Monolithic 100 mW Yb waveguide laser fabricated using the femtosecond-laser direct-write technique

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A femtosecond-laser-written monolithic waveguide laser (WGL) oscillator based on a distributed-feedback architecture and fabricated in ytterbium-doped phosphate glass is reported. The device was lased at 1033 nm with an output power of 102 mW and a bandwidth of less than 2 pm when bidirectionally pumped at 976 nm. The WGL device was stable and operated for 50 h without degradation. This demonstration of a high-performance WGL opens the possibility for creating a variety of narrow-linewidth laser designs in bulk glasses. © 2009 Optical Society of America


There is an ever-growing need for integrated optical devices for use in guided-wave applications such as communications and sensing. Technologies used for the fabrication of such devices include ion exchange [1] and vapor deposition [2]. A relatively new fabrication method is that of ultrafast laser direct writing [3] wherein a focused femtosecond laser pulse is used to induce permanent refractive index changes in dielectric media. The optical processes that create the refractive index change are highly nonlinear and cause the change to be localized at the focal point of the laser beam. Thus, by translating the material through the focus of a femtosecond laser beam, a pathway of refractive index change can be produced. In many glasses femtosecond laser irradiation results in an increase in refractive index and hence waveguiding, while in crystalline hosts such as YAG [4] and LiNbO3 [5], waveguiding can only be achieved through suppressed cladding arrangements or induced stress fields, as the index change is typically negative. By varying the writing geometry, the material, and femtosecond laser properties, 2D and 3D optical waveguide devices with different characteristics can be fabricated in the bulk of many transparent materials [6].

Ultrafast laser writing has been successfully applied to active materials resulting in the creation of waveguide amplifiers and waveguide lasers (WGLs) [4,7–10]. For example, a femtosecond-laser-encoded distributed-feedback (DFB) color-center laser was reported in a LiF crystal operating in a pulsed mode at 704 nm using an optical parametric oscillator as a pump [7]. However, the grating structure of this device was incoherent, the linewidth was significantly broader than that normally expected of DFB lasers, and no output powers were reported. More recently, bulk-glass WGL devices have been demonstrated using external-fiber Bragg gratings to complete a cavity around a rare-earth-doped waveguide amplifier [8,9]. This configuration is a bulk-glass waveguide analogue to a fiber laser and allows for efficient pumping with standard fiber pigtailed diode lasers. Output powers up to 80 mW with slope efficiencies of 21%, at 1.5 μm using Er–Yb codoped glass, have been reported [8].

To make a truly monolithic device, we previously reported on the fabrication of a C-band WGL constructed from a waveguide-Bragg grating (WBG) acting as a DFB resonator [10]. While being the first demonstration of a new class of laser, this device had a modest output power of the order of 1 mW and a low slope efficiency and only operated slightly above threshold, which made device characterization difficult. An alternative to the 1.5 μm Er–Yb [10] is the high gain Yb-only system operating around 1 μm. Trivalent Yb offers a lower quantum defect than Er, which reduces phonon-induced heating in the grating structure, thus lessening pump-induced thermal chirp of the WBG. In this Letter, we report a Yb WGL with a maximum single-end output power of 102 mW at 1032.59 nm. The pump power threshold was approximately 115 mW, and the optical efficiency was over 17%.

The femtosecond-laser direct-write technique was used to create the waveguide and the WBG simultaneously and in a single processing step. The laser used to fabricate this device was a 1 kHz repetition rate, 120 fs pulse length, 800 nm regeneratively amplified Ti:sapphire laser that was focused into the glass sample using a 20× microscope objective. The writing-laser beam was circularly polarized to minimize waveguide propagation losses [11] and focused at a depth of 170 μm below the surface of the substrate. The glass sample was translated at 25 μm/s through the focused writing beam that was 100% intensity modulated at approximately 75 Hz and with a 50:50 mark-space ratio to create the required 335 nm period refractive index perturbation that corresponded to a first-order WBG. This method of intensity modulation to create a WBG is similar to that reported in [12], and further details pertaining to device fabrication can be found in [10].

The substrate used was a “QX” phosphate glass host (Kigre Inc., USA) doped with 9% (by weight) ytterbium. The peak in absorption was at 974.5 nm, 0146-9592/09/030247-3/$15.00 © 2009 Optical Society of America
(absorption coefficient 10 cm⁻¹) and the material exhibited a gain bandwidth of approximately 80 nm centered around 1030 nm. The waveguides had a typical physical diameter of 8 μm and guided a single transverse mode with a 1/e² diameter of 13 μm. Refractive index profilometry (Rinck Electronik, measured at 633 nm) indicated the peak refractive index contrast of the waveguide was 1.4 × 10⁻³. Test WBGs written at 1535 nm (outside the absorption band of Yb) were used to provide an upper bound of the grating strength, resulting in a βkL of 2.1 for a WBG of length 9.5 mm. From this value, the refractive index change between the waveguide and the bulk material.

Pumping of the waveguide was achieved using single-mode optical fibers and wavelength division multiplexors (WDMs) to deliver a combined pump power of up to 726 mW at 976 nm. Laser output was collected from both ends of the WGL, as shown in Fig. 1. The position of the optical spectrum analyzer and power meter could be interchanged to compare the laser output from each end. To better match the 13 μm mode field diameter (MFD) of the WGL to the MFD of the pump–collection fibers, short sections of graded index optical fiber (GIF625) were fusion spliced to the fiber tips to act as mode field converters [13].

Initially, the prepared WBG length was 23.2 mm and, when bidirectionally pumped, each end was found to lase independently of the other, indicating that the sample length was longer than that suitable for the available double-end pump power. Pumping the WGL and collecting the laser light from a single end resulted in a pump threshold of 116 mW and a maximum output power of 38 mW (using a single-end pump power of 400 mW).

To enable effective double-end pumping the WBG was cut back to a length of 9.5 mm, thereby creating a device with an original facet on the left-hand side (LHS) and a new facet on the right-hand side (RHS). The single-end pump power thresholds and output powers of the original uncut sample and of the 9.5 mm WGL were nearly identical. This indicated that the effective single-end pumped laser length had not changed. For the short 9.5 mm device the forward propagating WGL power was 17 mW at the maximum single-end pump power. The reverse-propagating output power as a function of incident pump power for the 9.5 mm long WGL is shown in Fig. 2. The output power increased by up to 25% by reducing the bulk glass temperature to approximately 20°C below ambient, as shown in the inset of Fig. 2. The increased output power at this wavelength is characteristic of Yb in glass, which operates in the three-level regime with moderate ground-state thermal depopulation.

Using the maximum amount of available bidirectional pump power we obtained 102 mW of output at 1032.59 nm with a slope efficiency of 17.3% from the RHS laser facet. The output from the LHS of the WGL decreased from the single-end pumped value of 17 to 2 mW when dual-end pumped. Given that the WGL was designed to be symmetric, a simplistic interpretation of the device architecture would have equal powers emanating from each facet. However, small perturbations to the period and phase of the WGL were cut back to a length of 9.5 mm, thereby creating a device with an original facet on the left-hand side (LHS) and a new facet on the right-hand side (RHS). The single-end pump power thresholds and output powers of the original uncut sample and of the 9.5 mm WGL were nearly identical. This indicated that the effective single-end pumped laser length had not changed. For the short 9.5 mm device the forward propagating WGL power was 17 mW at the maximum single-end pump power. The reverse-propagating output power as a function of incident pump power for the 9.5 mm long WGL is shown in Fig. 2. The output power increased by up to 25% by reducing the bulk glass temperature to approximately 20°C below ambient, as shown in the inset of Fig. 2. The increased output power at this wavelength is characteristic of Yb in glass, which operates in the three-level regime with moderate ground-state thermal depopulation.

The output spectrum of the WGL operating at maximum input power is shown in Fig. 3. The shape of the laser spectrum was the same when viewed from either end. The WGL output spectrum is dominated by a single peak at 1032.59 nm and has a 3 dB full width that was limited by the 10 pm instrument resolution. Measurements of the WGL output on a scanning Michelson interferometer wavemeter indicated an upper bound of the linewidth of 2 pm. The side-mode suppression ratio of the WGL is at least 20 dB, and the laser output is accompanied by weak amplified spontaneous emission that falls within the estimated grating reflection bandwidth of 300 pm (the bandwidth of representative C-band WBGs writ-
The femtosecond laser direct-write technique enabled us to fabricate narrow-linewidth monolithic WGLs with arbitrary laser wavelengths. The WGLs typically operated on two degenerate polarization modes but could be restricted to a single-polarization mode through the use of polarized pump light. Given the flexibility of the femtosecond laser direct-write technique for creating WBGs on a per period basis (where each grating period can be individually specified in position), there exists the potential to further improve device performance and create novel DFB designs by tailoring the WBG to annul pump-induced thermal chirp or use sampled grating structures to create multiple laser output lines. Our investigations in this field are ongoing.

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References