# Ultrafast laser-written dual-wavelength waveguide laser

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We report the performance of a dual-wavelength waveguide laser based on a phase-modulated sampled-grating architecture fabricated using the femtosecond laser direct-write technique. The waveguide laser was written in Yb-doped phosphate glass and had a narrow linewidth (<10 pm), high signal-to-noise ratio (>60 dB), 5 mW output power per channel, and wavelength separation of 10 nm. © 2012 Optical Society of America

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The femtosecond laser direct-write technique has matured as a technology capable of producing high-quality photonic devices inside bulk transparent materials without the need for lithography and associated clean-room facilities [1–4]. Optical waveguide devices can be directly written into a transparent material simply by moving the sample through the focus of a femtosecond laser beam creating a pathway of refractive index modification induced via localized nonlinear light–matter interactions. With the use of high-resolution motion control stages, complete control of the position of each index modification that comprises a single fiber Bragg grating can be made. Furthermore, with the inclusion of discrete phase shifts, complex grating structures can be realized [5,6]. The use of such complex grating structures in rare-earth-doped bulk materials can lead to the realization of monolithic multiwavelength laser sources. Multiwavelength lasers are of particular interest for applications in terahertz generation, optical sensing, high-resolution spectroscopy, and wavelength division multiplexing (WDM) communication. To date, multiwavelength lasers have been realized in *optical fiber* using Bragg grating comb filters [7,8], four-wave mixing techniques [9], and complex distributed feedback (DFB) structures [10–15]. A dual-wavelength laser has also been reported in the *crystalline* material Nd:$YVO_4$ using a femtosecond-laser-written channel waveguide coupled with specifically designed external dielectric mirrors [16].

In this Letter, we present a phase-modulated sampled grating fabricated in *bulk glass* using the femtosecond laser direct-write technique. Additionally, we demonstrate, for the first time to our knowledge, a monolithic multiwavelength waveguide laser (WGL) centered around 1030 nm with approximately 5 mW output at each wavelength using this grating architecture.

The combination of waveguides and waveguide Bragg gratings (WBGs) written in active glasses form the basis of a stable, monolithic WGL platform. Previously we have demonstrated single-wavelength structures based on doped phosphate glasses; these allow laser operation near 1535 and 1030 nm and output powers in excess of 100 mW [17,18]. When designing multiple wavelength WGLs, it is important to know the available gain bandwidth and the minimum wavelength spacing of the laser lines. To explore the range of workable wavelengths (gain bandwidth), we wrote DFB grating structures in a 10 mm long Yb-doped (9% by weight) phosphate glass sample, ranging from the pump wavelength at 976 nm up to the Yb band edge at 1100 nm. The experimental setup for device fabrication is shown in Fig. 1. Further details pertaining to device fabrication can be found in [17,18]. Laser operation was possible at 985 nm, less than 10 nm away from the zero phonon line/pump wavelength, and up to 1075 nm (and up to 1085 nm using a 20 mm long sample). The output spectra from these lasers are shown superimposed in Fig. 2; each laser had an output power greater than 10 mW. The ability of the material to lase at 985 nm implies that, with the pump power available to us, we are pumping around 75% of the available Yb ions to inversion. With such high inversion ratios (hence high gain) and a gain bandwidth of approximately 100 nm, the simultaneous operation of multiple laser lines should be possible with an appropriate grating design.

DFB laser devices can be unidirectionally or double-end pumped with the laser power emitted from opposite facets, and the fraction of the total output, controlled by the position of a phase shift in the grating structure [19]. Our method of fabricating WBGs enables complete control of the position of each grating index perturbation such that the incorporation of phase shifts are easily achieved. An example of this level of control can be seen in Fig. 3 where a $\pi/2$ phase shift was inserted at the center of a 20 mm long WBG fabricated in Yb-doped phosphate glass at approximately 1545 nm, a wavelength far from any emission/absorption features of the glass. The characteristic peak in the transmission bandgap due to the phase shift is clearly seen. In order to achieve more

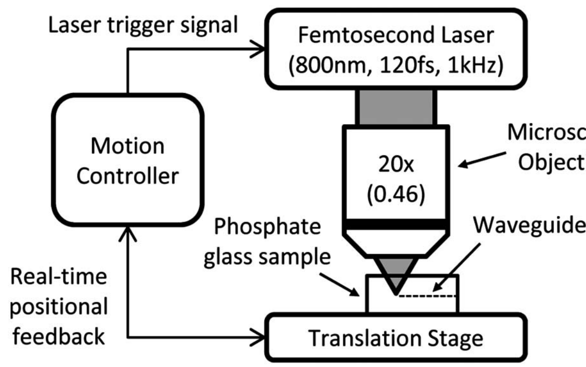


Fig. 1. Experimental setup for multiwavelength WGL fabrication.

 

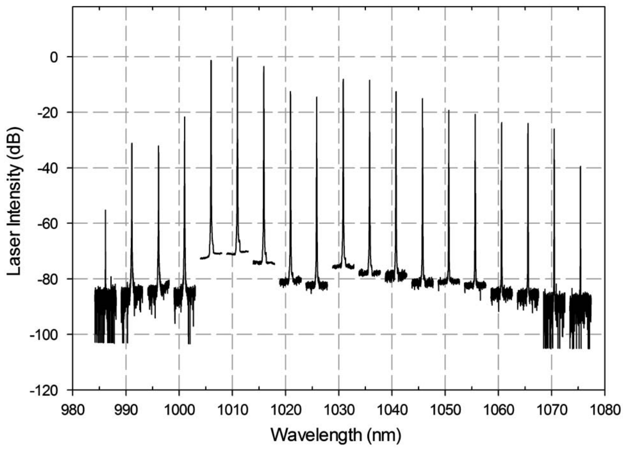


Fig. 2. Output spectra of multiple 10 mm long WGLs plotted on the same axes demonstrating a gain bandwidth of approximately 100 nm.

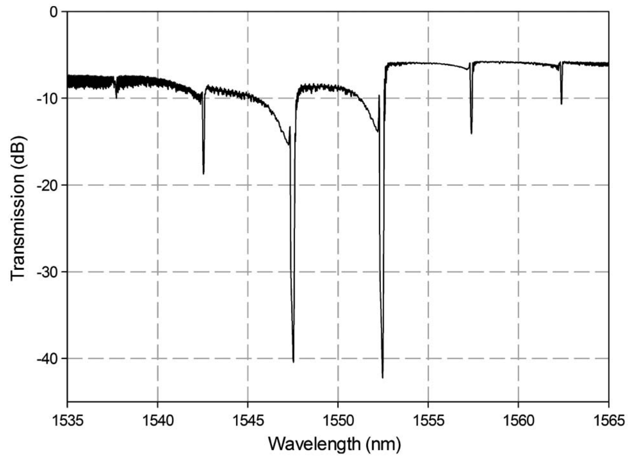


Fig. 4. Transmission spectrum of a $\pi/2$ phase-modulated sampled WBG fabricated in Yb-doped phosphate glass. The central Bragg resonance is suppressed while odd harmonic sideband resonances emerge. This complex grating structure was written in a single fabrication step without any postprocessing.

than one DFB laser line in such a grating, more phase shifts are required [14].

It is known that, in a periodically phase-modulated sampled grating, the fundamental Bragg resonance is suppressed and equally spaced sideband resonances in frequency emerge about the depleted Bragg resonance [5,20]. By inserting a $\pi/2$ phase shift at approximately every 300 Bragg periods (corresponding to a 5 nm first-order sideband spacing at 1550 nm), we fabricated a phase-modulated sampled grating in a 10 mm long Yb-doped phosphate glass sample centered about a Bragg resonance at 1550 nm. The transmission spectrum of the grating (Fig. 4) shows the odd harmonic sideband resonances decrease in strength extending symmetrically about the null center resonance.

When this type of grating is combined within a gain material, multiple laser lines may be resonant within the cavity; however, the $\pm 1$-order resonances will lase with a lower pump threshold because they have the strongest feedback. We fabricated a range of $\pi/2$ phase-modulated sampled WBGs in a 10 mm long Yb-doped phosphate glass around its gain peak at 1030 nm with different sideband resonance spacings. Using a bidirectional pumping scheme incorporating two 976 nm/1060 nm WDMs and 700 mW of available pump power, we obtained room-temperature dual-wavelength laser operation with separations ranging from 10 to 20 nm. An example output spectrum of such a dual-wavelength WGL at full pump power is shown in Fig. 5. This laser exhibited two lines spaced by 10 nm (3 THz at 1030 nm) and because of its symmetrical structure had approximately equal output powers of 5 mW per channel that were stable within 2 dB of each other. The 3 dB linewidths of the peaks were $<10$ pm, and the signal-to-noise ratios (SNRs) $>60$ dB. No polarization controllers/selective components were used in our laser cavity.

At wavelength separations $<10$ nm, only single-wavelength operation was obtained. We believe that this was due to the fact that, in our cavity design, the two cavity resonances have only partially separated spatial

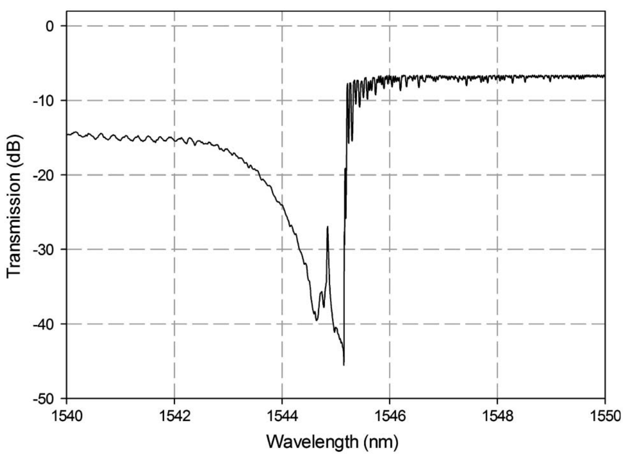


Fig. 3. Transmission spectrum of a 20 mm long WBG in Yb-doped phosphate glass with a $\pi/2$ phase shift spatially located in its center. The gradual decrease in transmission up to the Bragg resonance is indicative of the radiation modes of the grating in a geometry that has no well-defined cladding.

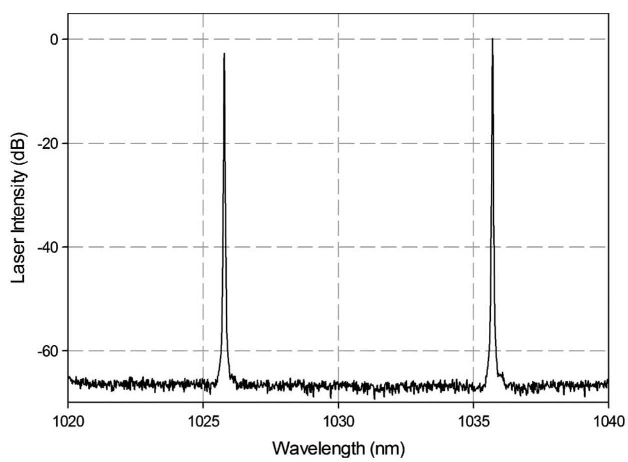


Fig. 5. Output spectrum, at full pump power, of a dual-wavelength laser fabricated in a 10 mm long Yb-doped phosphate glass using a $\pi/2$ phase-modulated sampled DFB WBG. The ordinate axis scale is referenced to the peak.

electric field distributions typical of DFB structures with a single phase change [19]. With the electric field maximizing around the phase change and each maxima separated by approximately 35 $\mu$m, there is insufficient space for dephasing between wavelengths separated less than 10 nm to occur. Hence, the two allowed laser lines share and therefore compete for the available gain. This is supported by the fact that we were able to select which of the two $<10$ nm spaced laser lines operated by adjusting the gap between the WGL chip and the coupling fibers. This gap formed a weak external Fabry–Perot cavity, which provided a small additional amount of wavelength-selective feedback to either laser line enabling it to preferentially lase. To enable operation without competition for gain between more closely spaced wavelengths, the spatial overlap between the electric fields of the laser's wavelength modes must be reduced, thereby forming effectively two separated cavities. This approach has been successfully used in fiber-based platforms that have used cavities with fewer phase shifts (with a minimum of two) to create dual-wavelength lasers with line separations down to 1 pm (in a 15 cm long cavity giving 50 $\mu$W output power) [14] and maximum output powers of 4 mW (in a 5.7 cm long cavity producing a laser line separation of 440 pm) [13]. In our ongoing work, we are investigating the application of similar cavity designs to realize compact and high-power dual-wavelength WGLs with wavelength separations equivalent to 1 THz ($\approx$3.5 nm at 1030 nm).

In summary, room-temperature dual-wavelength WGLs based on phase-modulated sampled-grating architectures fabricated in Yb-doped phosphate glass using the femtosecond laser direct-write technique were demonstrated. Narrow linewidths ($<10$ pm), high SNRs ($>60$ dB), and stable 5 mW output powers per channel were achieved with wavelength separations $\geq$10 nm. Presently strong mode competition within the host's homogeneously broadened gain bandwidth places a lower bound on the laser line separation. We believe that improvements can be made and that operation can be scaled to additional wavelengths using more complicated grating structures, and this area of study forms part of our ongoing work.

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