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Advances in Solid Core Photonic Bandgap Fiber Amplifiers

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Abstract: We present recent development of photonic crystal fiber amplifiers containing photonic bandgap structures for enhanced spectral and modal filtering functionality.

OCIS codes: (060.0060) Fiber optics and optical communication; (060.3510) Lasers, Fiber

1. Introduction

The rapid development and deployment of high peak power and high pulse energy ytterbium-doped (Yb-doped) fiber amplifiers have been fuelled by the development of more and more complex Large Mode Area (LMA) fiber designs [1-6]. The demand for large effective area is driven by the need to mitigate nonlinear effects such as Four-Wave Mixing (FWM), Self-Phase Modulation (SPM), and Stimulated Raman Scattering (SRS), which can distort pulse amplification due to spectral and/or temporal broadening. To successfully apply fiber amplifiers, in for example semiconductor and solar cell scribing applications or frequency conversion applications, fiber amplifiers need to generate high beam quality with good pointing stability in order to deliver precise and stable performance. For this, Single-Mode (SM) fibers have a major advantage since Higher-Order Modes (HOMs) are suppressed by the fiber design and not by coiling or launch conditions. As fiber amplifiers are maturing other practical issues arise such as the need for compact fiber coils, beam delivery, suppression of Amplified Spontaneous Emission (ASE) and/or suppression of detrimental wavelengths generated through FWM, which can destroy the pumps since these wavelengths are not well isolated in standard pump reflectors.

Furthermore, fiber amplifiers operating with built-in spectral gain shaping has recently emerged as a novel method for generating non-standard wavelengths such as 589nm by frequency doubling an 1178nm Yb-doped amplifier [7, 8] or using cladding pumped Raman amplification. Both types of amplifiers require distributed spectral filtering to either suppress the ytterbium gain at lower wavelengths or to suppress the second Stokes wavelength to limit cascaded Raman processes [9].

Photonic BandGap (PBG) structures can be successfully incorporated into Photonic Crystal Fiber (PCF) amplifiers to provide suppression of Higher-Order Modes (HOMs), gain shaping, ASE and SRS suppression, as well as provide improved bending performance for achieving smaller form factors. In this paper, we present our latest results on LMA yb-doped fiber amplifiers having PBG structures enabling efficient amplification of high spectral brightness signals.

2. Single-mode ROD PCF amplifiers

Suppression of nonlinear effects is crucial for generating high peak power pulses in fiber amplifiers. The most common approach is to increase the effective mode area and increase the pump absorption, thereby reducing the effective nonlinear figure of merit. However, when increasing the core size of step-index fibers to beyond 15 μ m the core supports many spatial modes and this can significantly degrade the beam quality and cause beam instabilities. Fabricating large cores that only support one spatial mode requires tight index control to achieve the required low NA. Furthermore, tolerances on preform materials etc make production of low-NA fibers (approx <0.06) very challenging unless tolerances can be compensated during fiber draw.

Inset of figure 1a shows the endfacet of a so-called DMF rod fiber amplifier [6] having an 85 μ m core with ~0.01NA. The fiber core is formed by 19 index-matched yb-elements and the cladding is formed by 5 rings of airholes arranged in a hexagonal lattice. The cladding furthermore consists of 30 Germanium-doped rings arranged in kagome lattice within the hexagonal air lattice. These rings form precisely tuned Distributed Mode-Filtering (DMF) elements that filter HOMs out of the core and allows for SM operation. As with other resonant methods, these rings are tuned to filter HOMs in a specific wavelength region. Figure 1a shows a transmission plot of such as fiber. The oscillations in the spectrum are caused by mode beating between the Fundamental Mode (FM) and HOMs. Between 1050-1070nm there are no oscillations and the fiber core only supports one spatial mode. Below 1050nm, the FM couples to the DMF elements and becomes leaky (leaky regime). The pump absorption is ~27dB/m@976nm,

which gives an effective amplifier length of 70-90cm depending on configuration. Figure 1b shows the slope efficiency of a 70cm rod amplifier in a wavelength-locked Q-switched laser configuration [10]. The rod delivers 14ns pulses with up to 2mJ pulse energy and 0.4nm spectral width in a diffraction limited output with $M^2 < 1.2$. The output beam has very high spectral brightness and was frequency doubled to 515nm with 48% conversion efficiency.

Fig. 1. Transmission plot of the DMF rod fiber [6] (a). Inset shows a micrograph of the endfacet of the DMF rod fiber. Slope efficiency of the DMF rod fiber in a Q-switched laser cavity (b) [10].

Generating high-power ps pulses with high spectral brightness in fiber amplifiers is typically very challenging because SPM causes spectral broadening. However, recent results [11] have shown very efficient ps amplification using the DMF rod fiber in the leaky regime, delivering >200W of output with >70% slope efficiency and 0.3nm spectral width.

3. Single-mode PBG PCF amplifiers

Frequency doubling of lasers and amplifiers operating in the 1150-1200nm region produces yellow-orange light from 570-600nm. Yb-doped fibers have a very broad fluorescence spectrum extending up to 1200nm and the small-signal gain per unit length can be as high as 0.8dB/m hence the net gain can easily exceed 10dB at 1178nm [7]. However, the large gain between 1030nm and 1100nm creates very strong ASE and can lead to parasitic lasing. Parasitic lasing will limit the available gain at 1178nm and thereby the power scalability. In order to overcome the problem of parasitic lasing, a full PBG structure provides wavelength-filtering and efficient suppression of ASE at the conventional ytterbium gain wavelengths between 1030 and 1100 nm. The fiber structure is shown in the inset of figure 2a. The single-cell core consists of index-matched yb-doped silica and the cladding consists of Germanium-doped high-index parabolic rods forming the PBG structure. Two boron rods on each side of the core create birefringence for maintaining the polarization through the the fiber. As shown in figure 2a, using 40meters of fiber, sufficient gain is accumulated and 167W of output power has been generated at 1178nm with a slope efficiency of 61% [8]. Figure 2b shows the transmission spectrum of the PBG fiber together with the amplified output spectrum. As shown, the fiber efficiently suppresses gain below 1178nm and allows for 16dB of net gain at 1178nm [8].

Fig. 2. Slope efficiency for 1178nm amplification, inset shows micrograph of the endfacet of the PBG fiber [8] (a). Transmission plot of the PBG fiber and the amplified output spectrum [8] (b).

3. Single-mode hybrid PCF amplifiers

Full PBG structures provide excellent gain filtering, but the inherent all-solid structure makes core size scaling difficult if SM performance is to be maintained. To scale the core size, and thereby the effective mode area, hybrid PCF structures are more promising [12]. The cladding of hybrid PCF structures contains several rings of airholes as conventional PCFs but some of the airholes have been replaced with Germanium-doped high-index PBG elements to provide wavelength filtering. Two different hybrid PCF structures are shown in figure 3. The fibers in figure 3 contain two groups of Germanium-doped high-index rods arranged in either a single row or with three adjacent rows. The designs are asymmetric, which means that the diameter of the rods on the left and right side of the core are not identical. In these cases, the right row of rods is scaled to ~85% of the left row of rods. This asymmetry provides one more degree of freedom in the design of the wavelength filtering, and it is possible to further narrow the PBG spectrum down to ~3-4% spectral width and provide very robust bending performance with 10-15cm bending diameter possible for core sizes of 35-45 μm [13], while maintaining SM performance.

Fig.3. Micrographs of hybrid PCF fibers having one-row (a) and three-rows (b) of PBG elements for enhanced spectral filtering.

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