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Yb,Er:glass Microlaser at 1.5 µm for optical fibre sensing: development, characterization and noise reduction

Alexey Pniov[1], Andrey Zhirnov[1], Dmitriy Shelestov[1], Konstantin Stepanov[1], Evgeny Nesterov[1], Valery Karasik[1], Paolo Laporta[2], Gianluca Galzerano[3], Stefano Taccheo[4], Luigi Piroddi[5], Michele Norgia[5], Alessandro Pesatori[5], Cesare Svelto[5]

[1]Bauman Moscow State Technical University (BMSTU)- Centre for Photonics and Infrared Technology, 2-ya Baumanskaya ul. 5, 105005 Moscow, Russian Federation
[2]Politecnico di Milano (POLIMI) – DFIS-POLIMI, piazza Leonardo da Vinci 33, 20133 Milan, Italy
[3]National Research Council CNR-IFN, piazza Leonardo da Vinci 33, 20133 Milan, Italy
[4]Swansea University, Singleton Park, SA2 8PP Swansea, Wales, UK
[5]Politecnico di Milano (POLIMI) – DEIB-POLIMI, via Ponzio 34/5, 20133 Milan, Italy

ABSTRACT
A fiber-pumped single-frequency microchip erbium laser was developed and characterized with the aim of using it in coherent Optical Time Domain Reflectometry (OTDR) measurements and sensing. The laser is pumped by a fiber-coupled 976 nm laser diode and provides 8 mW TEM_{00} single-frequency output power at 1.54 µm wavelength, suitable for efficient coupling to optical fibers. The amplitude and phase noise of this 200 THz oscillator were experimentally investigated and a Relative Intensity Noise (RIN) control loop was developed providing 27 dB RIN peak reduction at the relaxation oscillation frequency of 800 kHz.

Section: RESEARCH PAPER

Keywords: optical fiber sensing; erbium; solid-state laser; amplitude noise; stabilization

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Corresponding author: Cesare Svelto, e-mail: cesare.svelto@polimi.it

1. INTRODUCTION

Single-frequency low-noise laser sources operating around 1.5 µm wavelength [1]-[3] find several applications in optical fibre telecommunications, eye safe measurements, optical fibre sensors, remote monitoring and diagnostic over distributed measurement areas, precision measurements, *etc.*. The quality of analogue optical systems [4] is significantly affected by the instability of the laser source in terms of its amplitude and phase/frequency noise [5]. In particular, for Coherent OTDR (C-OTDR) [6], [7], a very low phase noise [8] in the time interval relevant to the measurement is extremely important as well as low laser intensity noise [9], [10] in the measurement bandwidth.

The aim of this work is to develop and characterize novel compact and single-frequency solid state lasers, operating in the spectral region from 1.53 µm to 1.56 µm, with very low noise characteristics and suitable for fibre measurements, in particular for C-OTDR remote-sensing applications. Within the framework of an international cooperation between BMSTU and POLIMI, a fibre-pumped evolution of the Yb,Er:glass microchip laser [11] was recently developed and characterized, as discussed in the following. Compared to previous research on the Yb,Er:glass microchip laser [12], this is the first time that the monolithic glass chip is end-pumped by perfectly circular, single-transverse- and single-longitudinal-mode, 976 nm pump radiation from a fibre-coupled DFB pump laser diode. This allows the best mode-matching with the erbium TEM_{00} laser mode within the Yb,Er:glass microchip and less pump-induced amplitude and phase/frequency noise of the erbium laser. The laser intensity noise and wavelength stability were measured for the first time since not previously available for the microchip laser in the literature. Also, active amplitude noise suppression for the microchip laser was never achieved before and now this monolithic 1.5 µm source reached a RIN level at or below -100 dB/Hz at any Fourier frequencies.

Section 2 describes the microlaser system and its properties. Section 3 provides the laser basic characterization in terms of output power and single mode operation. In Section 4 results of the experimental characterization regarding amplitude and frequency noise are presented. Section 5 discloses recent achievements in active amplitude noise reduction by an optoelectronic control loop providing significant noise suppression at the laser relaxation oscillation frequency. In the Conclusion, after summarizing the main results, future perspectives and next steps of this work are discussed.

2. THE LASER SYSTEM

The erbium microchip laser set-up is shown in Figure 1. The laser active medium [11] is a phosphate glass, doped with Er^{3+} ions at 1.5×10^{20} ions/cm^3 and co-doped with Yb^{3+} ions at 2×10^{21} ions/cm^3, to provide for short-length pump absorption at 976 nm and allow efficient energy transfer to the lasing erbium ions. The laser emits at 1.5 µm wavelength in a quasi-three level laser scheme [13] and the active medium is cut as a thin-disk microchip with a few millimetres diameter and approximately 200 µm thickness. The monolithic microchip structure [12], obtained with multi-dielectric coating on the input and output surfaces of the chip, allows having an optical resonator coincident with the active medium itself. This short cavity length gives wide longitudinal mode separation and hence allows for single mode oscillation at the erbium peak emission wavelength. The two facets of the laser disk are multi-dielectric coated to provide for the required dichroic reflectivities at both pump and laser wavelengths. The mirror at the input facet, in fact, is coated for high transmission (T_P>95 %) at the pump wavelength of 976 nm and for broadband ultra-high reflectivity (R_1>99.9 %) at around 1.54 µm. The output mirror, instead, provides for a high reflectivity at the pump wavelength (R_P>90 % at 976 nm) and laser output coupling of 2 % (R_2=98 % broadband at 1.54 µm). Laser material gain and coupling losses were calculated to support emission at the Erbium peak emission wavelength so to reduce adjacent-mode competition.

The pump source is a fibre coupled InGaAs semiconductor laser coupled to a single mode optical fibre, with available output power up to 250 mW at the temperature tuned central wavelength of 976 nm. Out of the fibre, the pump beam is passed through a simple telescopic system made of two lenses (see Figure 1) to provide for a pump beam waist diameter of ~50 µm within the active medium. In this way, efficient mode matching with the TEM_{00} fundamental laser mode as well as double-pass pumping along the microchip thickness is achieved. Such microlaser can demonstrate good slope efficiency (in the order of 10 %) and low pump threshold (~30 mW to 50 mW).

The proposed microlaser setup requires minimum number of adjustments and once produced is quite easy to repeat, promising for significant cost reduction in industrial manufacturing of such laser sources. Considering the reduced number of laser components and their costs (pump LD, two lenses, and the microchip active medium), the final cost in a mass production will be limited by the fibre coupled pump diode, which however is an already well developed commercial product. The final goal is to achieve a complete microlaser cost in the order of 500 USD, for a single-frequency and low-noise solid-state compact laser operating at 1.5 µm wavelength.

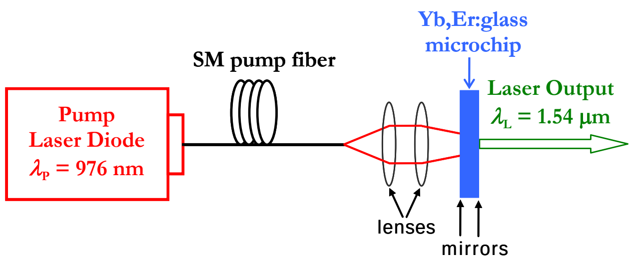

Figure 1. Set-up of fiber-pumped Yb,Er:glass microchip laser.

3. MICROLASER CHARACTERIZATION

The output power from the erbium microlaser was measured using a calibrated optical power meter, with InGaAs detector, commercially available from OPHIR (mod. Vega). A silicon plate long-wave-pass filter was placed before the power meter, in order to remove the residual component of the pump radiation exiting the microlaser cavity from the output mirror (with transmission 10 % at 976 nm and residual pump power levels in the range of a few milliwatts). In this way a correct, or even underestimated, measurement of the erbium laser optical power was taken as a function of the input pump power. The measured points are shown in Figure 2 and from these one can get a very low laser threshold P_{th}=32.7 mW and a differential slope efficiency η=9.7 %.

Single transverse mode operation was verified by the transverse profile and divergence of the laser beam (resulting in a pure TEM_{00} Gaussian mode with quality factor M^2<1.1). Single longitudinal mode operation was observed on the optical spectrum of the laser radiation (see Figure 3), showing a single peak at λ=1534.14 nm with two adjacent longitudinal modes at −60 dB from the oscillating single mode power level. The longitudinal mode spacing of 3.2 nm is consistent with the microchip thickness of ~240 µm. Raising the incident pump power above 120 mW, additional longitudinal modes can start

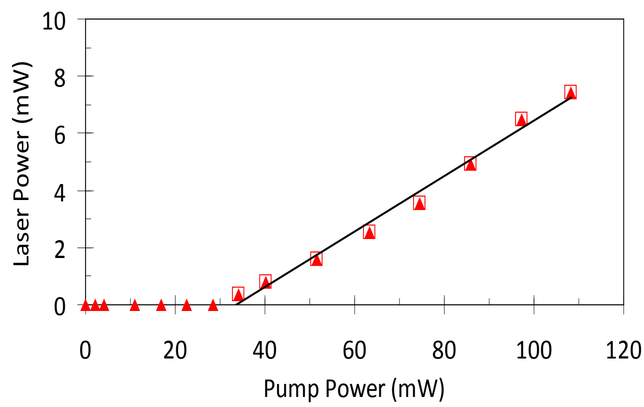

Figure 2. Measured input output laser behaviour with a linear regression of the data points above threshold showing the laser threshold and slope efficiency in single-mode operation.

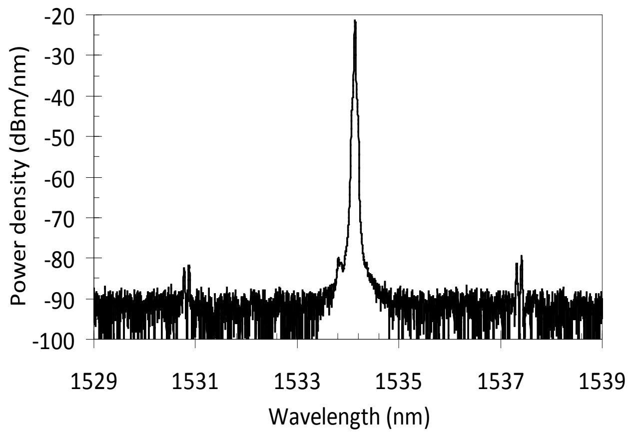

Figure 3. Measured optical spectrum of the erbium microchip laser.

lasing with significant power and for now the maximum single mode output power is below 10 mW. The power level, however, is not a critical issue since a few milliwatts are more than enough for most optical- fibre applications.

4. AMPLITUDE AND FREQUENCY NOISE MEASUREMENTS

The amplitude noise (Relative Intensity Noise, RIN) of the pump diode is shown in Figure 4. The measured noise level, relative to the average optical power, was at −75 dB/Hz from DC up to 100 kHz with a roll off at −20 dB/decade for higher Fourier frequencies. Some residual technical noise at the power supply frequency (50 Hz and harmonics) is observable in the low-frequency part of the noise spectrum, but peak values are quite low and they could be eliminated by battery supplying the LD current driver. Due to the high divergence of the pump beam at the fibre tip (NA=0.22) - which implies negligible back reflections from the lenses - and due to the high transmission at pump wavelength of the first microchip facet, the effects of back reflections into the LD are small and can be made negligible by slightly tilting the flat input facet of the active medium. Therefore, no optical isolation in the pump path is used, saving additional and costly components.

The amplitude noise of the erbium microchip laser was characterized in terms of its RIN in the spectral region from DC to 10 MHz (see Figure 5), since this is the typical frequency band where fibre sensors and C-OTDR systems perform their measurements. The relaxation oscillation peak occurs at a relatively high frequency, of about 2 MHz, due to the short laser cavity. The measured peak value is at −70 dB/Hz, relative to the carrier power, and outside of the spectral region of

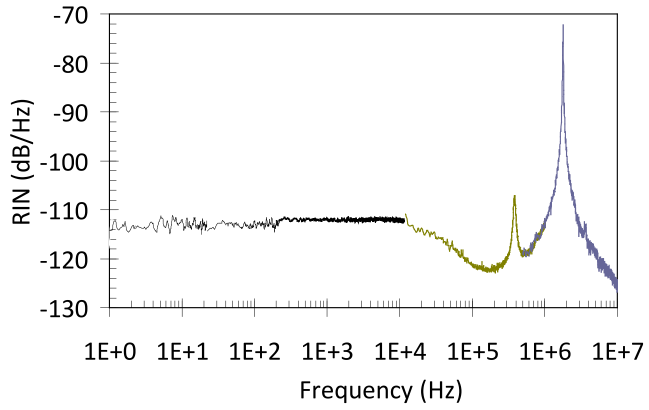

Figure 5. RIN spectral density for the Yb-Er:glass single-mode laser.

relaxation oscillations, RIN is below −110 dB/Hz. Form this amplitude noise figure, it is clear that to improve the amplitude stability of this microlaser it is primarily important to reduce the RIN peak level, being this peak (40 dB above the floor level) the main contribution to the laser amplitude noise.

Frequency and wavelength stability of the microlaser was characterized by a precision wavelength meter (Ångstrom Wavelength Meter, model WSU2), recording wavelength deviations over time. Figure 6 plots the laser wavelength values over a time interval of 10 minutes, with a sampling period of 110 ms. The average laser wavelength was λ=1534.8576 nm with a standard deviation σ_λ=0.06 pm over the observed 5 500 samples taken in the 10 minutes time interval. The relative wavelength or frequency stability was $\sigma_\lambda/\lambda=\sigma_\nu/\nu=5\times10^{-8}$ *i.e.* 50 parts per billion. This result was achieved working in standard laboratory environment with no active temperature stabilization of the laser set up neither of the laboratory. On longer time records the short- and medium-term frequency stability remains the same whereas long-term frequency drifts become observable. Form this frequency noise figure, it is clear that the monolithic microchip laser is inherently short- and medium-term frequency stable and only to improve its long-term frequency stability temperature control/stabilization becomes important. For C-OTDR measurements, the interrogation time of the optical fibre is below a few seconds and the temperature effects are negligible, over such time intervals. Therefore, no need for laser or ambient temperature stabilization is needed.

5. AMPLITUDE NOISE REDUCTION

Considering the significant amplitude noise at around the relaxation oscillation frequency (see Figure 5), an optoelectronic

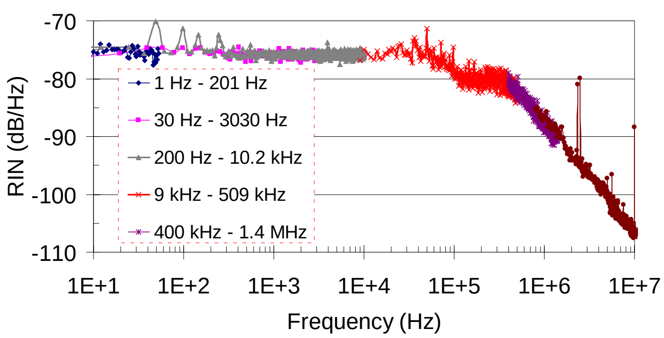

Figure 4. RIN spectral density for the pump laser.

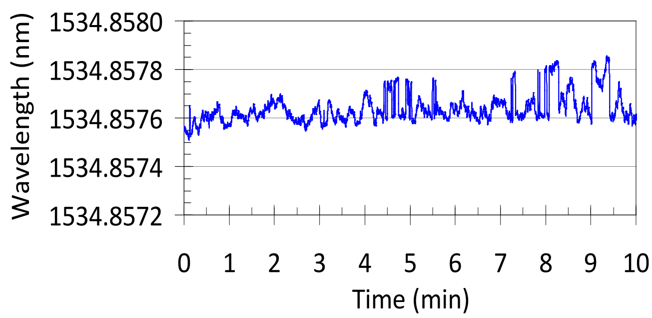

Figure 6. Laser wavelength stability over 10 minutes.

control loop was designed in order to reduce the RIN peak. Experiments of amplitude noise suppression in diode-pumped solid-state lasers in the near-infrared region were performed by different groups using Nd:YAG [14]-[16], Nd:YLF [17], Yb,Er:glass [18]-[20], and Ho,Tm:YAG [21] active media. In all cases a fraction of the laser output power is photodetected and converted into an electrical signal whose fluctuations are negatively fed back to the pump diode driver thus reducing the solid-state laser original amplitude fluctuation. One significant difference between our Yb,Er:glass microchip laser and other microlasers is the much shorter optical length of the resonator, being ~300 μm for our microchip and some 10 mm to 30 mm in the other experiments. This shorter laser cavity length implies a RIN peak located at higher Fourier frequencies [22], where typically it is more difficult to achieve efficient amplitude noise suppression. In the experiments found in the literature, the RIN peak frequency could range from 50 kHz to 500 kHz, whereas in our microchip laser it can be as high as 2 MHz at high pump power levels and operating the laser well above threshold condition. In order to simplify the stabilization loop it can be useful to reduce the RIN peak frequency.

The experimental setup for the amplitude-noise-reduction control loop, used for the first time with the erbium microchip laser, is depicted in Figure 7. A small fraction of the NIR laser radiation is detected with a fast (125 MHz bandwidth) and high-gain (40 V/mA) commercial low-noise InGaAs/PIN photoreceiver (New-Focus, Mod. 1811-FS). The photodiode has an optical-to-electrical responsivity of ~1 A/W at 1.54 μm wavelength and keeps linear operation up to 100 μW of input optical power incident on the 0.3 mm diameter semiconductor surface. Therefore, the maximum input DC optical power is 0.1 mW corresponding to an output voltage of ~4 V in linear operation. After the photoreceiver, the electrical signal is AC-amplified by a commercial low-noise amplifier (FEMTO, Mod. HVA-10M-60B), with selectable gain of 40/60 dB over a 10 MHz −3 dB bandwidth. The amplifier output is fed to a custom capacitive band-pass filter in order to achieve adjustable correct phase margins at both 0 dB crossing points of the control loop gain curve, on the left and on the right of the RIN peak frequency. After the filter, a variable attenuator provides fine tuning of the overall loop gain in order to maximize the amplitude noise suppression without exciting spurious oscillations due to improper combination of loop gain and phase margin [23].

Using the described optoelectronic control loop, a significant reduction of the laser amplitude noise was achieved, as shown in Figure 8. The figure shows different traces recorded with an Electrical Spectrum Analyser (ESA) at the voltage amplifier output. The recorded power traces were normalized to the DC electrical power (DC voltage squared and

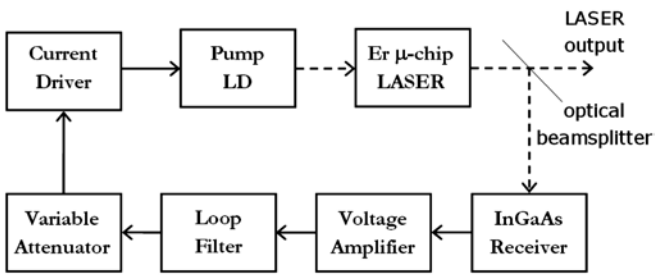

Figure 7. Experimental block diagram of the control loop for the microchip laser intensity noise suppression.

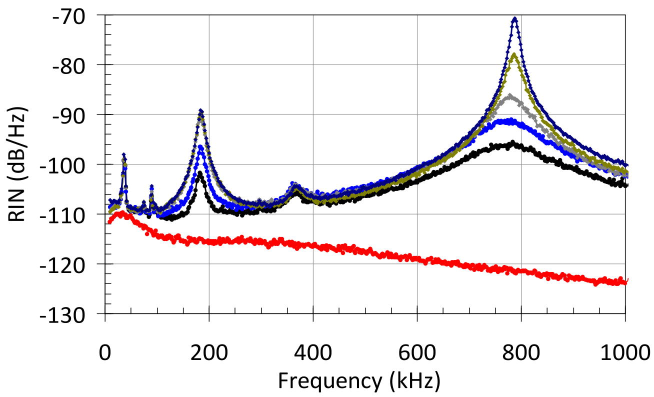

Figure 8. RIN spectral densities (higher traces) at different control loop gains. Lowest trace is the electronic noise floor of the measurement system.

divided by the ESA 50 Ω input impedance) and divided by the ESA resolution bandwidth of 3 kHz, providing the RIN spectral densities in the figure. During these experiments, as compared to the ones of Figure 5, the RIN peak was located at a reduced ~0.8 MHz as obtained by active medium tilting and some lowering of the optical pump power level. By changing the electronic loop gain, the RIN peak value could be lowered from the original level of −70 dB/Hz down to approximately −100 dB/Hz level, with a RIN maximum suppression of 27 dB. Intermediate RIN levels were achieved, as shown in Figure 8, by using different values of the loop gain. As mentioned, the RIN peak of Figure 8 is located at lower Fourier frequency then the one shown in Figure 5, namely at about 0.8 MHz instead of 2 MHz. This happens because in the stabilization experiments, performed a few months after the laser characterization experiments, the laser gain and pump power level above-threshold were both reduced, thus lowering the relaxation oscillation frequency (frequency of the RIN peak). In fact, the microchip was slightly tilted with respect to the incident pump power direction to reduce backreflections into the pump diode. In addition, the pump power level was reduced to ensure stable single longitudinal and transverse oscillation of the erbium laser. Both of these actions reduce the RIN peak frequency providing for a simpler (at lower frequencies) control loop and a reduced amplitude noise at frequencies in the range from 1 to 5 MHz (since the RIN peak happens before) where the C-OTDR detection is working.

6. CONCLUSIONS

A novel fiber-pumped single-mode Yb,Er:glass microchip laser was developed and characterized. Single-frequency output power up to 8 mW was observed with a laser slope efficiency of ~10 % and a laser threshold as low as 30 mW.

The free-running laser amplitude noise was observed being dominated by the relaxation oscillation phenomenon resulting in a RIN peak of −70 dB/Hz at around 0.8 MHz. By an optoelectronic control loop acting on the pump LD the RIN peak was successfully reduced by 27 dB and down to the constant laser amplitude noise level at approximately −100 dB/Hz in the 0.6÷1 MHz spectral region.

The developed low-noise 1.5-μm microlaser showed great potentials for precision, eye-safe or fibre-coupled, optical measurements. Stable NIR radiation is in fact needed for a number of optical monitoring techniques also to assess reliability of power plants and large-size structures. In particular, this laser was designed for use in C-OTDR systems aimed at remote optical fibre sensing applications on large-area/length systems such as pipelines, plants, dams, security perimeters, *etc*.. Further optimization of the laser source is in progress and its use in practical phase-sensitive OTDR measurements [24] will be the future activity.

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