Long period gratings written in large-mode area photonic crystal fiber

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Abstract We report for the first time, to the best of our knowledge, on the fabrication and characterization of CO$_2$-laser written long-period gratings in a large-mode area photonic crystal fiber with a core diameter of 25 µm. The gratings have low insertion losses (<1 dB) and high attenuation (>10 dB) at the resonant wavelengths, making them particularly interesting for high power applications.

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1 Introduction

Long period fiber gratings (LPG) are characterized by a longitudinal periodic variation of the core or cladding effective index of a waveguide which leads to a resonant coupling between two co-propagating modes. This coupling takes place if there is a spatial overlap between the modes and the phase-matching condition ($n_{\text{eff,1}} - n_{\text{eff,2}} = \lambda / \Lambda$) is fulfilled [1]. $n_{\text{eff,1/2}}$ denotes the effective indices of the two modes, $\Lambda$ is the grating period, and $\lambda$ the resonant wavelength. Comparable to fiber Bragg gratings (FBGs), the most common technique to inscribe LPGs is the irradiation of a photosensitive fiber with a UV-laser through an amplitude mask [1]. Using a LPG a fiber-integrated spectral filter with designable characteristics can be achieved by coupling a guided core mode to a leaky or lossy cladding mode. Depending on the wavelength range LPGs have been written into fibers with core diameters of at most 10 µm, i.e., into standard single-mode fibers. However, due to performance limitation by nonlinear effects and fiber damage, the generation and delivery of high power and high brightness laser radiation relies on fibers with significantly larger mode area in order to reduce the intensity inside the fiber core. Diffraction-limited high power fiber laser sources with powers well above the kW barrier have already been reported [2]. Such systems demand fiber-integrated components compatible to their fiber dimensions and geometries. Photonic crystal fibers (PCF) [3] offer an enhanced index control capability due to a micro-structured cladding region. Therefore, with these fibers larger intrinsically single-mode fiber cores with low numerical apertures are possible. Single-mode Yb-doped PCFs with core diameter of larger than 50 µm have been reported [4]. An LPG can be written in these fibers by periodic collapsing (at least partly) the holey cladding structure by illumination with a CO$_2$-laser. LPGs in PCFs have already been demonstrated, but they were written in fibers with core dimension of just 10 µm and exhibited rather high insertion losses or strong side wings in the notch spectrum [5–7].

In this contribution we report for the first time on the inscription of long period gratings in a 25 µm core large-mode area photonic crystal fiber. The spectral signature of these LPGs is characterized by a well defined notch with an attenuation of 12 dB at the design wavelength and very low insertion losses, making them suitable fiber-integrated filter devices for high power fiber applications.
Fig. 1 Schematic setup to inscribe LPGs into large-mode area PCF; OSA: optical spectrum analyzer

Fig. 2 Cross section of PCF (LMA-25) (left) and the same fiber cleaved at a CO$_2$-laser modified region (right)

2 Experimental setup and results

The setup used to write LPGs into large-mode area PCFs is shown in Fig. 1. A water-cooled CO$_2$-laser (Synrad 48S series) is directed to and focused onto the PCF by two plane and one off-axis parabolic mirror ($f = 2.5''$) mounted on a translation stage ($x$-direction). The fiber is placed on a second translation stage ($y$-direction) and a weight is applied to keep the fiber straight. A halogen lamp acts as white light source. The PCF transmission spectra are characterized using an optical spectrum analyzer ANDO AQ6370 with a resolution of 2 nm. The large-mode area PCF (LMA-25) used in the experiments has been fabricated by Crystal Fibre A/S. Four rings of air-holes surround the core formed by one missing hole. The relative hole size is $d/\Lambda = 0.484$ and the distance between the holes is $\Lambda = 17 \mu$m, resulting in a core diameter of $25 \mu$m. The fiber guides the fundamental mode only in the wavelength region from 900 nm to 1700 nm. The cladding diameter is $268 \mu$m. A cross section of the fiber is shown in the left of Fig. 2. The gratings are written by moving the parabolic mirror ($x$-translation stage) along the fiber with the step size equal to the grating period. By moving the second translation stage back and forth the focused laser beam crosses the fiber. The laser power together with the speed of the $y$-translation stage defines the dose of heat, the strength of the localized modification, and ultimately the strength of the resonant coupling between the core and cladding modes. This process is repeated until the desired number of periods is obtained, defining the length of the grating. The CO$_2$-laser power is set to $\approx 1$ W, and the spot size at the fiber surface is approximately $100 \mu$m. The optimum index contrast, i.e., the optimum coupling strength, is achieved by repeatedly scanning the grating with identical parameters (typically 2 to 10 scans). The entire process is computer-controlled.

Figure 3 shows the transmission spectra of several LPGs written in the large-mode area PCF with different grating periods. All of these gratings have 20 periods, with resulting grating lengths from 38 to 50 mm. The spectra are characterized by a low insertion-loss of less than 0.5 dB and a well defined attenuation at the resonant wavelength of up to 12 dB. The FWHM bandwidth of the spectral attenuation peaks is about 20–25 nm. As an example, the calculated effective index at 1150 nm of the fundamental core mode and the fundamental space filling mode (FSM) of the PCF cladding are 1.44786 and 1.44832, respectively. The index of the FSM corresponds to the effective index of the infinitely extending holey cladding without the missing hole. It is assumed that coupling occurs between the fundamental core mode and at least one of the cladding modes, which are close to