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We report on the power scaling to 103 W of a 1.1 μm continuous-wave Yb³⁺-doped silica fiber laser incorporating a point-by-point (PbP) fiber-Bragg grating inscribed directly into the active core using 800 nm femtosecond laser pulses. The spectrum of the laser exhibited a narrow linewidth that broadened to 260 pm at 103 W. The output was frequency doubled using an 11 mm long periodically poled MgO:LiNbO₃ crystal to generate 2.1 W of green with an internal conversion efficiency of 10% at high power and 0.81% /W at low power. © 2007 Optical Society of America

Rare-earth-doped fiber lasers have become an important tool in many industries with applications ranging from material processing to telecommunications. Their prominent properties include high slope efficiencies, power scalability, broad wavelength tunability, and diffraction-limited beam qualities at high power. High-power fiber lasers emit in the near-infrared spectral region, thus nonlinear frequency conversion is necessary for applications requiring light in the visible spectral region. For this purpose, the output from fiber lasers is required to have high peak power, narrow linewidth, and preferably linear polarization. Standard continuous-wave (cw) laser systems with simple geometries, however, typically have spectrally broad outputs [1]. Different approaches have been proposed to address these requirements. Examples include bulk-optic solutions [2] and master-oscillator power-amplifier (MOPA) arrangements, which have been used to generate narrow linewidth radiation with up to 82% linear polarization for an output power of 100 W [3,4]. An all-fiber solution is desirable however, as these systems are generally complex and expensive.

Fiber Bragg gratings (FBGs) can be utilized to generate a narrowband laser output, but their use in high-power fiber lasers is limited due to the poor power handling capability of gratings written with single-photon UV processes into the active core [5]. Consequently, for high-power laser systems, gratings are typically written into standard photosensitive fibers without rare-earth dopants and spliced onto the fiber containing the active core. This procedure produces an additional step in the fabrication process, introduces an additional loss to both the pump and laser light, and diminishes the overall robustness of the laser.

Recently, the so-called point-by-point (PbP) technique to inscribe FBGs in standard telecom fibers was introduced [6]. The approach utilizes a femtosecond laser pulse to modify the refractive index in a small area within the core of a fiber and, by synchronizing the translation of the fiber with the repetition rate of the femtosecond laser, highly reflecting narrowband gratings with good thermal properties can be fabricated at various wavelengths [7]. Since the PbP technique is a multiphoton process, it does not require the fiber to be photosensitive to inscribe a FBG, and direct inscription of FBGs into the active core becomes possible. These FBGs exhibit some polarization-dependent characteristics [5] and were used initially to produce a distributed feedback Er³⁺:Yb³⁺-codoped fiber laser with a 0.2 mW narrowband output [8]. More recently, a PbP FBG was inscribed directly into the active core of a double-clad Yb-doped fiber, to realize a 5 W narrow linewidth (<15 pm) laser [9]. The output power and laser linewidth of the fiber laser were highly stable over a 4 h period, thus indicating that further power scaling was feasible.

In this Letter we present a 103 W cw Yb³⁺-doped double-clad fiber laser operating at 1097 nm that utilizes a FBG inscribed directly into the active core using the PbP grating writing technique. The output of the laser was spectrally narrow with a maximum bandwidth of only 260 pm at the maximum output power of 103 W. Finally, we demonstrate single-pass...
Fig. 2. Measured reflection spectrum of the point-by-point written FBG. The inset shows a high-resolution scan of the grating peak on which the laser operated.

Frequency doubling using an 11 mm long periodically poled MgO:LiNbO$_3$ (MgO:PPLN) crystal to generate 2.1 W of green with an internal conversion efficiency of 10% at high power and 0.81%/W at low power.

The experimental arrangement is shown in Fig. 1. The active fiber was an Yb$^{3+}$-doped silica fiber (Optical Fibre Technology Centre) with an 8 μm core diameter [numerical aperture (NA) 0.11], Yb$^{3+}$-ion concentration of 7400±800 ppm and a peak effective absorption coefficient of the pump core at 978 nm of 0.09 dB/m. The fiber had a 300 μm hexagonally shaped inner cladding (NA 0.45). To fabricate the FBG, the fiber was mounted on a high-precision air bearing translation stage, the outer polymer cladding stripped away, and femtosecond laser pulses were focused into the active core using a 0.8 NA, 20× oil immersion objective lens. The pulses, which were generated by a regeneratively amplified Ti:sapphire laser operating at 800 nm, had <120 fs pulse duration, at a 1 kHz repetition rate and a pulse energy of 220 nJ. The FBG, which acted as the highly reflecting mirror, was 15 mm long and had a period of 1.13 μm, which corresponds to a third-order grating for 1097 nm light. Fresnel reflection at the cleaved end face of the fiber acted as the output coupler. The fiber was pumped using a focused 250 W stacked diode laser array system with an NA of 0.4. The pump wavelength varied from 974 nm at low power to 977 nm at high pump power with a bandwidth of ~5 nm. The launch efficiency into the fiber was ~66%. A dichroic mirror filtered the remaining unabsorbed pump. Finally, a half-wave plate and a polarizing beam cube were used to investigate the polarization of the laser before the light was focused into a MgO:PPLN crystal to allow frequency doubling experiments.

The reflection spectrum of the FBG is shown in Fig. 2. The FBG had a center wavelength of $\lambda_c = 1097.58$ nm with a FWHM of $\Delta \lambda = 54$ pm. An absolute measurement of the grating reflectivity could not be obtained due to experimental difficulties in obtaining stable and efficient coupling from the core of the double-clad fiber to the optical spectrum analyzer. However we measured the laser light emitted from the grating end of the laser and determined that the maximum reflectivity of FBG was 90% (10 dB) at $\lambda_c$. The insertion loss in the region of the grating could not be measured accurately because of the difficulties associated with ground-state absorption.

The output power measured as a function of launched pump power is shown in Fig. 3. The fiber length was optimized to 23.5 m for an operating wavelength of 1097 nm, and the maximum recorded output power was 103 W, limited by the available pump power. There were no indications of output saturation or stimulated Brillouin scattering (SBS). The slope efficiency of the fiber laser using an intra-core Bragg grating was 64% compared with 70% for the same fiber using a dielectric mirror as the high reflector. The lower slope efficiency of the former laser can be attributed to the comparatively lower reflection coefficient of the Bragg reflector.

The center wavelength of the laser was observed to shift toward longer wavelengths at higher pump powers due to an increase of the effective refractive index of the grating via the thermo-optic effect. Above an output power of 10 W, the spectral line was narrow and Gaussian-like, but $\lambda_c$ was unstable and fluctuated over a 2 nm range, an effect attributed to the fluctuations in the ambient temperature surrounding the grating. The stability of the center wavelength was greatly improved after cooling the FBG with a fan, and the jitter in $\lambda_c$ was reduced to less than 10 pm at all power levels over several minutes of operation. Instabilities in the pump coupling configuration prohibited a long term investigation of the performance of the fiber laser at high pump power.

The output spectrum is shown in the inset to Fig. 3. The laser linewidth was 260 pm (64.8 GHz) at an output power of 103 W, which to the best of our knowledge, is significantly narrower than any commercially available source at these power levels [10]. Shown in Fig. 3 is the linewidth as a function of the pump power. The linewidth increased linearly (at 0.55 pm/W after an initial offset of 11.3 pm) up to the output power of 38 W. We attribute this broadening to chirping of the grating due to a longitudinal temperature gradient resulting from photodarkening-induced absorption of the exponentially decreasing...
laser light along the grating. Above 38 W output power, the broadening ceased to be linear, which we attribute to insufficient cooling of the FBG.

Figure 4 shows the fraction of the total laser power in a single linear state of polarization as a function of the output power. It can be observed that the output is between 53% and 59% partially polarized and that the stability of the polarization deteriorates above 38 W. We attribute this latter feature to insufficient cooling of the FBG. From Fig. 4 it is clear to see that a fiber laser utilizing a dielectric mirror for feedback rather than a PbP FBG is completely unpolarized, and hence the FBG must be inducing the partial polarization of the laser in the latter case. The partial polarizing nature of the FBG relates to transversally asymmetric stress fields originating from the cylindrically shaped damage spots comprising the grating. These stress fields are believed to cause local birefringence, generating slightly dissimilar grating strengths for the two polarization eigenstates. Naturally, factors such as the grating writing power, the grating length, the grating order, and the transverse position of the grating in the core will influence the degree of polarization of the fiber laser output.

The frequency-doubled green power as a function of the launched polarized infrared light is shown in Fig. 5. The infrared light after the polarizing beam cube was oriented parallel to the z axis of an uncoated 11 mm long MgO:PPLN crystal that had a domain period of 7 μm and a 50% duty cycle. The maximum green power generated within the crystal was 2.1 W with an internal conversion efficiency of 10% at high power and 0.81%/W at low power, values commensurate with previously reported values [11]. The saturation of the green power for polarized infrared power levels above 21 W (i.e., 70 W from the fiber laser) relates to the linewidth broadening beyond the maximum phase matching bandwidth, which was calculated to be 0.2–0.22 nm.

In conclusion, we have demonstrated power scaling to the 100 W level of a narrow linewidth Yb3+-doped silica fiber laser that utilizes a FBG inscribed directly into the active core using the PbP technique. Stabilization of the center wavelength, bandwidth, and output power of the fiber laser was achieved by temperature control of the FBG. Direct inscription of FBGs into the active core of a fiber using the PbP approach allows the generation of spectrally narrow, high power laser light with the convenience of a straightforward fabrication process and a superior overall robustness.

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