Single-frequency fiber laser operating at 2.9 μm

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We report the demonstration of a single-longitudinal-mode fiber laser operating at 2914 nm, which exhibits a spectrometer-limited linewidth of <0.4 nm, in a 49 mm long holmium/praseodymium co-doped ZBLAN fiber. Narrow-linewidth feedback is provided by a fiber Bragg grating inscribed directly in the ZBLAN fiber using the femtosecond laser point-by-point technique. Measurements of the temporal stability and coherence confirm that the laser is operating on a single longitudinal mode. © 2013 Optical Society of America

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Single-longitudinal-mode (SLM) lasers have found application in a wide range of fields including spectroscopy [1], LIDAR [2], and coherent beam combining [3]. In the visible and near-infrared (IR) wavelength range, SLM lasers have been realized in the form of semiconductor diodes operating in distributed feedback mode, distributed Bragg reflection mode, or external cavity mode. Likewise, short fiber laser cavities with strong, narrow-bandwidth fiber Bragg gratings (FBGs) have exhibited single-frequency operation at 1 μm in Yb3+-doped silica fiber [4], at 1.5 μm in Er3+, Yb3+-doped silica fiber [5], at 1.7 μm in Tm3+-doped silica fiber [6], and at 2 μm in Ho3+-doped silica fiber [7]—as well as at 1.2 μm in Ho3+-doped ZBLAN fiber using FBGs in silica fibers that were spliced onto the doped fiber [8].

In the mid-IR wavelength range, quantum cascade lasers (QCLs) have provided tunable SLM laser emission from ~4 to 16 μm. The output power of QCLs in the 3 μm range, however, has been limited due to the conventional QCL material (InGaAs/InAlAs) not having sufficiently deep quantum wells. Recent experiments involving the new QCL material, InGaAs/AlAsSb, have shown progress toward developing shorter wavelength transitions [9], but these systems have yet to reach the level of performance of more conventional QCL technology. While FBGs in silica fibers are well understood and robust, FBGs in ZBLAN fibers were only recently demonstrated in [10,11]. In that work, the index modifications were produced through a phase mask using femtosecond laser pulses at 800 nm. Femtosecond laser inscription is required due to the low UV photosensitivity of ZBLAN glass.

In this Letter, we demonstrate an SLM fiber laser based on an Ho3+, Pr3+ co-doped ZBLAN gain fiber with a lasing wavelength of 2.91 μm, exhibiting a spectrometer-limited linewidth of 0.4 nm. Narrow-linewidth feedback is provided by the cavity by an FBG inscribed directly in the Ho3+, Pr3+-doped fluoride fiber using femtosecond laser pulses and the point-by-point (PbP) inscription technique [12,13]. To the best of our knowledge, this represents the first PbP grating inscribed in a soft-glass fiber and the longest wavelength single-frequency fiber laser that has been reported. We confirm SLM operation via a fringe contrast measurement in a Mach–Zehnder interferometer.

The experimental layout of the SLM fiber laser is shown in Fig. 1. Two polarization-multiplexed 1150 nm diodes are used to pump the double-clad Ho3+, Pr3+ gain fiber, which has an outer core diameter of 125 μm and a numerical aperture (NA) of 0.50. The 10 μm inner core has an NA of 0.16, while the Ho3+ and Pr3+ concentrations are 3 and 0.25 mol%, respectively [14]. In Ho3+-doped ZBLAN fiber, the lower laser level for the ~3 μm transition has a longer lifetime than the upper laser level; therefore this transition is potentially self-terminating.

We have investigated two methods to alleviate this situation: co-doping with Pr3+ (which reduces the lower laser level lifetime from 12 to <1 ms) and cascaded lasing [15]. In the current work we use the co-doped fiber approach.

The laser cavity is formed by a high-reflector PbP:FBG and a partially reflecting dielectric mirror. The dielectric mirror (DM-2) was butt-coupled to the input face of the fiber ($R = 50%$ at 2.9 μm, $T = 99%$ at 1150 nm). In this initial demonstration, the fiber was cladding-pumped and thus had comparatively low pump absorption; the addition of the dichroic mirror was required to achieve a higher cavity finesse that allowed lasing in the 49 mm length of gain fiber.

To achieve SLM operation, the feedback bandwidth of the grating has to be sufficiently small compared to the free-spectral range of the cavity, so that there is sufficient discrimination between modes, so that one mode

Fig. 1. Schematic of the experimental setup of the single-frequency Ho3+, Pr3+ doped ZBLAN fiber laser. DM-1 is a dichroic mirror with high transmission at 1150 nm and 99% reflection at 2914 nm. DM-2 is a dichroic mirror that transmits the pump and provides 50% reflection at 2914 nm. The acrylate coating of the fiber was completely removed, and the end of the PbP:FBG was angle-cleaved to avoid a coupled cavity.
dominates [12]. Our grating inscription technique, incorporating a fiber-guiding system with submicrometer transverse control and femtosecond laser inscription, is described in detail elsewhere [13]. Femtosecond laser pulses (120 fs, 800 nm) are focused into the fiber core at a constant repetition rate using a high-NA objective, and the fiber is continuously translated relative to the focal point of the laser such that single femtosecond pulses each inscribe a single point feature in the grating. Thus the grating period is defined by the ratio of the translation speed of the fiber to the pulse repetition rate of the laser. A 20 mm long, first-order grating at ~2.9 μm (grating period ~986 nm) was inscribed with 190 nJ pulses. Measurements using a mid-IR spectrometer confirmed the spectral linewidth of the grating was no greater than the resolution limit of the spectrometer (<0.4 nm).

In contrast to PbP gratings written in silica fibers at this pulse energy, the modifications in the ZBLAN fiber do not include microvoids, but a strong type I-IR modification [16]. This was confirmed by brightfield and differential interference contrast (DIC) micrographs of a grating inscribed under identical conditions in a separate piece of ZBLAN fiber. By comparing the DIC contrast in the silica fiber PbP gratings, the type I-IR index modifications in ZBLAN are much stronger than those observed in silica fiber [17]. DIC micrographs of PbP gratings inscribed in silica and ZBLAN fibers are shown below Fig. 2. The ability to inscribe strong type I-IR modifications in ZBLAN without microvoids is highly promising for the realization of strong, low-loss gratings in ZBLAN fiber using the PbP technique.

The laser had a lasing threshold of 420 mW of pump light and a slope efficiency of 1.4% with respect to the incident pump power, and a maximum laser power of 11 mW. As expected, a similar length of gain fiber without the FBG exhibited no lasing, as the threshold was too high without the addition of a high-reflectivity FBG. The output spectrum of the laser, measured using a spectrometer with 0.4 nm resolution, is shown in Fig. 3. This measurement reveals the laser output wavelength (and correspondingly the grating central wavelength) at 2914 nm. The linewidth in this measurement is limited by the resolution of the in-house spectrometer of 0.4 nm.

The temporal power stability was measured on a photodiode over the course of several minutes (see Fig. 4). After a change in pump power, the laser power spiked dramatically (by ~300%) in the first 60–80 s. After 60–80 s, however, the fluctuations diminished and a stable output power was recorded (having a <15% fluctuation). We attribute this behavior to mode competition between two longitudinal modes within the lasing bandwidth. Given the timescale of this phenomenon, we believe the cavity experiences pump-power-induced temperature changes. A change in the effective cavity length drives the laser from single-mode operation to two-mode operation, which results in mode competition and hence large power fluctuations. Eventually, one of the modes drifts closer to the central reflection wavelength of the FBG and begins to dominate, forcing more stable output power. This explanation aligns with the observation that the same temporal behavior could be observed at each new pump power level.

We performed a measurement of the fringe contrast using a Mach–Zehnder interferometer with 50 mm of path-length adjustment in order to test for SLM operation of the fiber laser. The Mach–Zehnder interferometer limited back reflections into the fiber laser, as free-space isolators operating in this wavelength range were not
readily available. If the fiber laser operated multimode, the interferometer would reveal beats indicating the degree of coherence [18] as the waves accumulate phase as a function of delay. For two-mode operation, the free-spectral range of our laser cavity suggests that the degree of coherence would reduce by 30% over a 2.5 cm path-length delay. As the number of longitudinal modes increases, the coherence falls, as indicated by the simulations shown in Fig. 5. Comparison between the experimental coherence and the simulated coherence reveals the laser is operating in the SLM regime.

The standard technique for measuring the linewidth of fiber lasers is the delayed self-heterodyne method [19]. In this method, a long length of fiber (1–100 km) is used to delay one arm of an interferometer with a length sufficient to remove any temporal coherence effects, while the other arm is shifted by a radio-frequency amount. The beams are then recombined, and the linewidth is determined by the heterodyne beat on an rf analyzer. This technique has found great application in the near-IR region where long lengths of silica fiber are inexpensive and transparent and fiber couplers are well developed. Unfortunately, in the mid-IR wavelength range, reliance on specialty ZBLAN fiber is currently prohibitively expensive and fiber couplers are not yet commercially available. Other standard near-IR techniques for high-resolution linewidth measurements such as a scanning Fabry–Perot interferometer or a fast photodetector (>2 GHz) for observation of longitudinal mode beating are not yet available in the mid-IR. Given the finesse of the fiber laser cavity, when the fiber laser is operating in the SLM, the Schawlow–Townes linewidth has the potential to be subhertz, but technical noise from thermal variations and mechanical vibrations will broaden the linewidth.

In summary, we have demonstrated the longest wavelength (2914 nm) single-frequency fiber laser. The FBG used in this laser represents the first PbP grating written in a ZBLAN fiber and allowed us to observe a spectrometer-limited linewidth of <0.4 nm. The temporal intensity measurements indicated initial longitudinal mode competition followed by substantially more stable single-mode operation. Furthermore, the coherence length was observed to exceed the limit imposed by two-mode operation of the fiber laser. Our results highlight the potential for PbP inscription to provide low-loss gratings in ZBLAN fibers more generally for other fiber laser and sensing applications.

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