Waveguide Lasers in Er:Yb-Doped Phosphate Glass Fabricated by Femtosecond Laser Writing

[1]Giuseppe Della Valle*, [1]Roberto Osellame, [1]Stefano Taccheo, [1]Nicola Chiodo, [1]Gianluca Galzerano
[1]Giulio Cerullo, [1]Paolo Laporta, [1]Roberta Ramponi, [2]Uwe Morgner, [3]Andrea C. Ferrari
[1]Department of Physics, Politecnico di Milano, and IFN-CNR Milan, P.zza L. da Vinci 32, 20133 Milano, Italy
Tel: (+39) 02 2399 6021, Fax: (+39) 02 2399 6126, e-mail: giuseppe.dellavalle@polimi.it
[2]Institut fur Quantenoptik - University of Hannover, Welfengarten 1, Hannover, Germany
[3]Engineering Department - Cambridge University, 9 JJ Thompson Avenue, Cambridge, UK

ABSTRACT
Advanced waveguide lasers, operating both in continuous wave and pulsed regimes, have been realized in an active phosphate glass by direct writing with femtosecond laser pulses. Stable single mode operation was obtained; the laser provided more than 50 mW in single longitudinal and transverse mode operation with 21% slope efficiency. Furthermore, by combining a high gain waveguide and an innovated fiber-pigtailed saturable absorber based on carbon nanotubes, a mode-locked ring laser providing transform limited 1.6 ps pulses was demonstrated.
Keywords: femtosecond laser written waveguides, single-mode laser, mode-locked laser, carbon nanotubes.

1. INTRODUCTION

An innovative technology for fabrication of optical waveguides is the direct writing by femtosecond laser pulses [1]. This is a simple and low cost technique, that avoids any photolithographic process and allows 3D fabrication.

In the last few years, the quality of femtosecond laser written waveguides has shown a substantial improvement, culminating in the demonstration of a cw waveguide laser [2] at 1.5 μm. The next challenge consist in the realization of advanced erbium-ytterbium waveguide lasers, providing efficient single frequency operation or stable ultra-short pulses, to be potentially employed in real applications.

Actually, single-frequency lasers at 1.5 μm are essential tools for a variety of applications in spectroscopy, optical communications, and optical sensing. In many cases, such as free space optical communications, laser radar, satellite based remote sensing, distribute fiber-optic sensors, and frequency domain reflectometry, the requirements may become extremely demanding in terms of power, compactness, insensitivity to environmental disturbance, and high temporal coherence. Waveguide lasers [3, 4] (as well as short fiber lasers [5]) are compact devices with monolithic structure which have the potentialities to satisfy all the requirements previously outlined.

Furthermore, a great effort has been recently devoted to passive mode-locking of waveguide lasers, because of their inherent simplicity and compactness with respect to fiber lasers [6]. Er-Yb-doped glass waveguides can in fact generate large gains over short lengths (2 – 4 dB/cm), thus allowing compact cavities and high repetition rate operation without the need of harmonic mode-locking with its associated instabilities. Such lasers will provide low-noise and inexpensive light sources for applications in optical communications, optically sampled analog-to-digital converters [7], and in spectral line-by-line pulse shaping for arbitrary optical waveform synthesis [8]. Classically, semiconductor saturable absorber mirrors are employed for passive mode-locking of lasers, but recently a new technology based on carbon nanotubes (CNTs) has emerged as an alternative for the realization of saturable absorbers. CNTs show strong saturable absorption with ultrafast recovery [9], polarization insensitivity, and high optical damage threshold [10].

In this paper we report on two advanced waveguide lasers manufactured by femtosecond laser writing in an erbium-ytterbium doped glass substrate: an ultra-compact and efficient waveguide laser operating in single longitudinal and transverse mode with more than 50~mW output power [11], and a pulsed waveguide laser operating in very stable passive mode-locking regime by means of an innovative saturable absorber based on carbon nanotubes [12].

2. SINGLE FREQUENCY WAVEGUIDE LASER

2.1 The linear waveguide laser cavity set-up

The waveguide laser cavity employs a linear configuration where the active waveguide is butt-coupled on both sides to fiber Bragg gratings (FBGs) fabricated in standard single-mode-telecom fibers (see Fig. 1). A broad-band flat top FBG with 1-nm bandwidth (FWHM) provides high reflectivity (99.8%) at one side, and a narrow-

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bandwidth FBG with about 0.1-nm FWHM is used as output coupler. An index-matching fluid able to support high power density at 980 nm is inserted between waveguide and fiber ends. Two fiber pigtailed InGaAs laser diodes with a bi-propagating pumping scheme supply up to 510 mW incident pump power (260 mW at 980 nm from pump 1 and 250 mW at 97 nm provided by pump 2) through 980/1550 nm wavelength-division-multiplexers (WDMs). In order to remove the parasitic interaction between the counter-propagating pumping beams, a single-stage optical isolator is connected to pump 1, and, in addition, a half-wave fiber polarization controller is inserted along the fiber connecting pump 2 to the waveguide. By rotating the axis of the polarization controller, the polarization of the counter propagating pumping beams is set orthogonal to each other, thus avoiding any interference which is detrimental for the pump efficiency. Following the method described in Ref. 14, a peak net gain of 5.7 dB at 1535 nm has been measured under maximum pump power available.

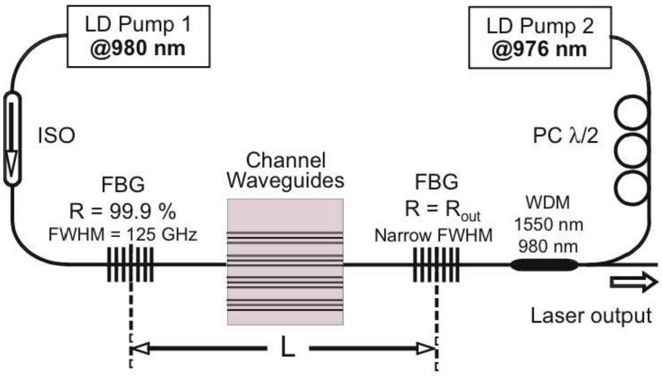

Figure 1. Waveguide linear laser cavity. A bi-directional pumping scheme is adopted. Pump interaction is removed by means of an optical isolator (ISO) and a half-wave polarization controller (PC λ/2).

2.2 Experimental results in single mode operation

In order to achieve single mode operation, the output coupler was a narrow bandwidth fiber Bragg grating and the cavity length was reduced by cutting the FBG fiber. Among the available fiber Bragg gratings, we selected the one providing the narrowest bandwidth and an output coupling as close as possible to the measured optimum value. Our choice was a 57% output coupler with 64 pm FWHM bandwidth (corresponding to about 8 GHz). After cutting the FBG fiber, a linear laser cavity of $L = 5.5$ cm length was obtained. 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. In this condition, single frequency operation was easily obtained by making one longitudinal mode coincident with the reflectivity peak of the output FBG, being all the adjacent modes suppressed by the frequency depending losses of the narrow bandwidth output coupler. Figure 2*a* shows the input-output characteristic of the laser cavity. The threshold pump power was 124 mW with 21% slope efficiency. To ascertain single mode operation we monitored the laser power spectrum by means of a scanning confocal Fabry-Perot interferometer (free spectral range of 8 GHz, finesse of 100, and 26 dB signal to noise ratio on the photodiode).

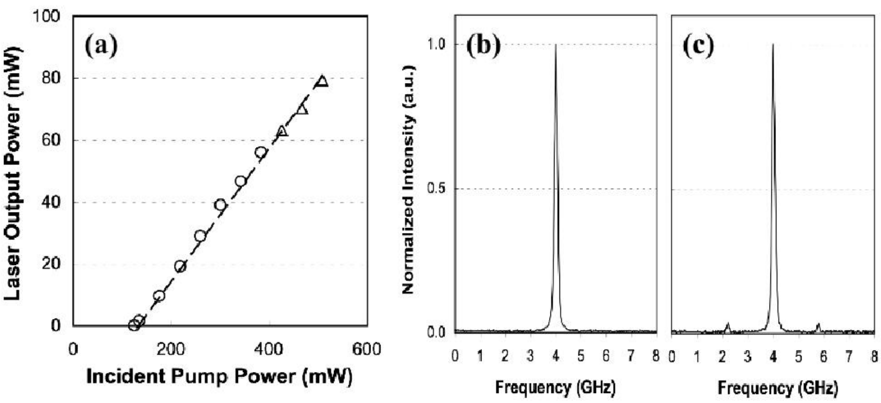

Figure 2. (a) Input-output characteristic of the 5.5-cm long waveguide laser cavity: single mode operation (circles); slightly multimodal regime (triangles). Fabry Perot spectrum (a) in SM operation at 55 mW output power and (c) in slightly multimodal regime at 80 mW output power.

Single mode operation was maintained till a maximum pump power level of 400 mW, corresponding to an output power of 55 mW (see Fig. 2*b*). At higher pump power a slightly multimodal regime appears, with weak side peaks 1.8 GHz apart from the central mode, thus corresponding to adjacent longitudinal modes (see Fig. 2*c*).

3. MODE-LOCKED WAVEGUIDE LASER

3.1 The mode-locked waveguide laser set-up

Figure 3 shows a schematic of the mode-locked waveguide laser in a ring cavity configuration. Two 976-nm laser diodes, providing 480 mW total incident power, are coupled to the 36-mm long active waveguide in a bi-propagating pumping scheme by means of wavelength division multiplexers (WDMs). Previous gain measurements on this sample performed at 1.5 μm showed net gain in the whole C-band, with 7.3-dB peak value at 1535 nm for an incident pump power of 460 mW. A broad-band fiber coupler is used to couple 5% of the intracavity radiation out of the resonator. Uni-directionality of the ring is imposed by an optical isolator, which also prevents mode-locking instabilities caused by back-reflections. 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. The CNTs, produced by laser ablation as described in [13], are then mixed with polyvinyl alcohol (PVA) and dried at room temperature to obtain a freestanding film with a thickness of 50 μm. The absorbance spectrum of the film has a broad band centered at 1.5 μm, with peak absorbance of about 0.36 (corresponding to 1.52 dB absorption, of which 0.6 dB are saturable). Such film has high laser damage threshold (more than 600 MW/cm^2) and a saturation intensity of about 80 MW/cm^2. Typical recovery times are lower than 1 ps.

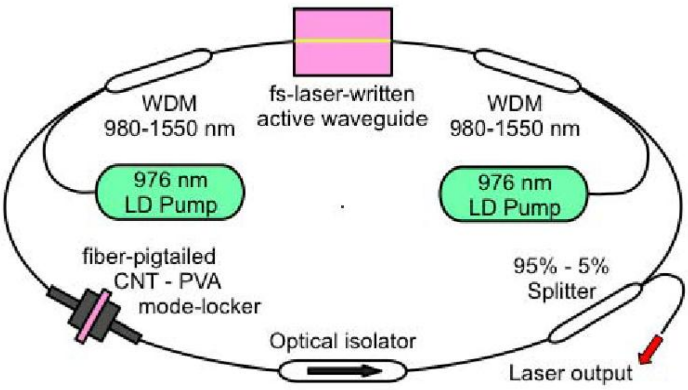

Figure 3. Schematic set up of the mode-locked ring laser cavity configuration.

3.2 Experimental results

Fig. 4*a* shows the laser output spectrum recorded with an optical spectrum analyzer. Continuous wave laser action starts at 450 mW incident pump power and self-starting single-pulse stable mode-locking is observed just above laser threshold.

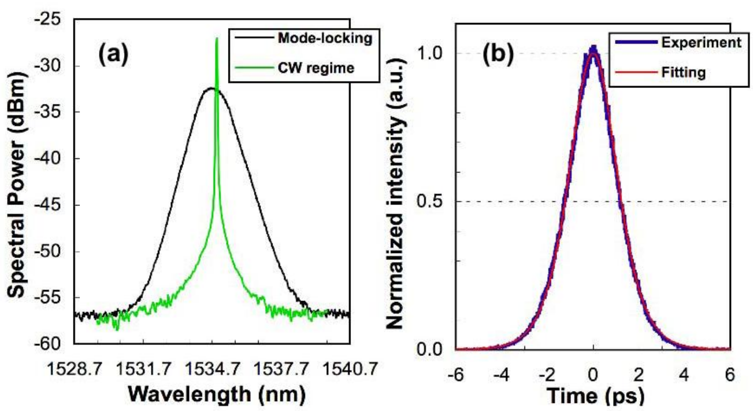

Figure 4. (a) Laser output spectrum in continuous wave and mode-locking regimes. (b) Autocorrelation trace of the mode-locking pulse.

The laser central wavelength in the mode-locking regime is 153 nm, with an oscillating bandwidth (at -3dB) of 1.6 nm. By means of an autocorrelator (see trace in Fig. 4*b*) the pulse duration was estimated to be about 1.6 ps, resulting in a time bandwidth product of 0.329, in fairly good agreement with the 0.315 value for transform limited $sech^2$ pulses. The repetition rate of this cavity was 16.7 MHz, but a much higher repetition rate can be obtained using a linear cavity where the saturable absorber is directly placed on the waveguide facet. As an example, according to the saturation intensity of the nanotube absorber, 1 GHz operation could be feasible with an intracavity average power of about 100 mW. Such a power level was already demonstrated in similar waveguide lasers operated in cw [14].

To investigate the stability of the pulse train we measured the radio-frequency spectrum of the pulses around the 8^{th} harmonic of the repetition rate (133.89 MHz) by means of a fast photodiode (250 MHz bandwidth) connected to an electrical spectrum analyzer. By following the von der Linde method [15], we estimated a low relative timing jitter $\Delta t/T = 10^{-4}$ in a bandwidth of 700 Hz, (being T the train period).

4. CONCLUSIONS

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 and transverse mode. This source is a promising candidate for several laser-based systems where high output power, single frequency operation and reduced size are simultaneously required. We also demonstrated passive mode-locking of a waveguide laser manufactured by direct femtosecond laser writing using a specially designed fiber-pigtailed CNT-PVA saturable absorber. Our work expands the capability of femtosecond laser writing towards manufacturing of complex photonic devices. An upgraded version of this technology, whereby a CNT absorber is incorporated into a monolithic laser structure, could provide very compact mode-locked laser sources with repetition rates in the 1 – 3 GHz range. Moreover, by reducing intracavity losses and optimizing dispersion, it should be possible to exploit the whole Er gain bandwidth and achieve femtosecond operation.

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