Mode-locked and single-longitudinal-mode waveguide lasers fabricated by femtosecond laser pulses in Er:Yb-doped phosphate glass

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Abstract: Mode-locked and single-longitudinal-mode waveguide lasers, manufactured by femtosecond laser writing in Er-Yb-doped phosphate glasses, are presented. Transform-limited 1.6-ps pulses and a cw output power exceeding 50 mW have been obtained in the two regimes.

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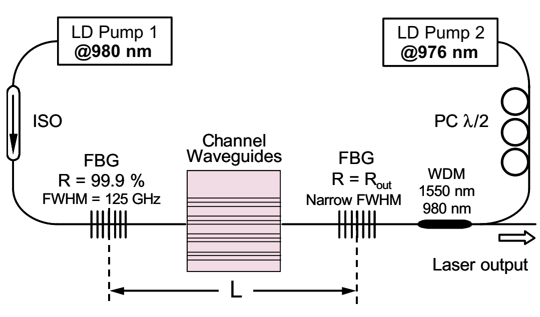
Direct writing by femtosecond laser pulses is an innovative technology for fabrication of optical waveguides in glasses [1]. It is a simple and low cost technique, that avoids photolithographic processes and allows 3D fabrication capabilities. In the last few years, the quality of femtosecond laser written waveguides has shown a substantial improvement. In particular, high quality active waveguides have been produced culminating in the demonstration of cw waveguide lasers on a commercial Er:Yb:phosphate glass (Kigre Inc., mod. QX) [2]. Recently, a great effort has been devoted to passive mode-locking of waveguide lasers, because of their inherent simplicity and compactness [3]. Such lasers will provide low-noise and inexpensive light sources for applications in optical communications, optically sampled analog-to-digital converters, and spectral line-by-line pulse shaping for arbitrary optical waveform synthesis. On the other hand, single-frequency lasers at 1.5 μm are essential tools for a variety of applications in spectroscopy, optical communications, and optical sensing with requirements that may become extremely demanding in terms of power, compactness, insensitivity to environmental disturbance, and high temporal coherence [4].

Here we report on the demonstration of advanced waveguide lasers, operating both in continuous wave and pulsed regimes, based on active waveguides fabricated by femtosecond laser pulses.

The substrate used is a phosphate glass doped with 2% wt of Er_2O_3 and 4% wt of Yb_2O_3. The writing system is based on a diode-pumped, cavity-dumped Yb:KYW oscillator at 1040 nm and the sample is translated by motorized stages in a direction perpendicular to the laser beam. A high numerical aperture objective (100x with oil-immersion) is used to focus the pulsed laser inside the glass substrate [2]. The set of writing parameters adopted to fabricate the waveguide is: 505 kHz repetition rate, 436 nJ energy per pulse and 100 μm/s writing speed. The waveguide coupling loss to standard telecom fibers is about 0.1 dB/facet, while propagation loss is below 0.4 dB/cm. With a pump power of 500 mW, a 3.5 dB/cm internal gain per unit length is demonstrated at 1535 nm.



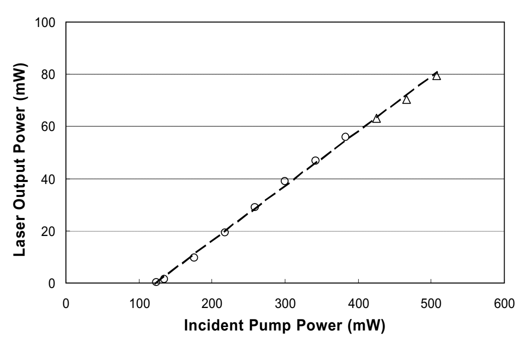


Fig.1. (a) Waveguide linear laser cavity. A bi-directional pumping scheme is adopted. Pump interaction is removed by means of an optical isolator (ISO) and a half-wave polarization controller (PC λ/2). (b) Input-output characteristic of the 5.5-cm long waveguide laser cavity. Single mode operation provides up to 55 mW output power (circles). A maximum output power of about 80 mW is achieved in a slightly multimodal regime (triangles).

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Using a 20-mm-long waveguide and optimized narrow bandwith fiber bragg gratings (67 pm FWHM, 57% output coupling) a very compact linear laser cavity of 6 cm length is realized (Fig.1a). Such a compact cavity results in a large FSR of 1.82 GHz thus consistently reducing the number of modes falling within the FWHM bandwidth of the FBG. The laser provides more than 50 mW in single longitudinal and transverse mode operation with 21% slope efficiency, and achieved 80 mW maximum output power in slightly multimodal regime (Fig.1b).

In a second experiment, by combining a 37-mm long waveguide and an innovative fiber-pigtailed saturable absorber, based on a carbon nanotubes film, a mode-locked laser in a ring cavity configuration is demonstrated. The laser provides transform limited 1.6-ps pulses with very low timing jitter at 16.7 MHz repetition rate.

Figure 2a shows a schematic of the mode-locked waveguide laser in a ring cavity configuration. Two 976-nm laser diodes, providing 500 mW total power, are coupled to the waveguide in a bi-propagating pumping scheme.

A broad-band fiber coupler is used to couple 5% of the intracavity radiation out of the ring resonator. The mode-locker is a single-wall CNTs-polymer film saturable absorber, packaged by sandwiching the film in the fiber-pigtailed FC/PC connector with index matching fluid at both fiber ends (see Fig.2a). Such film has high threshold for laser damage (more than 600 MW/cm^2) and a saturation intensity of about 80 MW/cm^2. A recovery time less than 1 ps was reported for CNTs-polymide composites.

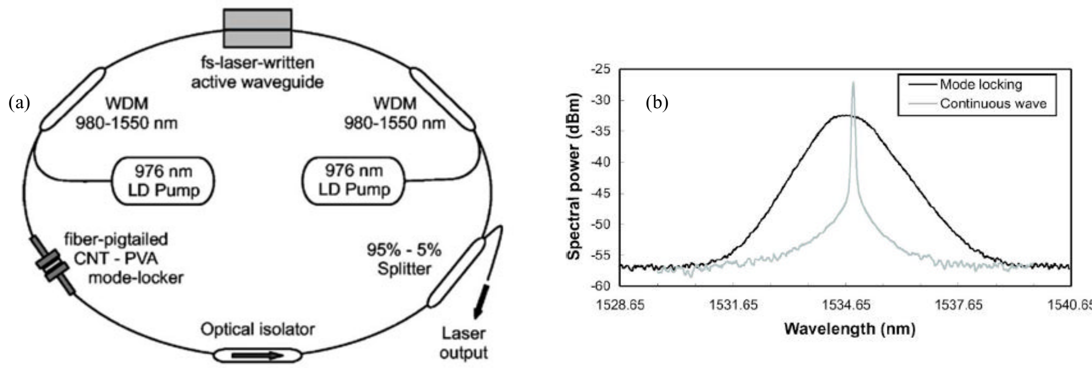

Fig.2. (a) Schematic set up of the ring laser cavity configuration. (b) Laser output spectrum in continuous wave and mode-locking regimes.

Continuous wave laser action starts at 450 mW incident pump power. Self-starting single-pulse stable mode-locking is observed just above laser threshold (Fig.2b). No self-Q-switching instabilities are observed and the mode-locking regime is stable for several hours. The laser output power is measured to be ~0.1 mW. Such a low value is due to the relatively high insertion losses along the ring cavity. The sech^2 pulse duration at the output of the laser is $\Delta\tau = 1.60$ ps, very close to the transform limit for the 1.6-nm spectrum observed.

In conclusion, we demonstrated a very compact and efficient waveguide laser at 1.5 µm, based on a femtosecond laser written waveguide, providing up to 55 mW maximum output power in single-longitudinal-mode and 1.6 ps pulses when passively mode-locked. Our work expands the capability of femtosecond laser writing towards manufacturing of complex photonic devices. These sources are promising candidates for several laser-based systems where single frequency or short pulse operation is required together with a reduced size.

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