Tunable single-longitudinal-mode ErYb:glass laser locked by a bulk glass Bragg grating

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A single-longitudinal-mode ErYb:glass laser with a linewidth of 90 kHz is demonstrated by locking the laser wavelength to 1552.6 nm with a bulk glass Bragg grating. Using a piezoelectric actuator, the wavelength could be tuned over a range of 0.25 nm (31 GHz) in steps of 17 pm (2.1 GHz), with an output power of a few milliwatts. © 2006 Optical Society of America

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Single-longitudinal-mode lasers around 1.5 μm have a number of applications, including free-space telecommunications, pump sources for nonlinear frequency conversion to the mid-IR, and seed sources for laser and nonlinear amplifiers, as well as in differential wavelength spectroscopy. Single-mode operation of a laser usually requires a wavelength-selective filter to prevent all longitudinal modes but one from lasing. Filters used previously for wavelength restriction in bulk solid-state lasers include etalons[1–4] and fiber Bragg gratings.[5] In this Letter we demonstrate the use of a new type of filter for locking solid-state lasers, Bragg gratings in a bulk glass material, which can provide single-mode operation in a simple, and thus stable and robust, setup. These gratings have been used earlier for wavelength locking of both high-power diode lasers[6] and optical parametric oscillators.[7] With a holographic technique, the gratings are recorded in a photosensitive glass, where they are subsequently fixed by heat treatment.[8] In this way a sinusoidal variation of the refractive index is imposed, which gives a narrow reflection peak for the wavelength that fulfills the Bragg condition. By adjusting the period and the amplitude of the refractive index modulation as well as the length of the device, it is possible to tailor the grating to give a reflection at a desired wavelength with a given reflectivity and bandwidth.[9] These gratings are commercially available with reflectivities up to 99% and bandwidths around 0.3 nm in devices a few millimeters long. This bandwidth is about 2 orders of magnitude narrower as compared with ordinary multilayer coatings, mainly because of a much longer periodic structure in combination with a low index variation.

In this work we use a double-cavity configuration, with the ErYb:glass gain medium in an internal cavity and the Bragg grating in an external one, similar to the setup in Ref. 5. The internal cavity provides the high-finesse cavity needed to sustain laser action in the three-level ErYb system at 1.5 μm, while the external feedback is used to select only one of the internal cavity's longitudinal modes, thereby enabling single-longitudinal-mode operation. By changing the length of the internal cavity, the longitudinal mode and thus the laser wavelength can be tuned over the whole bandwidth of the Bragg grating feedback. In contrast to double-cavity setups using only ordinary mirrors,[2,3] our approach is not restricted to locking in close proximity to the gain peak. Instead, the use of a proper Bragg grating gives access to the whole gain bandwidth of the laser. To use the Bragg grating directly as an output coupler in a single cavity is obviously a more straightforward approach. However, this has not been pursued in this work, since the low-gain ErYb-system is not compatible with the relatively high outcoupling from our grating.

The laser setup is depicted in Fig. 1. The internal cavity was built up from a 1 mm thick flat–flat ErYb-doped phosphate glass disc and a concave mirror, with an optical path length of 3.8 mm, giving a longitudinal mode spacing of 0.32 nm (39 GHz). The ErYb:glass was doped with 1×10^{20} cm^{-3} of Er^{3+} and 2×10^{21} cm^{-3} of Yb^{3+}. The front facet had a highly reflective coating ($R > 99.9\%$) at 1.55 μm and a highly transmitting coating at 975 nm, while the opposite facet was antireflection coated ($R < 0.5\%$) at 1.55 μm. The output coupler had a radius of curvature of 10 mm and a 98% reflection coating at 1.55 μm. A ring-shaped piezoelectric stack was mounted between the ErYb:glass disc and the outcoupler, which was fixed with respect to the external cavity. The piezo stack enabled fine-tuning of the internal cavity length by up to 3 μm with a voltage of 150 V, corresponding to moving the longitudinal modes 1.2 nm (150 GHz).

The laser was end-pumped by a fiber-coupled InGaAs diode laser at 975 nm delivering a power of 240 mW. The pump light was imaged from the delivery fiber to form a 40 μm $1/e^2$ radius spot in the laser medium, giving optimal overlap with the lowest-order transversal mode supported by the laser cavity.

The laser's external cavity was formed by the internal cavity's outcoupler, a plano–convex lens, and the bulk glass Bragg grating, with total optical path length of 70 mm, giving a mode spacing of 17 pm

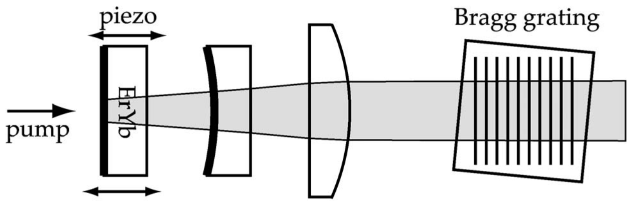

Fig. 1. Laser setup.

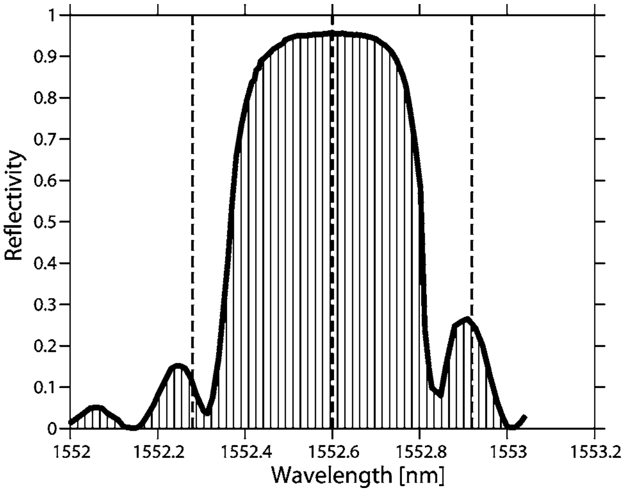

Fig. 2. Reflectivity spectrum for the Bragg grating with indication of the internal (dashed lines) and external (solid lines) modes of the laser.

(2.1 GHz). The lens was antireflection coated for 1.55 μm with a focal length of 25 mm and collimated the laser output at the Bragg grating. The bulk glass Bragg grating (purchased from Optigrate, Florida) was 5 mm thick with a clear aperture of 5 mm × 7 mm. The reflectivity of the grating, as measured using a tunable narrowband diode laser, is shown in Fig. 2. The peak reflectivity was 96% at 1552.6 nm with a FWHM bandwidth of 0.44 nm. The facets of the grating were not coated, but polished at a 6° angle to the grating vector to avoid parasitic effects from the surface reflections, giving a single-pass loss of 5%.

For comparison, the performance of a free-running laser based on only the internal cavity was studied. It showed multiple longitudinal modes lasing around 1535 nm with a power of 31 mW. When the Bragg grating feedback was added, the laser was locked at 1552.6 nm. Given the strong feedback from the Bragg grating, some care had to be taken to make sure that the alignment of the reflected beam was perfect; otherwise the feedback caused higher-order transversal modes to oscillate. Because of the uncoated surface of the Bragg grating, the laser gave three output beams, one from the transmission through the grating and the other two from the uncoated surface reflection within the external cavity. The laser output power was 3–7 mW through the grating and 4–5 mW for each surface outcoupling, adding up to a total of about 13 mW (see Fig. 3). The reduction in output power as compared with a free-running laser is due to the (not optimal) high grating reflectivity. The polarization of the laser emission was found to be random, which is to be expected, since there are no polarization-selective elements in the cavity.

To examine the locking and tuning behavior of the laser, the internal cavity length was tuned by giving a voltage ramp to the piezo actuator. The voltage was tuned from 2 to 78 V over a period of 5.5 s. This tuned the longitudinal modes of the internal cavity to three times over the Bragg grating peak; see Fig. 3. The outcoupling from both the Bragg grating and one surface reflection are shown together with the corresponding wavelength, measured by an optical spectrum analyzer. Looking at the plot from 30 V upward, we see how one longitudinal mode of the internal cavity is being tuned over the modes of the external cavity. At the Bragg grating peak at about 42 V, the internal laser power has increased as seen from the surface reflection, while the power from the grating outcoupler has decreased, as expected for the stronger feedback. Consecutively, when the feedback goes down while tuning off the Bragg peak, the next internal mode starts to lock instead around 56 V. By inspecting the wavelength, the range over which only one internal cavity mode was lasing at the time was found to be more than 0.25 nm (31 GHz). In contrast, while in the transition region between two adjacent internal modes, the laser jumps between the modes when changing the piezo voltage just slightly.

To study the tuning in more detail, the laser output was sent via an optical isolator to a scanning Fabry–Perot interferometer. The laser was locked in the region around the Bragg peak, and the piezo voltage was scanned while the relative position of the laser frequency given by the Fabry–Perot was monitored (see Fig. 4). The laser jumps from one external mode to the next, with a mode spacing that corresponds well to the 2.1 GHz inferred from the cavity length. Since 2.1 GHz is the smallest mode spacing available in the laser, we can conclude that the laser is indeed lasing in a single longitudinal mode. Also, there is an indication of a mode-hop-free tuning of the order of 100 MHz, given by the slight inclination of the curve in between the mode jumps, though this is at the limit of the resolution of the measurement method.

The scanning Fabry–Perot interferometer was also used to determine the temporal frequency stability of the device for a constant piezo voltage. Over a period of 4 h, no change in the output frequency could be detected above the measurement's resolution limit of approximately 150 MHz. Further investigation of a longer time interval of 24 h showed a mode-jump free output, though more precise measurements could not be done because of a large signal drift of 1.4 GHz,

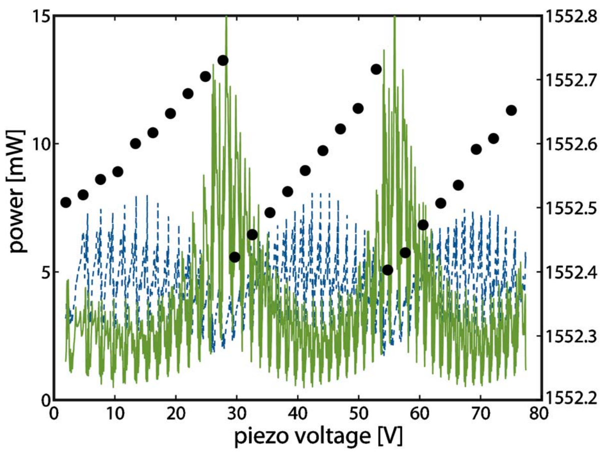

Fig. 3. (Color online) Coarse tuning, showing the output power from the Bragg grating (solid green curve) and surface reflection (dashed blue curve), as well as the corresponding wavelength (dots), as a function of the piezo voltage.

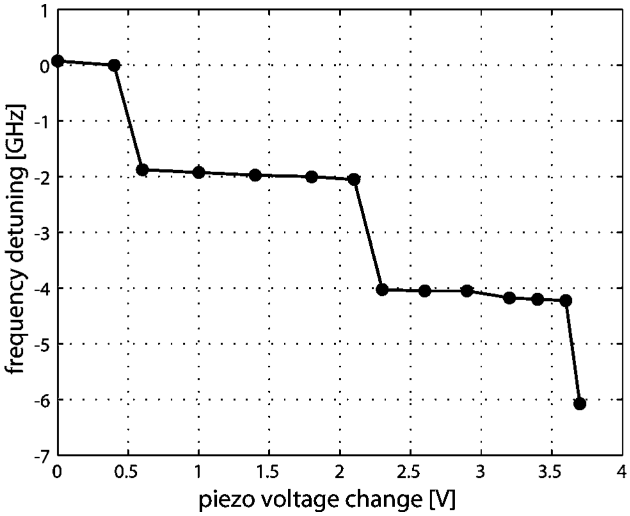

Fig. 4. Fine-tuning measured by a scanning Fabry–Perot interferometer.

which we believe is due to the scanning Fabry–Perot itself.

Going one step further toward higher resolution, the laser bandwidth was measured by a self-heterodyne detection scheme, built from single-mode fibers in a Mach–Zehnder configuration.[10] The fiber setup consisted of first an optical isolator followed by a 3 dB coupler, splitting the light into two arms. In one arm, the light was delayed by 130 μs in a 26 km long fiber followed by a polarization controller. In the other arm, the light was coupled out of the fiber and through an acousto-optic modulator, driven at 65 MHz, from which the first diffracted order was coupled back into the fiber. Finally, the light from the two arms was merged in another 3 dB coupler and measured by a 1 GHz InGaAs photodetector. The signal from the photodetector was analyzed in an electrical spectrum analyzer. The polarizations from the two arms were made to overlap on the detector by adjusting the polarization controller to get a maximal signal.

To develop a theoretical model for the self-heterodyne detection,[11] we assume that the mechanism causing the finite bandwidth of the laser can be modeled as phase fluctuations in the time-domain electric field of the laser, with a Gaussian distribution for the relative phase change during a time interval τ with a variance of $\Delta\omega\tau$. Then the time-domain autocorrelation function for the electric field falls off exponentially with a time constant $2/\Delta\omega$, corresponding to a frequency-domain Lorentzian with a FWHM linewidth $\Delta\omega$. By delaying the light in one of the arms longer than the coherence length of the laser, the interference at the detector can be made incoherent. The spectrum at the detector is then a convolution of the laser line by itself, resulting in a Lorentzian with twice the bandwidth, as confirmed by a detailed investigation.[11] Given the 130 μs delay, this model is valid for laser linewidths down to around 5 kHz. The extra frequency modulation from the acousto-optic modulator in one arm shifts the center of the spectrum to 65 MHz, a regime with a much better signal-to-noise ratio than the one around 0 Hz.

The measurement data obtained from the electrical spectrum analyzer had a signal-to-noise ratio of about 3 dB, for an instrument resolution of 3 kHz and a sweep time of 90 ms. By fitting the data to a Lorentzian, a laser linewidth of 90 kHz could be deduced. This linewidth was achieved both at the center of the Bragg peak as well as when tuned 0.1 nm off the peak.

In conclusion, we have demonstrated a single-mode ErYb:glass laser locked by a bulk glass Bragg grating, with a linewidth of 90 kHz. The laser wavelength is tunable over a range of 0.25 nm (31 GHz) around 1552.6 nm in steps of 17 pm (2.1 GHz), giving an output power of some milliwatts. Since we use just a few components the laser setup is very compact and simple, which gives good stability using only passive components. Given the tailorability of the Bragg grating used for locking and the demonstrated functionality for a low gain laser system such as ErYb, we believe that this technique should be applicable not only over the whole ErYb range from 1530 to 1560 nm, but for other laser systems as well.

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