Single-pump high-power robust single-frequency waveguide lasers fabricated by ion-exchange techniques

S. Taccheo (1), G. Della Valle(1), A. Festa(1), K. Ennser(2), G. Sorbello(3), C.Cassagnettes(4) and D. Barbier(4)
(1): Dipartimento di Fisica Politecnico di Milano and CNISM, Italy, e-mail taccheo@polimi.it
(2): Institute of Advanced Telecommunications, Swansea University, Swansea UK
(3): DIIT, Università di Catania, Italy
(4): Teemphotonics, Grenoble, France

Abstract: *We report on a waveguide laser with output in excess of 20 mW in robust single-frequency operation. The active medium was only 9-mm long. The cavity length was <60 mm including butt-coupled fiber-Bragg-grating mirrors Conditions for robust single-frequency opeeration and power scaling to 100 mW are discussed. Preliminary experiments are performed using longer waveguides.*

Introduction

Single-frequency lasers at 1.5 µm are key elements for applications to several fields such as spectroscopy and optical sensing. In many cases, such as free space optical communications [1], laser radar and satellite based remote sensing [2], distribute fiber-optic sensors [3], and frequency domain reflectometry [4], device specifications may become very demanding in terms of power, compactness, insensitivity to environmental disturbance and high temporal coherence. Bulk laser cavities may exploit large modal volumes and are able to provide high output powers. However are generally quite sensitive to technical noise and are not compact devices, despite recently compact large-mode area laser were proposed [5]. On the contrary, short fiber lasers [6] and, in particular, waveguide lasers [7,8] are compact devices with monolithic structures which have the potentialities to satisfy all the requirements previously outlined. However, looking at the literature up to now only few mW output level waveguide laser were demonstrated except few tens of mW power level using Th:Sapphire pumping and large waveguide area [7] or few tens of mW in a not-stable single-frequency cabity were mode-hopping occourred [9].

In order to meet the demand of high-power highly-doped materials are required in order to keep the device length at around a few cm to allow a simple linear cavity structure with large free-spectral range. This requirement make not suitable glass-on-silicon technology. In fact in this case the Erbium concentration is usually limited to avoid quenching effects [10], while other glasses may offer better solubility. In particular phosphate glass offers a far better solubility and efficient codoping with Yb thanks to high phonon energy that optimize energy transfer process [2] and therefore the pump efficiency. The use of Yb is also the key element for high pump absorption over short length. Among several methods to fabricate an active waveguide in a phosphate glass base the most reliable and of highest quality is the ion-exchange techniques [11].

In this paper we demonstrate that optimized laser configuration can produce more than 20 mW robust single-frequency output power by using an Er:Yb-doped phosphate glass waveguide only 9-mm long, corresponding to more that 22 mW/cm. The cavity was formed by two butt coupled fiber-Bragg grating (FBG) mirrors. We also found that single-frequency operation can be obtained by using cavity lengths of up to 60 mm that is, in our opinion, an upper limit value. We believe that 50 mm active waveguides could provide up to 100 mW output power and we report prelimary test. Cavity shortening using integrated mirrors is also discussed.

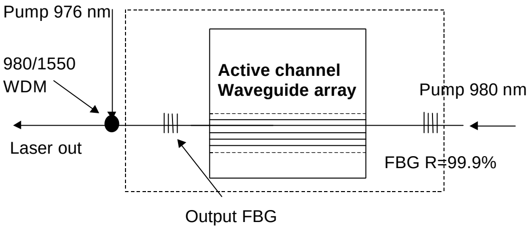

Fig.1: Waveguide laser set-up

Waveguide fabrication and laser set-up.

The ion-exchange method that is a reliable, rugged and low cost technique and was already demonstrated both using Ag-Na [11,12] and K-Na [7]. We used a two-step fabrication technique and a commercial Schott IOG-1 phosphate glass base with Er and Yb concentration of 3.5 10^{20} and 2.6 10^{20} ions/cm^3, respectively. In the first fabrication step the substrate was immersed in fused salts at 330°C for 8 minutes and the Ag concentration was adjusted to produce a maximum refractive index change of 0.02 [13] to ensure single transverse mode operation. In order to reduce the waveguide propagation loss and coupling loss to circular waveguides a second burial step was performed. We obtained a circular mode-field profile compatible with standard SMF-28 telecom fiber. In total we fabricated a linear array consisting of sixteen 250-µm spaced buried channel waveguides. Fig.1 shows the laser cavity set-up. Two FBGs were butt-coupled to the waveguide by using a suitable index matching fluid. Pump diodes providing up to about 250 mW pump power at 980-nm wavelength were available.

Laser experiment

We first made a set of measurements to evaluate the optimum output coupling. To ensure robust single-frequency opeartion we used a 9-mm waveguide. Figure 2 shows the slope efficiency, pump power threshold and output power for several FBG output couplers centered at 1533 nm and with different reflectivities. The high-reflective FBG was R=99.8% and 125-GHz reflectivity bandwidth (FWHM). During the test the cavity length was of the order of 1 m and the laser was therefore not operating in single-frequency. However the laser bandwith was of few GHz, as defined by FBG transmission spectrum, and only few modes were oscillating within about 1.5 GHz bandwidth. Note that in all cased we used a 976 nm pump diode to enhance absorption by matching the Yb absorption peak.

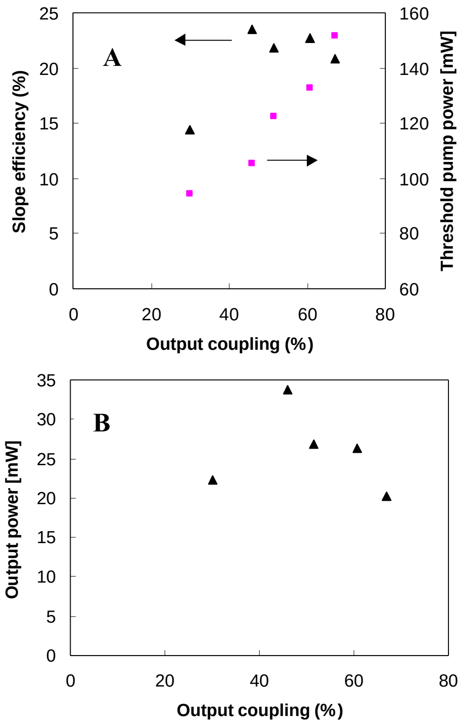

Fig.2: A: slope efficiency (traingles) and pump power threshold (diamonds) vs. output coupling. B: maximum output power. Maximum pump power was 270 mW obtained with 976-nm pump diode.

From Fig.2 the FBG with 54% reflectivity (46% output coupling) gave the best results. However a second consideration is the FBG FWHM. We therefore preferred to use the R=48% FBG because it was narrower with FWHM of about 80 pm (10 GHz) against 100 pm (12.5 GHz) of the R=54% FBG. Once cavity design was defined we made a short cavity by almost butt-coupling the two FBGs to the waveguide. We estimated an overall cavity length of about 55 mm. The 9-mm active material was placed asymmetrically in order to suppress longitudinal mode competition due to spatial-hole burning.

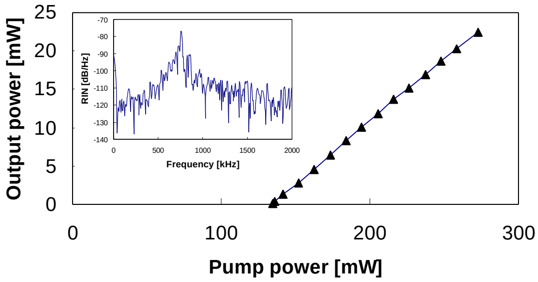

Fig.3: Single-frequency output power. Inset shows RIN spectrum

Figure 3 shows the output power characteristics. We noticed a remarkably stable single-frequency operation at all pump power, even in absence of thermal stabilization. Figure 4 shows the single frequency operation recorde by an high-finesse Fabry-Perot interferometer. This means that 60-mm long cavity ensures only one longitudinal mode can oscillate. Inset shows the relative intensity noise spectrum we measured. The relatively high peak value is due to discrete component cavity. We plan now to bond the two FBG to the waveguide in order to obtain a monolithic structure. Result will be presented at the conference. The final results of 22 mW output power with 17% slope efficiency is quite remarkable and gives a figure of 24 mW/cm as output power per unit length of active waveguide. To the best of our knowledge is the highest output power ever reported for robust single-frequency operation and single-pump scheme. The further work is to evaluate if we can have same figure of merit over a 50 mm waveguide in order to achieve 100 mW output power.

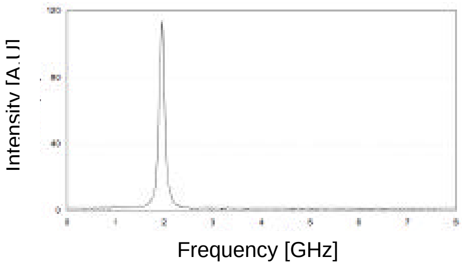

Fig.4: Single-frequency spectrum. Offset shows drift without mode hopping.

Power scaling

Based on the previous results we evaluate power scaling towards 100-mW power level. We observed that 55-mm long cavity was able to ensure stable single-frequency operation without mode-hopping. This means that probably a laser with 40-mm to 50-mm active material is still suitable for single-frequency operation. Once spatial-hole burning is removed by and very narrow FBGs are used. To evaluate power scaling we made a second waveguide using same active material but 45-mm long. Figure 5 shows the waveguide. We need to use two pump diodes (at 976 nm and at 980 nm) and probably the pump wavelength of 976 nm was not the best solution for such a long waveguide having too short absorption length. The overall test cavity was now long about 1 m. Figure 6 shows the set-up. Still we obtained useful insights. Figure 7 shows results of output power versus pump power. We tested several FBG reflectivity and using 21.5% reflectivity we obtained 164 mW output power with 500 mW pump power. In this case the single-frequency operation was quite unstable and usually at least two modes were oscillating so data refer to multi-longitudinal mode operation.

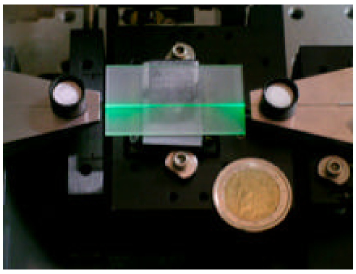

Fig. 5: 45-mm long waveguide.

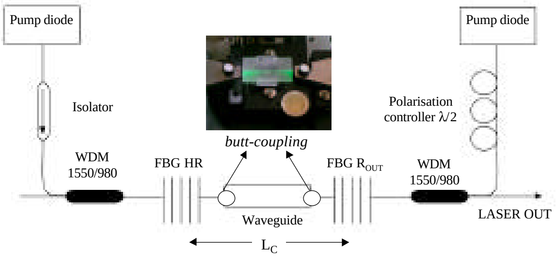

Fig. 6: Set-up for 45-mm long waveguide.laser

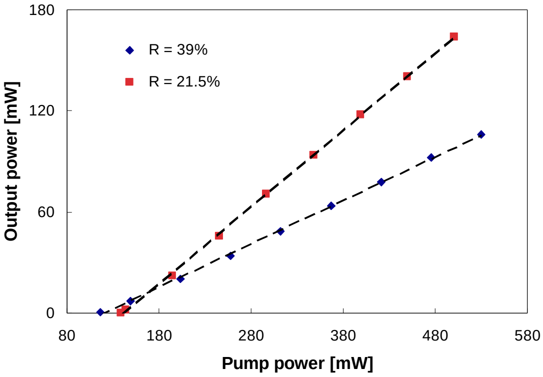

Fig.7: Output power vs. pump power for 45-mm long waveguide

Nevertheless if we now consider the figure of merit defined as output power/active material length at 270 mW pump power we obtain about 15 mW/cm. The lower value compared with 9-mm long waveguide is due to not optimized pump wavelength. In addition our longer waveguide needed for a two-pump scheme that is not suitable for compact devices. To evaluate sinlge-pump longer waveguide we test a 50-mm long waveguide made by Teemphotonics by ion exchange. The waveguide was optimised for single-pump scheme and has Er and Yb concentration of 2% and 4% respectively.

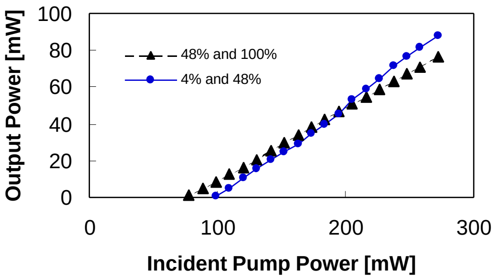

Fig.8: Output power vs. pump power for 50-mm long waveguide

Figure 8 shows the output power we obtained with preliminary measurements. We used the narrow 48% FBG and as second mirror both 100% 125-GHz FWHM mirror end 4% Fresnel reflection from glass/air inferface. Despite the non-optimised coupling we obtained over 80 mW in almost single-frequency operation. In the case of 4% coupler the cavity was 10-cm long but still only one longitudinal mode oscillates carrying over 85% of total power. Residual power was due to transverse mode oscillation. Slight mode-hopping also occured due to long cavity. We believe that use of single transverse mode cavity and a shorter cavity will allow to chieve the 100-mW output power level cavity. A single-transverse mode waveguide is under development -

A further step towards compact cavity is the integration of grating mirrors into the waveguide structures. Surface pattern by mask litography or by laser irradiation [14] could achieve the desired results and test are planned.

As last investigation we evaluated possible competition by glass on silicon technology for waveguide laser. We evaluated the figure of merit of a silica fiber with 0.6% Erbium concentration (no Yb codoping) that reasonably simulates performance of glass-on-silicon waveguide devices. We obtained about 2 mW/cm in multi-longitudinal mode operation with 15 mW from a laser using a 7 cm length active fiber. We believe that probably no more that 3 mW/cm in single-frequency operation can be achieved even considering to double the doping concentration. Waveguide laser based on glass on silicon technology will need to improve Er solubility in glass host to compite with phosphate glasses.

Conclusions

We reported on a stable single-frequency operation waveguide laser able to provide more than 20 mW output power using only 9-mm long active element. We also evaluated that output power scaling to 100 mW is achievable using phosphate glasses while silica glass, and therefore glass on silicon waveguide technology, will probably not able to reach same performance. We therefore conclude tha ion-exchange technique is a promising solution to achieve 100-mW output power out of a waveguide lasers.

Acknowledgments
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