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Er:Yb phosphate glass laser with nonlinear absorber for phase-sensitive optical time domain reflectometry

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Abstract. A novel laser for phase-sensitive optical time-domain reflectometry (Φ -OTDR) is presented. The advantages of a compact solid-state laser are listed, current problems are shown. Experiments with a microchip single-optical-element laser, from setup construction to usage in Φ -OTDR system, are presented. New laser scheme with two-photon intracavity absorber is suggested and its advantages are described.

1. Introduction

Narrow linewidth lasers at 1.5 μm are very promising devices in different areas, e.g. Light Detection And Ranging(LIDAR), Φ -OTDR, and as a local oscillator (LO) for optical frequency comb metrology. Nowadays most popular lasers of this kind are: stabilized fiber lasers (FL), semiconductor external-cavity laser diodes (ECLD) with feedback via Bragg grating, and whispering gallery mode (WGM) lasers. High price, defined by complicated production technology, is their common disadvantage. The main goal of this work is to develop optical systems, based on narrow linewidth laser, more widespread by creating less expensive light source.

This paper is organized as follows. In the first part we describe application of narrow linewidth laser in a Φ -OTDR system. In the second part we describe our experiments with single-optical-element microchip laser. Thirdly we present a new scheme and its components. In the fourth part we show our future steps in narrow-linewidth laser development.

2. Φ -OTDR system

Φ -OTDR is nowadays a popular distributed fiber optic sensor [1-3]. Its working principle is presented in figure 1. Light from a laser source (1) is amplified in EDFA-booster (2) to obtain the required power level [4, 5]. Then it is formed into pulses via acousto-optical modulator (3). Through circulator (4) the optical pulses go into sensing fiber (5) with a time period longer than round-trip-time needed to pass fiber (5) forward and backward. From each local section of the sensing fiber a small part of pulse power is backscattered by inhomogeneities – Rayleigh scattering centers. All scattered light waves from these inhomogeneities in the range of one optical pulse are summed in amplitude also taking into account their phases due to the laser source narrow linewidth and the corresponding large coherence length. Since optical phases are randomly distributed, we obtain one-dimensional back-reflected



speckle signal or interferogram which attenuates to the far end of the sensor. This returning signal is collected by the circulator and amplified by a second EDFA (6). Amplified spontaneous emission noise generated by the second EDFA is cut off by a narrow-band optical filter (7). Finally we obtain signal by detection on photoreceiver (8), transform it to digital via analog-to-digital converter (9) and then process it on personal computer (10). Received signals are called reflectograms. Their shape remains quite stable while there are no acoustical or vibration sources in proximity of the sensor. Any acousto-mechanic perturbation of the fiber sensor will change the position of backscattering centers and hence the optical phases of reflected waves and the result of their summation, thus altering the reflectogram shape. Analysis of reflectograms fluctuations can give us information about events happening in proximity of the sensor: events “localization”, as distance from the modulated laser source, as well as events “strength” can be continuously monitored in this way.

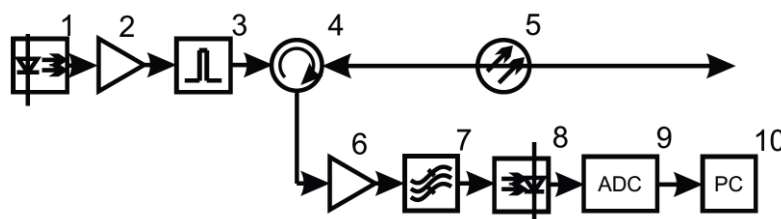


Figure 1. Φ -OTDR scheme: 1 – laser source, 2 – EDFA-booster, 3 – optical modulator, 4 – optical circulator, 5 – sensing fiber, 6 – EDFA-preamplifier, 7 – optical filter, 8 – photoreceiver, 9 – ADC, 10 – personal computer.

In this scheme the quality of the laser source plays a crucial role. It must have sufficiently large coherence length to obtain coherent summation of waves by amplitudes instead of typical summation by power happening in commercial telecommunication OTDRs [6] using low-coherence sources. Also, for reflectogram stability, the laser source must be stable in terms of its optical frequency (or wavelength). Since obtained signal is interference between backscattered light waves, the fluctuations of laser wavelength will strongly influence on summation result. Existing research shows that requirements for the source frequency stability are: laser linewidth less than 1 MHz over 1 ms [7] and frequency fluctuations no more than 100 MHz over 1 min.

Design and construction of such a low-noise 1.54 μm laser source, satisfying the above requirements and quite simple/inexpensive in production, is the goal of this work.

3. Single-element microchip laser

Our first step in the source development was to test a microchip laser assembled according to the scheme in figure 2. Pump at 976 nm from fiber-coupled LD goes through a telescopic focusing system to enlarge spot size diameter from the original 6 μm at fiber output up to 42 μm . The active medium is an athermal phosphate glass doped with Er^{3+} and Yb^{3+} ions ($\text{Yb}^{3+}:\text{Er}^{3+}$ ratio is 20:1). The microchip thickness is 230 μm as measured from longitudinal modes separation. Coatings parameters at the different laser and pump wavelengths are the followings. For the first surface $R_{1976\text{nm}}=0.2$ and $R_{1540\text{nm}}=0.999$, for the second surface $R_{2976\text{nm}}=0.9$ and $R_{21540\text{nm}}=0.98$. More detailed data about this laser can be found in [8].

Unexpected feature of this monolithic source was the significantly high amplitude noise due to relaxation oscillations at a Fourier frequency of ~ 1 MHz. This large intensity instability, up to 20 % of the mean value, is shown in the oscilloscope trace of figure 3. In Φ -OTDR system these fluctuations impact on reflectogram stability resulting in very poor Signal-to-Noise detection. Also this intensity noise makes linewidth measurements [9] a very difficult task. An opto-electronic feedback loop was used to decrease the oscillation peak by 27 dB but has a negative consequence. Laser wavelength of this microchip laser depends significantly on pump power [10], so feedback control by pump power also changes the laser wavelength. Influence of active feedback on frequency stability, at different

loop gains, is presented in figure 4 in terms of the laser fractional frequency ($\gamma = \Delta\nu/\nu$) Allan deviation [11] and in figure 5 in terms of frequency deviations plots as a function of time. This frequency instability, as seen in the end of Section 2, is undesirable in such a device.

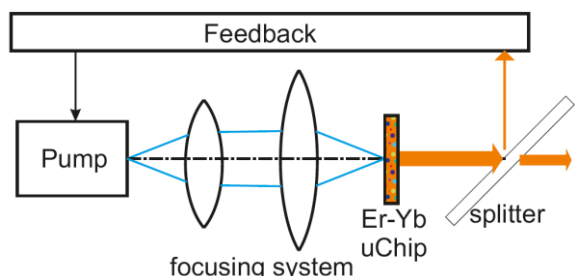


Figure 2. Scheme of single-element microchip laser with optoelectronic feedback loop.

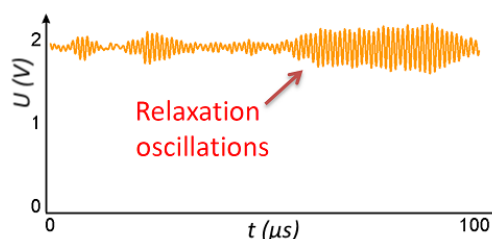


Figure 3. Graph of power intensity instability due to relaxation oscillations.

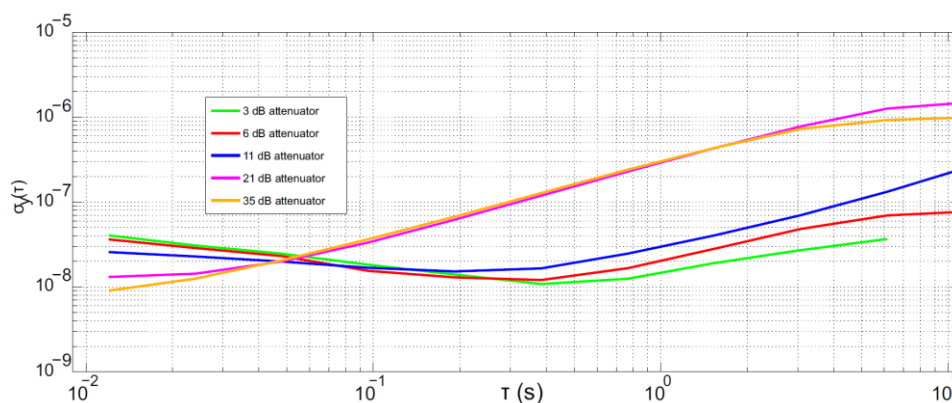


Figure 4. Allan deviation of laser frequency with different gain feedback.

To conclude of this step of laser source design, we tested the microchip laser in the Φ -OTDR scheme shown in figure 6. This scheme is different from the scheme in figure 1. Firstly, we need more gain to amplify radiation entered into fiber because of non-optimal input coupling (can be fixed in future). So instead of one EDFA-booster we have two EDFAs (2, 4) with optical filter 3 to suppress spontaneous emission from EDFA 2. Secondly, microchip laser operates at ~ 1534 nm, which is erbium emission spectrum peak, instead of 1550 nm of the laser wavelength in figure 1. Because of operation at the erbium emission peak we have higher noise level from EDFA-preamplifier (6 in figure 1) which is even higher than reflectogram level. This is the reason for using detecting part of the system (8, 9 and 10) without preamplifier but with more sensitive and slower photoreceiver. We used LCA-S-400K (FEMTO Messtechnik GmbH) with 400 kHz bandwidth and NEP 75 fW/ $\sqrt{\text{Hz}}$ instead of JDSU EPM605 with custom electrical amplifier scheme used in system from figure 1, having 5 MHz bandwidth and NEP 5 pW/ $\sqrt{\text{Hz}}$. The obtained reflectogram signals are presented in figure 7.

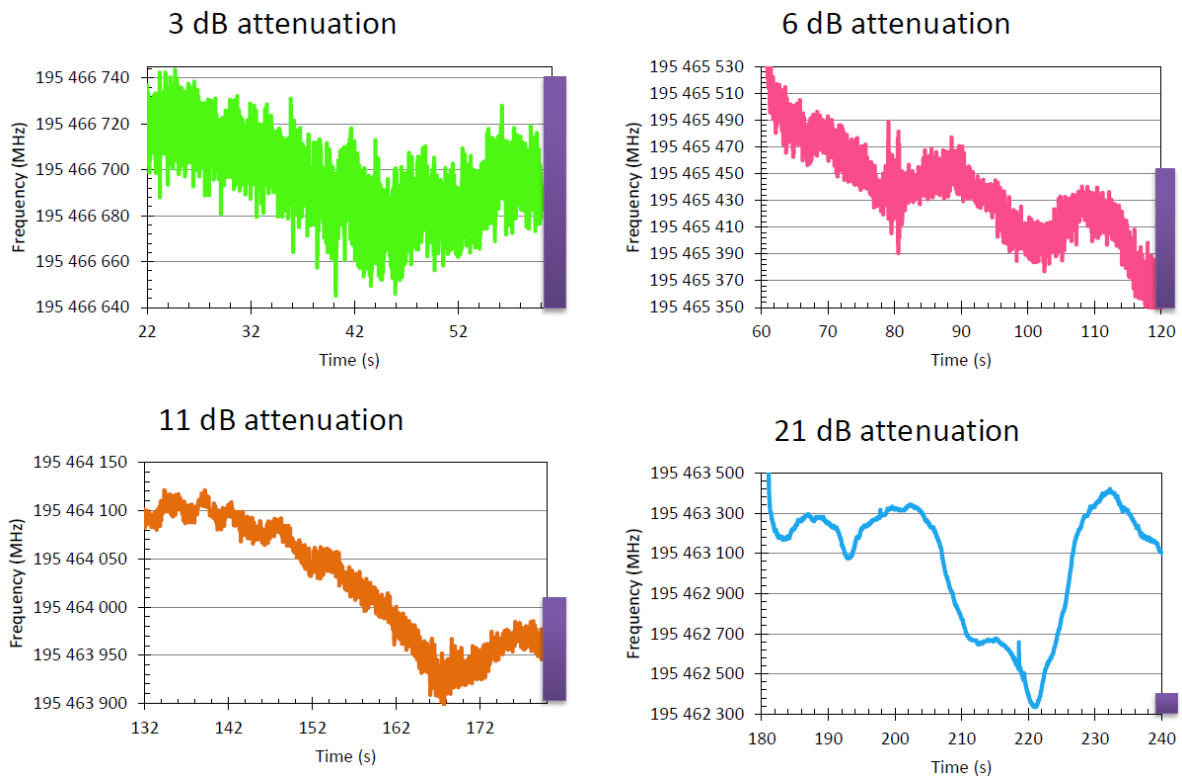


Figure 5. Laser frequency fluctuations during different observation times using different gain in the feedback loop. Violet bar on right side shows 100 MHz fluctuation scale.

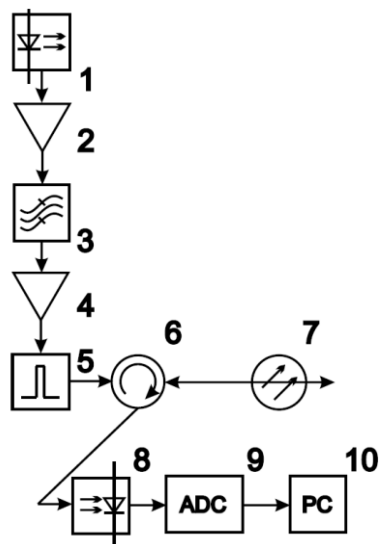


Figure 6. Φ -OTDR scheme for microchip laser testing.

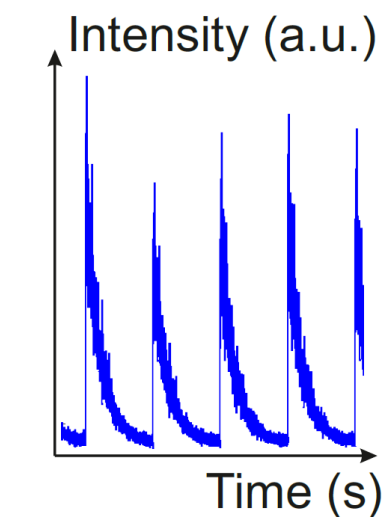


Figure 7. Graph of reflectograms time sequence.

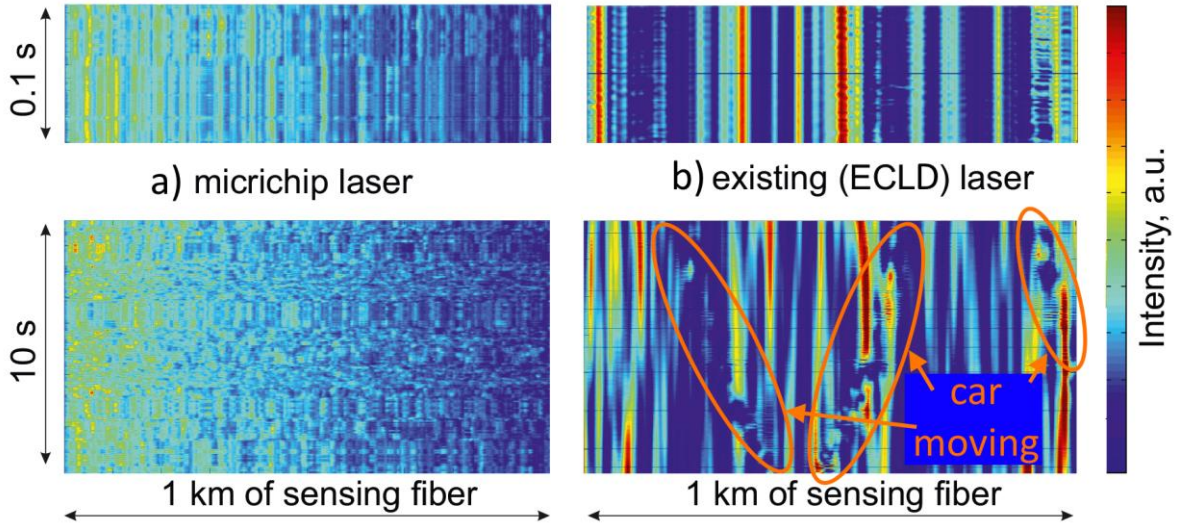


Figure 8. Signals from Φ -OTDR system with microchip laser (a) and ECLD (b).

To enable signal processing of this signal with unstable pulse intensity we used reflectogram normalization. Random nature of signal doesn't allow choosing one special point of reflectogram to compare its power with the others. Moreover, optical and electrical noise has quite stable intensity in the signal from the far sensor end. Accordingly, we calculated normalizing coefficient as follows:

$$NK_i = \frac{\sum_{t=20}^{500} I_{1,t}}{\sum_{t=20}^{500} I_{i,t}} \quad (1)$$

where NK_i is normalizing coefficient for the i -th reflectogram, $I_{i,t}$ is intensity from i -th reflectogram from t -th point of sensor. This equation allows avoiding the influence of large fluctuations in the beginning of sensor and noise from the far end. After normalizing each reflectogram

$$I_{i,t}^N = I_{i,t} NK_i \quad (2)$$

we obtained the signal presented in figure 8a. For comparison we also show signal from Φ -OTDR with nowadays used ECLD source in figure 8b. Analysis of figures 8a and 8b allows us to draw the following conclusions. Firstly, light from microchip laser has coherence length large enough to be used in Φ -OTDR systems, since we see random intensity modulation along the sensor. However, its contrast is less than 1 (intensity interference minima don't reach values about zero). Secondly, on small periods of time laser frequency is stable enough to analyze fluctuations of reflectograms, e.g. in figure 8a (picture with 0.1 s duration) positions of intensity peaks and valleys are stable. But signal from ECLD is much better also due to the lack of imprecise normalization procedure. Thirdly, higher EDFA noise at 1535 nm working wavelength instead of 1550 nm reduces the maximum sensing length to a few kilometers for the microchip laser as compared to the 40 km attainable length with the ECLD. Effect is that with ECLD we easily can see the car movements along the cable and with microchip laser we can not detect such events.

Results of the preliminary work with this laser showed that we need to reduce the laser intensity noise in particular at the relaxation oscillations frequency, make the optical frequency more stable and shift the working wavelength away from the erbium emission peak.

4. Scheme with two-photon absorber

On the basis of previous Section conclusions, we propose a new scheme, presented in figure 9, for the solid-state laser to be used in Φ -OTDR systems.

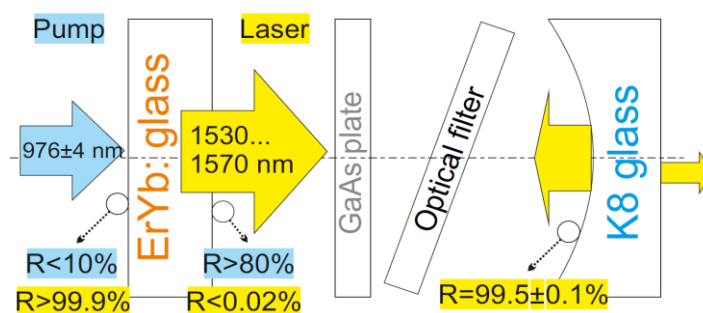


Figure 9. Scheme of Er-Yb:glass laser with two-photon absorber.

To fulfill the amplitude and frequency noise requirements, as well as wavelength tunability, we have to make a cavity with few elements. Laser cavity is formed by two mirrors: one on the first surface of active medium chip and the second one on the concave surface of K8-glass lens. This discrete-cavity design allows inserting in the laser resonator a few needed optical elements. The first element is a GaAs plate used to reduce relaxation oscillations due to the semiconductor nonlinear absorption at $1.54 \mu\text{m}$ [12]. In such a way we will be able to stabilize output intensity without influence on laser wavelength, that was a negative side of opto-electronic feedback from previous scheme in figure 2. The second intracavity element is an optical filter which allows choosing the laser operating wavelength and shift it away from the erbium emission peak to reduce noise from EDFA-preamplifier (6 in figure 1).

Suggested scheme is more sensitive to optical elements vibrations, so last step can be done to integrate a monolithic multi-element cavity, *e.g.* like in [13]. Before this final step, the optimal design of intracavity elements must be found also from experimental results.

Acknowledgments

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