LPGs were created in B/Ge fibers, a single set of resonances was observed in their spectra [1,5]. As we mentioned above, this set is formed by coupling to symmetric cladding modes. However, an antisymmetric mechanism should also make its contribution during grating inscription. To reveal resonances in the grating spectra belonging to antisymmetric cladding modes, we tried to create conditions such that the antisymmetric perturbation is stronger than usual. We positioned the fiber in a region of the arc where the average temperature is lower and the thermal gradient is higher: 100 μm closer to one of the electrodes and 50 μm below the line joining the electrodes [2]. To compensate lower temperature and higher viscosity of the fiber we applied higher pulling tension than in previous experiments [5]. This way we increased coupling to the antisymmetric modes and decreased coupling to the symmetric ones. Figure 1 shows the resulting spectrum of one grating (inscribed by 60 periods of 540 μm using a tension of 23 g and discharges with a current of 9 mA and duration of 0.5 s). A dual set of resonances appears in the spectrum. The set at longer wavelengths is normally obtained in gratings inscribed in B/Ge fibers. The set at shorter wavelengths appeared due to our special arrangement of the setup for the fabrication of the grating. The amplitudes of resonances in this set depend strongly on the position of fiber in the arc, and the resonances disappear if the fiber is placed in the center line be-

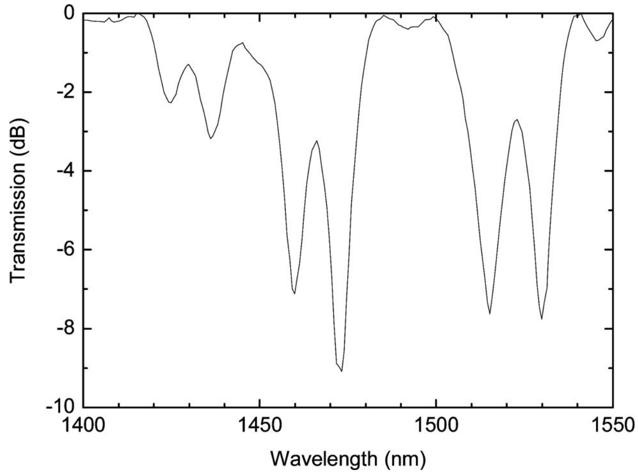

Fig. 1. Grating spectrum with a dual set of resonances.

tween the electrodes. According to our simulation, the set at shorter wavelengths is caused by an antisymmetric perturbation and the set at longer wavelengths, by a symmetric.

To verify that the two sets are formed by different mechanisms we performed thermal annealing of the grating at high temperatures. The grating under a pulling tension of 1.2 g was placed inside a tubular oven. This tension was used to keep the fiber straight and prevent bending under its own weight. The temperature was raised from room temperature up to 800°C and kept at this temperature for annealing. The spectral evolution of one pair of resonances of the grating during annealing at 800°C is shown in Fig. 2. As can be seen, both the resonances shift to longer wavelengths, and the amplitude of the right-side resonance decreases with time going to zero (~1 dB). Figure 3 demonstrates the behavior of the two sets of resonances in wavelength and in attenuation loss depending on annealing time. In Fig. 3(a) the annealing temperature was set to 800°C, while in Fig. 3(b) the temperature was increasing from 800 up to 1000°C. It is seen that the changes in the two sets with time are very different: the resonances of symmetric modes decrease and disappear, and the resonances of antisymmetric modes first decrease a

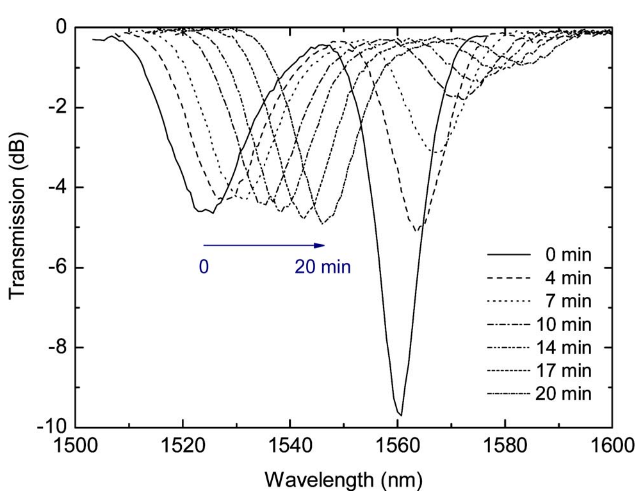

Fig. 2. (Color online) Spectral evolution of a pair of grating resonances during annealing at 800°C for 20 min.

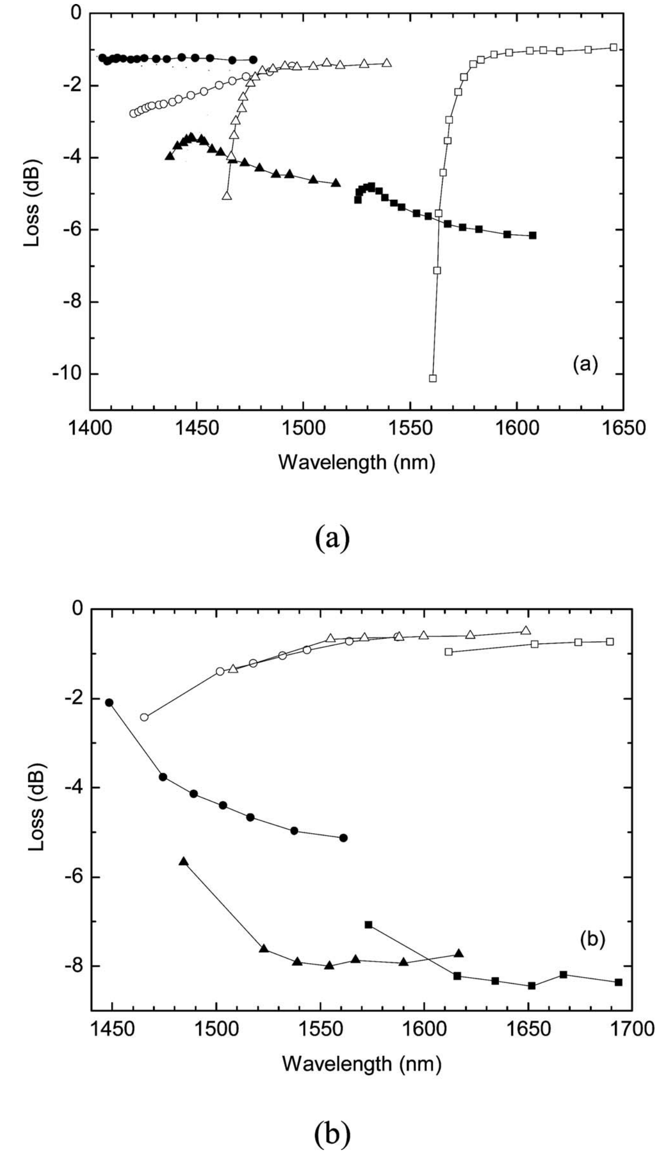

Fig. 3. Behavior of the resonance wavelengths and attenuation losses of three grating resonances during annealing (a) at 800°C for 62 min and (b) at temperature increasing from 800 up to 1000°C for 36 min. The curves with circles, triangles, and squares represent the thermal evolution of the three pairs of resonances in the spectrum shown in Fig. 1. The empty and filled symbols belong to symmetric and antisymmetric modes, respectively.

little (at 800°C) and then increase. At the same time, both sets shift to longer wavelengths. The increase in the amplitudes of the antisymmetric modes is probably related to that shift in wavelength and not to strengthening of the grating. Figure 4 shows the spectrum of the grating after 62 min of annealing at 800°C and a further increase of temperature up to 990°C during 24 min. Only one set of resonances corresponding to the antisymmetric modes remains in this spectrum.

In a previous work [5] it was observed that gratings arc-induced in B/Ge co-doped fiber degrade at temperatures above 700°C and disappear in less than 1 h at 800°C. It was also demonstrated that those gratings are produced by a symmetric pertur-

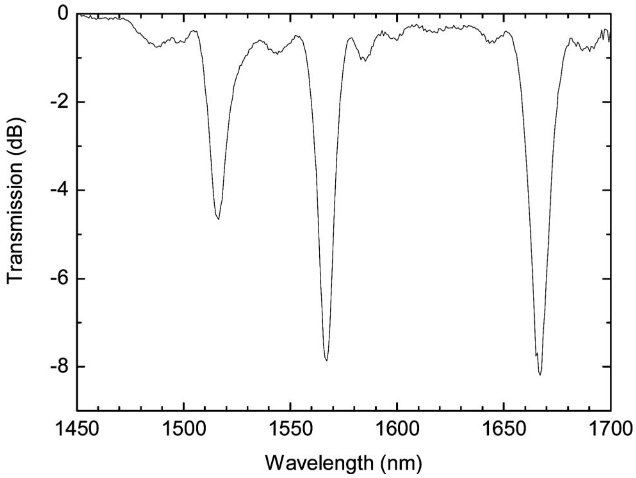

Fig. 4. Grating spectrum after annealing at temperature increasing from 800 up to 990°C for 24 min.

bation [1]. Therefore, the resonances at longer wavelengths behave like the resonances of the symmetric modes (LP_{0j}) and, therefore, may be produced by a mechanism such as densification [4]. The remaining resonances could withstand temperatures as high as 1000°C, behave similar to the resonances of gratings induced in standard fibers [6], and are formed by another mechanism. These resonances cannot belong to the LP_{0j} modes, because there is only one set of resonance wavelengths for the LP_{0j} modes, independent of the formation mechanism, as follows from the resonance condition $\beta_{co}(LP_{01}) - \beta_{cl}(LP_{mj}) = 2\pi/\Lambda$. These resonances cannot be for the LP_{0j} modes of other polarization, since the fiber is not birefringent. It should be noted that for gratings arc-induced in standard fibers the typical split of the resonance bands for two orthogonal polarizations is of the order of 1 nm [7]. For the excitation of modes with $m \geqslant 1$, perturbations of the corresponding symmetry should be created in the fiber. As we have shown in [2], a strong antisymmetric perturbation ($m=1$) is induced in the arc discharge due to thermal gradients. Perturbations of higher symmetries, $m \geqslant 2$, may also be present but are obviously weaker. The resonances of antisymmetric gratings induced in standard fibers can withstand temperatures above 1000°C [6] like the resonances at shorter wavelengths. Thus, we conclude that the resonances at shorter wavelengths are produced by coupling with the LP_{1j} modes.

By using the electric arc technique and a B/Ge codoped fiber, we induced a LPG whose spectrum exhibits a dual set of resonances that are formed by coupling to symmetric and antisymmetric cladding modes. The two sets behave differently at high temperatures: one set reduces its amplitude drastically when the grating is annealed at 800°C for 30 min, while the other set can withstand temperatures above 1000°C. The origin of the first set may be attributed to densification, while the second set may result from an antisymmetric mechanism such as microdeformation. Gratings with two such sets of resonances exciting modes of different symmetries can be useful in the development of sensors for simultaneous measurement of two physical parameters, where resonances should respond differently to changes in different parameters.

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