Single-frequency fiber oscillator with watt-level output power using photonic crystal phosphate glass fiber

A. Schülzgen, L. Li, V. L. Temyanko, S. Suzuki, J. V. Moloney, and N. Peyghambarian

College of Optical Sciences, The University of Arizona, Tucson, AZ 85721
axel@optics.arizona.edu

Abstract: Utilizing phosphate glass fiber with photonic crystal cladding and highly doped, large area core a cladding-pumped, single-frequency fiber oscillator is demonstrated. The fiber oscillator contains only 3.8 cm of active fiber in a linear cavity and operates in the 1.5 micron region. Spectrally broad, multimode pump light from semiconductor laser diodes is converted into a single-mode, single-frequency light beam with an efficiency of about 12% and the oscillator output power reached 2.3 W.

OCIS codes: (140.3510) Lasers, fiber; (060.2410) Fibers, erbium

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1. Introduction

Single-frequency lasers have a wide range of applications in optical sensor and communication systems. In particular, single-frequency oscillators that operate around 1.5 μm are crucial devices due to their compatibility with optical fiber communication lines and a wide range of existing photonics components. With sufficient output powers single-frequency lasers also find applications in nonlinear optical devices, e.g., as pump sources for optical parametric amplifiers. The fabrication of compact, single-frequency fiber lasers was enabled by the development of fiber Bragg grating (FBG) that can be directly written into single mode fiber cores. Combining narrow band FBGs with short, rare-earth doped, single-mode active fibers exclusive oscillation of just one laser mode in a linear cavity was achieved [1, 2]. In addition, single-frequency, traveling wave fiber lasers have been reported [3]. However, the increased complexity and reduced stability of fiber ring resonators give monolithic nonplanar ring resonators [4] a clear edge.

To date, compact, all-fiber, single-frequency oscillators with narrow linewidth have been demonstrated in both distributed Bragg reflector (DBR) and distributed feedback (DFB) linear resonator configurations [5]. However, the inherent short cavity length and correspondingly small pump absorption typically limits the power of single-frequency Er doped silica fiber lasers to power levels from hundreds of μW to a few mW. These low oscillator powers can be boosted using various power amplification schemes. The higher power, however, has to be paid for by increased noise and broadened laser linewidth, characteristics that are undesirable or even unacceptable in many applications. Recently, a 200 mW single-frequency fiber laser has been demonstrated that utilizes highly doped phosphate glass to significantly increase the absorption of pump light within a few cm of doped fiber [6]. The special phosphate glass allows for extremely large doping levels with negligible clustering effect and is consequently well-suited for compact single-frequency fiber lasers. In that study [6] the oscillator power was limited by the available single mode pump power that had been launched into the active fiber core. Although it is generally less efficient to absorb the pump light in a cladding pumping scheme, first few cm-long single-frequency fiber lasers have been demonstrated very recently using similar highly doped phosphate glasses as the active material [7,8]. For cladding pumping multimode semiconductor laser diodes providing much higher pump power and scaling of the output power depends mainly on improving the multimode pump absorption through optimized rare-earth doping and single-mode fiber designs with large mode areas.

A novel concept to increase the mode area while maintaining single transverse mode operation is the application of photonic crystal fibers (PCFs). PCFs consist of a regular array of air holes and a defect in its center which defines the core. The photonic cladding can be used to tailor the optical properties of these fibers and achieve, e.g. large dispersion, broadband single mode guidance, and extremely small or large mode areas [9]. Best studied PCFs with large mode areas are fibers where one central hole is replaced by a solid core. Experimentally, PCFs with the largest single mode cores have been realized with designs where more than one central air hole is removed and mode diameters on the order of 2000 μm^2 have been demonstrated in case of seven missing central air holes [10].

Here, we report on a 1.5 μm single-frequency DFB fiber oscillator that utilizes a phosphate glass PCF [11,12] with heavily Er/Yb co-doped large-mode-area core. Although several PCF based lasers and amplifiers with long active fiber lengths have been reported in recent years [for early PCF lasers see, e.g., 13-15 and 10 for PCF amplifier], here we present, to the best of our knowledge, the first application of PCF to build a single-frequency, short-length fiber oscillator. In contrast to previous work on cladding pumped single-frequency lasers that employed conventional step-index active fibers [7,8] our extremely short PCF oscillator did not exhibit any saturation for pump powers up to the available 20 W level. Single-frequency operation was achieved within a stable, single FBG configuration that did not require additional etalons and/or polarization management. These advances are enabled by combining short PCF with rather large active volume and high doping with active ions in

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the phosphate glass resulting in rapid absorption of the pump light launched into the active fiber cladding. A record of more than 2.3 W of output power was generated using only 3.8 cm of active PCF within a 5.8 cm long all-fiber cavity.

2. Active fiber and single-frequency oscillator design

The geometry of the linear-cavity single-frequency fiber laser is shown in Fig. 1. Three different fibers formed an all-fiber laser device that was held in a silicon U-groove. The silicon substrate was thermoelectrically cooled to provide effective heat dissipation during high power laser operation. 976 nm pump light from multimode semiconductor laser diodes was delivered through a multimode fiber with 105 μm core diameter, an outer diameter of 125 μm, and a numerical aperture of 0.22. The end facet of this fiber was coated with a dielectric stack of SiO_2 and Ta_2O_5 layers that transmits the pump light but acts as a high reflector at the lasing wavelength of 1.534 μm. The pump delivery fiber is butt-coupled to the active fiber.

The active fiber is a PCF fabricated from phosphate glasses that allow for high levels of rear-earth doping in the active core. Both doped and undoped phosphate glasses were provided by NP Photonics Inc. and the fiber was drawn at the College of Optical Sciences using the stack-and-draw technique. A cross-section of the active PCF is shown in lower left part of Fig. 1. The fiber consists of a triangular pattern of 87 unit cells in the center that are surrounded by a solid outer cladding. The PCF has an outer diameter of 125 μm making it compatible with standard silica fibers. The PCF has been designed to form a large area core of about 430 μm^2 that supports only one transverse mode which is well-confined through the array of axial air holes that run along the fiber. The measured mode quality factor M^2 of approximately 1.2, which is slightly higher than unity due to deviation of the mode shape from a circular symmetric Gaussian intensity distribution. To achieve these modal properties, we applied the recently introduced depressed-index core design that allows for single mode operation at relaxed tolerances for refractive index control [12]. Our PCF had an air hole period of 8 μm, air hole diameters of about 3.2 μm, and a nominal index difference between core and cladding glasses of $\Delta n = n_{core} - n_{clad} = -17 \times 10^{-4}$. The 7 central unit cells of the PCF that form the core have no air holes and consist of solid core glass that is doped with 1.6×10^{26} Er^{3+} ions/m^3 and 8.6×10^{26} Yb^{3+} ions/m^3. Large mode fiber design and high doping result in extremely efficient absorption of the cladding launched pump light with less than 10% pump transmitted through only 5 cm of the active PCF.

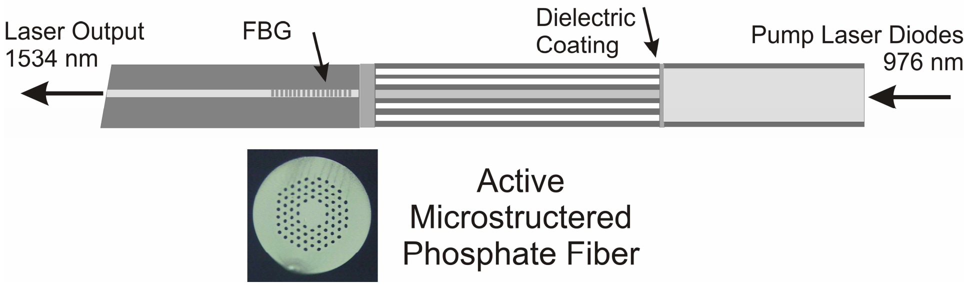

Fig. 1. Schematic of the single-frequency fiber laser. A microscope image of the active photonic crystal fiber with 125 microns outer diameter is shown in the lower left part.

At the fiber laser output side (left side in Fig. 1) the active fiber is spliced to a single mode silica fiber (Nufern PS-GDF-20/400) that has a large area photosensitive core. The nominal

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core diameter is 20 μm with a numerical aperture of 0.06. The original outer diameter of this fiber is 400 μm. To achieve a low loss fusion splice between the active phosphate PCF and the photosensitive silica fiber the latter has been etched to an outer diameter of 125 μm by hydrofluoric acid. In addition, a short (<300 μm) buffer of coreless phosphate fiber has been inserted between the PCF and the silica fiber to preserve the air holes in the PCF during fusion splicing. The fiber laser resonator is completed by a FBG written into the core of the silica fiber using 244 nm light and a 25 mm long phase mask. The reflection spectrum of the FBG in Fig. 2 shows a peak reflectivity of 17% at 1.534 μm and a 3 dB bandwidth of about 0.03 nm. Per roundtrip the complete fiber laser has a propagation loss of 3.8 dB due to the fusion splices and coupling losses between different fibers and the output loss is 7.7 dB. The roundtrip loss can easily be compensated by the large gain in the PCF with the highly doped, large area core.

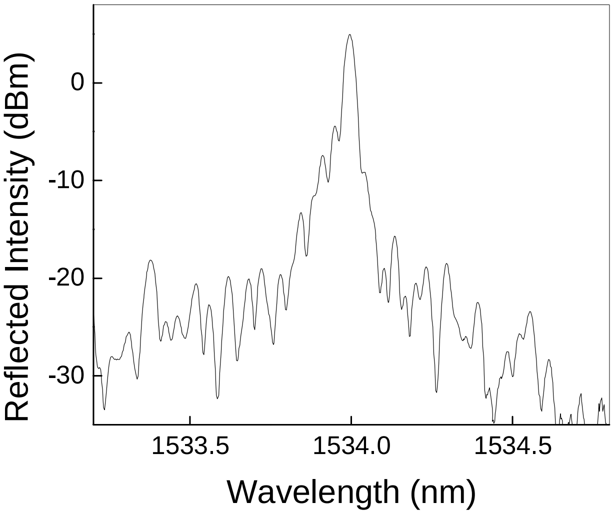

Fig. 2. Reflection spectrum of the FBG used in the single-frequency laser. The FBG has a peak reflectivity of 17% at 1534 nm and a 3 dB bandwidth of 0.03 nm.

3. Single-frequency oscillator performance

The output versus pump power characteristics of the single-frequency PCF laser is shown in Fig. 3. Measured by an optical spectrum analyzer (not shown) the laser emission spectrum is a resolution limited narrow line centered at the 1534 nm reflection peak of the FBG. An optical-to-optical conversion efficiency of a ~12% is observed up to pump powers of 20 W. This efficiency is more than twice as high as the maximum conversion efficiency of ~5% reported for similar single-longitudinal-mode fiber laser that uses conventional step-index fiber [7]. In addition, the previously reported step-index fiber lasers showed strong saturation effects at similar pump levels as illustrated by comparison of our results with data from Qiu et al. [7] in Fig. 3. Due to saturation, the optical conversion efficiency of step-index fiber lasers decreases below the 5% level at higher pump powers. A maximum output power over 2.3 W at 20 W of pump power demonstrates the advantages of our single-frequency, PCF based laser device over conventional step-index fiber lasers with respect to overall power. In the latter case a saturated maximum output power of 1.6 W output was achieved at pump levels slightly above 35 W [7].

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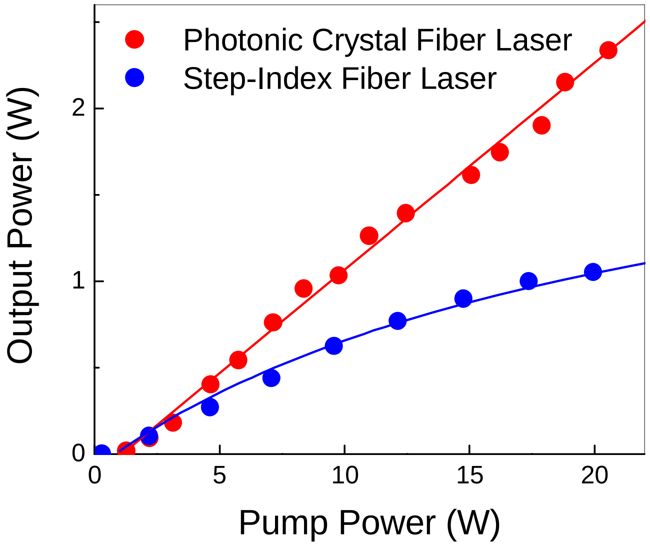

Fig. 3. Signal output vs. pump power of a fiber laser with only 3.8 cm of active PCF (filled circles). For comparison the performance of a similar laser using 4 cm of active step-index fiber is also shown (open circles) [7]. The lines are for eye guidance indicating no saturation for the PCF laser and a typical saturation behavior of the step-index fiber laser.

Thermal management problems currently prevent us to pump our PCF laser at comparable power levels. Assuming that the thermal problems can be solved and the saturation effects remain small output powers beyond 4 W can be reached launching 35 W of pump power. These numbers indicate the future potential of cladding pumped single-frequency PCF lasers.

To obtain more details on the laser emission a heterodyne measurement has been performed. A single-frequency signal from a high-accuracy (wavelength resolution of 0.1 pm) tunable diode laser was coupled to our fiber laser output and the resulting beat signal was analyzed using a radio frequency (RF) electrical spectrum analyzer (ESA). A typical RF spectrum collected during laser operation is shown in Fig. 4(a). Only one frequency component is observed within the full span of 3 GHz of the ESA. This single-frequency operation indicates another advantage of using a PCF as the active fiber; the noncircular symmetry of the core inherently results in polarization mode discrimination while in step-index fibers special polarization maintaining fiber has to be used to break the polarization degeneracy. Without any advanced temperature stabilization or vibration isolation the single-frequency operation of our fiber laser is very stable and virtually free of mode hopping up to pump levels of 10 W. The emission line has a width of ~2 MHz and frequency drifts over a period of 1 minute are typically below 1 MHz. Even at the higher pump levels single-frequency operation prevails, however, the laser operates from time to time at multiple emission lines as shown in Fig. 4(b). This multi-line operation allows obtaining the free spectral range (FSR) of the fiber laser cavity. The measured FSR of 1.74 GHz corresponds to a total cavity length of 5.8 cm. In addition, another transverse mode separated by 240 MHz appears in the RF spectrum of Fig. 4(b) that we tentatively assign to the orthogonal polarization. The robustness of single-frequency and single-polarization operation can be further improved by accurate temperature control and better mechanical stability.

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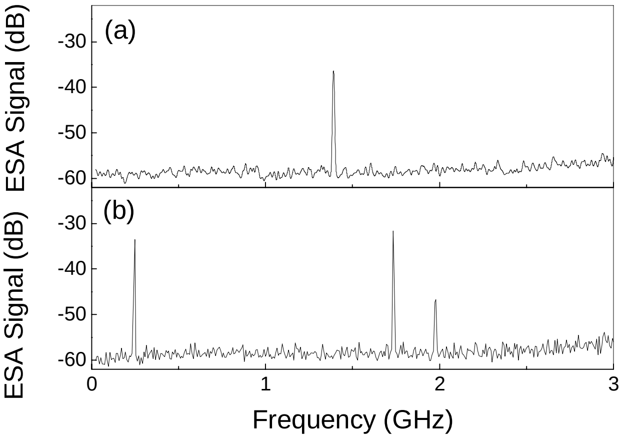

Fig. 4. RF beat signal between the emission of the PCF laser oscillator and a narrow linewidth single-frequency reference source measured by an electrical spectrum analyzer indicating (a) single-frequency and (b) multi-line operation of the PCF oscillator.

4. Conclusion

We have demonstrated a fiber oscillator that applies the concept of large core PCF to achieve high-power, single-frequency operation around 1.5 µm. Combining extremely high doping in phosphate glass and large core area sufficient multimode absorption has been achieved over only 3.8 cm active fiber length even in a cladding pumping scheme. This new concept enables utilizing readily available, high-power, multimode laser diodes to pump single-frequency fiber lasers and boost their output power to the level of several Watts.

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