14th IMEKO TC10 Workshop Technical Diagnostics
New Perspectives in Measurements, Tools and Techniques
for system's reliability, maintainability and safety
Milan, Italy, June 27-28, 2016

Er:glass Microlaser for Coherent OTDR Diagnostic

Alexey Pniov[1], Andrey Zhirnov[1], Dima Shelestov[1], Valery Karassik[1],
Paolo Laporta[2], Gianluca Galzerano[3], Michele Norgia[4], Alessandro Pesatori[4], Cesare Svelto[4]

[1] Bauman Moscow State Technical University - Centre for Photonics and Infrared Technology, 2-ya Baumanskaya ul., 5, Moscow, Russian Federation
[2] Politecnico di Milano, DFIS, piazza Leonardo da Vinci 33, Milan, Italy
[3] National Research Council CNR-IFN, piazza Leonardo da Vinci 33, Milan, Italy
[4] Politecnico di Milano, DEIB, via Ponzio 34/5, Milan, Italy
michele.norgia@polimi.it, alessandro.pesatori@polimi.it, cesare.svelto@polimi.it

***Abstract* – This work describes the development of a single-frequency 1.5-µm microlaser, diode-pumped by a fiber-coupled 976 nm laser diode. The laser is designed for coherent OTDR measurements used to perform remote diagnostic of gas and oil pipelines. The new microlaser provides some 10 mW single-frequency output power at 1533.5 nm wavelength, suitable for sensing and measurements with optical fibers. Amplitude and phase noise are under investigation for specific use OTDR remote sensing in the range of a few tens of kilometers.**

I. INTRODUCTION

Due to improvements in optical fibers and high-quality laser sources, fiber optic sensors [1] are finding many different application fields, also in the areas of remote monitoring and diagnostic over distributed measurement areas, in addition to the more conventional single-point fiber measurements. One very interesting exploitation of fiber sensors is in a phase-sensitive OTDR system [2], allowing continuous remote monitoring of a large "area", *e.g*. pipeline, railway, defense perimeter, *etc*.. This allows performing continuous diagnostic of extended plants.

The quality of analog optical fiber measurements [3] is strongly affected by the noise of the laser source in terms of its amplitude and phase or frequency unwanted fluctuations. In particular, for Coherent Optical Time Domain Reflectometry (C-OTDR) [4-6], a very low phase noise in the time interval relevant to the measurement is extremely important as well as low laser intensity noise in the measurement bandwidth.

II. PHASE-SENSITIVE OTDR SYSTEM

The proposed measurement scheme is shown in Fig. 1. Fiber-coupled 1.5 µm wavelength radiation from the laser source (1) is first amplified in an Erbium Doped Fiber Amplifier (EDFA) (2) and then amplitude modulated by an Acousto-Optical Modulator (AOM) (3). After an

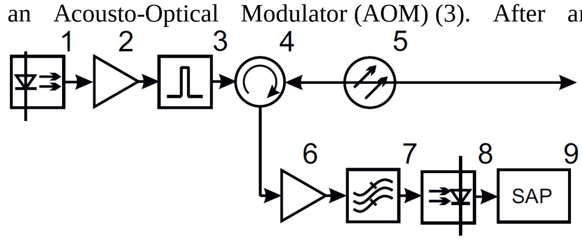

Fig. 1. Coherent-OTDR scheme.

optical circulator (4) light pulses with duration of about 1 µs are launched into the sensing fiber (5). In each portion of the sensing fiber a fraction of the traveling optical radiation is backscattered. If the coherent length of the laser is larger than the pulse length, an intensity modulation can be detected at the returning port of the circulator. This amplitude modulation is caused by the interference of different backscattered light waves arising from different scattering centers (inhomogeneities) along the fiber [7]. This backscattered signal is amplified in a second EDFA (6), band-pass optically filtered by an optical filter (7), to reduce amplified spontaneous emission from the EDFA, and finally detected by an InGaAs photodetector (PD) (8). Last electronic circuits provide for Signal Acquisition and Processing (SAP) (9) allowing for remote event detection and recognition. For example, phase-sensitive OTDR systems allow detection and ranging of human walking, digging, passing cars, acoustic noise, and *etc*. in the vicinity of the up to 50-km long fiber sensor (5).

III. Er:GLASS MICROLASER

The experimental set up of the Er:glass microlaser is given in Fig. 1. The laser active medium [8] is a phosphate glass, doped with Er^{3+} ions at 1.5×10^{20} ion/cm^3 and co-doped with Yb^{3+} ions at 2×10^{21} ion/cm^3, to provide for efficient pump absorption at 976 nm and

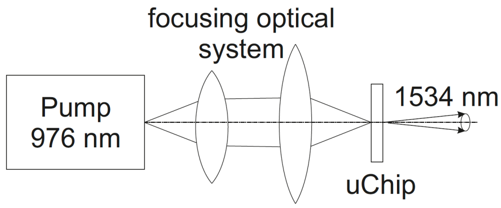

Fig. 2. Scheme of the microlaser setup.

allowing efficient energy transfer to the lasing erbium ions. The laser emits at 1.5 µm wavelength in a quasi-three level laser scheme [9] and the active medium is cut as a thin disk with few millimeter diameter and approximately 200 µm thickness, as needed to provide single-longitudinal-mode oscillation. 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>95 %) at the pump wavelength of 976 nm and for broadband ultra-high reflectivity (R_1>99.9 %) at around 1.55 µm. The output mirror, instead, provides for a high reflectivity at the pump wavelength (R>90 % at 976 nm) and laser output coupling of 2 % (R_2=98 % broadband at 1.54 µm). The pump source is a fiber coupled InGaS semiconductor laser coupled to a single mode optical fiber, with available output power up to 250 mW at the temperature-tuned central wavelength of 976 nm. After the fiber, the pump beam is passed through a two lenses telescopic system (see Fig. 1) to provide for a beam waist of diameter ~50 µm within the active medium. Efficient mode matching with the TEM_{00} fundamental laser mode is achieved as well as double-pass pumping along the microlaser thickness: good laser slope efficiency (in the order of 10 %) and low pump threshold (~30÷40 mW) in this way can be obtained.

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. Among the pump LD, two lenses, and the microchip active medium, the cost in a mass production will be limited by the fiber-coupled pump diode, which however is already well developed and produced for EDFA pumping: the final goal is to reach a whole microlaser cost in the order of 500 USD.

IV. LASER CHARACTERIZATION

Characterization of the Er:glass microlaser was performed in terms of output vs. input optical power characteristics, output optical spectrum, amplitude and frequency noise before any active stabilization system. In this regard, of paramount importance is the study of both amplitude and phase noise over different Fourier spectral regions. In fact, for phase-sensitive-OTDR applications and for several other precision optical measurements, the low noise feature of the laser source within the frequency band used for sensing and diagnostic is very important. For the OTDR application that we are investigating [10], the interrogation times of the backscattered signals from the remote sensing optical fiber are in the range from 0.5 ms to 1 s, while the useful detection bandwidth is 5 MHz.

Output power from the erbium microlaser was recorded by an InGaAs calibrated optical power meter, commercially available from OPHIR (mod. Vega). An interference long wave pass filter was placed before the power meter, in order to remove residual components of the pump radiation exiting the laser cavity from the output mirror (with transmission 10 % and residual pump power levels in the range of a few milliwatts). In this way a correct, or even underestimated, measurement of the 1.54 µm laser output was achieved as varying the input pump power. The measured laser power as a function of incident pump power is shown in Fig. 3. We can notice a laser threshold of about 35 mW and an optical-to-optical slope efficiency of 10 %.

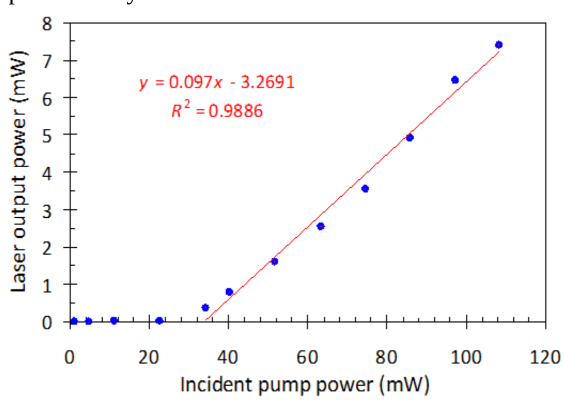

Fig. 3. Output vs. input power for the microlaser.

Single transverse mode operation was checked by observing 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 by the optical spectrum of the laser output beam, as shown in Fig. 4. Adjacent longitudinal modes, slightly visible in the picture, are more than 50 dB below the peak of the oscillating single mode at $\lambda \cong 1534.7$ nm.

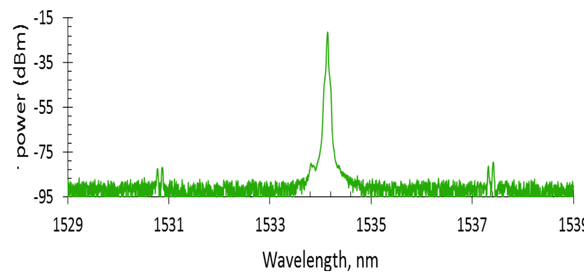

Fig. 4. Optical spectrum of the Er:glass microlaser.

Frequency and wavelength stability was characterized by a precision wavelength meter (Ångstrom Wavelength Meter, model WSU2), recording wavelength deviations over time. Figure 8 plots the laser wavelength values over a time interval of 10 minutes, with a sampling period of 110 ms. Average laser wavelength was λ=1534.8576 nm with a standard deviation $\sigma_{(\lambda)}$=0.06 pm over the observed 5500 samples. The relative wavelength 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.

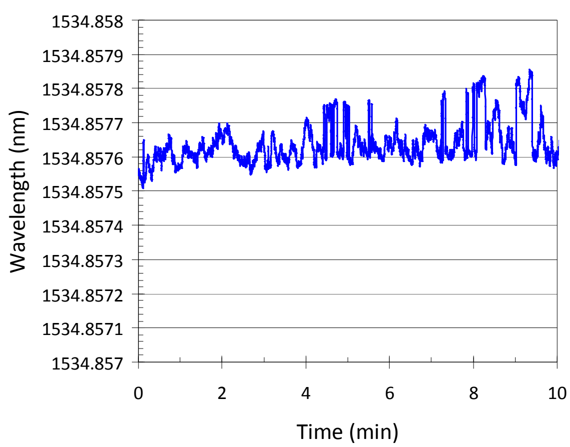

Fig. 5. Laser wavelength stability over 10 minutes.

Amplitude noise stability of the microlaser was characterized in terms of its Relative Intensity Noise (RIN) in the spectral region from DC to 10 MHz, since this is the typical frequency band where fiber sensors and phase-sensitive-OTDR systems perform their measurements. As shown in Fig. 6, the laser relaxation oscillation peak occurs at a relatively high frequency, of about 2 MHz, due to the very short laser cavity.

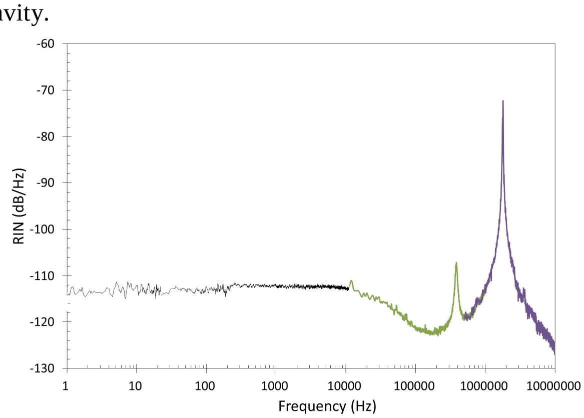

Fig. 6. Laser wavelength stability over 10 minutes.

The measured peak value is at -70 dB/Hz whereas, outside the spectral region of relaxation oscillations, RIN is below 110 dB/Hz. However, this result was achieved without isolating the pump diode from strong backreflections coming from the microlaser. Significant amplitude noise in the pump radiation was observed when the Er:glass µ-chip is in place and hence after we are now working on optical isolation to significantly reduce the pump and laser intensity noise. A commercial fiber-coupled polarization-insensitive 30 dB optical isolator at 980 nm was ordered and soon will be available for better measurements. With the use of this isolator the erbium microlaser will be ready for testing in the already available phase-sensitive-OTDR system. If needed, additional passive/active amplitude and frequency noise reduction will be performed on the laser system.

V. CONCLUSIONS

The developed Er:glass microlaser shows great potentials for OTDR systems aimed at remote sensing by optical fibers for diagnostic applications on large area/length systems such as pipelines, plants, dams, security perimeters. Further optimization of the laser source is in progress and its use in practical phase-sensitive-OTDR measurements is on the way. Diagnostics of large and hence remote plants/systems can greatly benefit from the use of distributed optical fibers that can cover the whole length/surface plant. Digital signal processing of the backscattered signal from the optical fiber allows continuous on-line diagnostic of the working state of the system, without the need of many sensors and sensor reading points.

ACKNOLEDGEMENTS

The Authors are grateful to the Rectors of both Politecnico di Milano -namely Professor Giovanni Azzone- and of the Bauman Moscow State Technical University -namely Professor Anatoly Alexandrovich Aleksandrov- for encouraging and continuously supporting this fruitful scientific cooperation. Specific gratitude regarding the experimental activity goes to different students and researchers of the Bauman Centre for Photonics and Infrared Technology, who helped in the laboratory over many phases of the experiments. In particular, we would like to thank Alina Borisova, Anton Khaperskiy, Konstantin Stepanov, and Evgeniy Nesterov for their useful assistance during the optical measurements and collection of the experimental data.

REFERENCES

[1] D.A. Krohn; T.W. MacDougall; A. Mendez, Fiber Optic Sensors: Fundamentals and Applications, SPIE Ed., 4th edition, 2015.

[2] Pnev A.B. *et al.*, "Mathematical analysis of marine pipeline leakage monitoring system based on coherent OTDR with improved sensor length and

sampling frequency”, Journal of Physics: Conference Series. – IOP Publishing, Vol. 1, 2015.

[3] C.H. Cox III, Analog Optical Links: Theory and Practice, Cambridge University Press, 2006.

[4] Y. Horiuchi, K. Mochizuki, and H. Wakabayashi, “Novel coherent heterodyne optical time domain reflectometry for fault localization of optical amplifier submarine cable system”, IEEE Photon Technol. Lett., Vol. 2, 1990, pp. 291-293.

[5] Y. Koyamada, M. Imahama, K. Kubota, and K. Hogari, “Fiber-Optic Distributed Strain and Temperature Sensing With Very High Measurand Resolution Over Long Range Using Coherent OTDR”, J. Lightw. Technol., Vol. 27, 2009, pp. 1142-1146 (2009).

[6] M. Imahama, Y. Koyamada, and K. Hogari, “Restorability of Rayleigh Backscatter Traces Measured by Coherent OTDR with Precisely Frequency-Controlled Light Source”, IEICE Trans. Commun., Vol. E91 B7, 2008, pp. 1243-1246.

[7] J.C. Juarez, H.F. Taylor, “Field test of a distributed fiber-optic intrusion sensor system for long perimeters”, Applied Optics, Vol. 11, 2007, pp. 1968-1971.

[8] S. Taccheo, P. Laporta, S. Longhi, O. Svelto and C. Svelto, “Diode pumped bulk erbium ytterbium lasers”, Appl. Phys. B, Vol. 63, 1996, pp. 425 436.

[9] P. Laporta, S. Taccheo, S. Longhi, O. Svelto and C. Svelto, “Erbium ytterbium microlasers: optical properties and lasing characteristics”, Opt. Materials, vol. 11, 1999, pp. 425 436.

[10] A.B. Pniov, A.A. Zhirnov, K.V. Stephanov, E.T. Nesterov, D.A. Shelestov, and V.E. Karasik, “Mathematical analysis of marine pipeline leakage monitoring system based on coherent OTDR with improved sensor length and sampling frequency”, J. Phys.: Conf. Ser., Vol. 584, 2015, pp. 425 436.