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Experimental study of self-induced transparency mode-locking in Ti:sapphire laser

M V Arkhipov^{1,2}, R M Arkhipov^{1,2,3}, A A Shimko¹, I Babushkin⁴, N N Rosanov^{2,3,5}

¹ St. Petersburg State University, 199034 St. Petersburg, Russia

² ITMO University, St. Petersburg 197101 Russia

³ Ioffe Institute, St. Petersburg 194021, Russia

⁴ Institute of Quantum Optics and PhoenixD, Leibniz University Hannover, Hannover 30167 Germany

⁵ Vavilov State Optical Institute, St. Petersburg 199053 Russia

Abstract. In this paper, passive mode-locking in Ti:sapphire laser with a coherent absorber cells with rubidium vapor placed in the cavity is demonstrated experimentally. For the best of our knowledge these experiments are the first time experimental demonstration of passive mode-locking based on self-induced transparency regime in the coherent absorber. Up to now, such a regime has not been observed experimentally and was predicted only theoretically.

1. Introduction

Passive mode-locking (PML) in lasers occurs when an absorbing medium having a nonlinear dependence of the transmission on the intensity is placed in the laser cavity [1]. In standard PML lasers it arises due to gain/absorption saturation in amplifying/absorbing media. In such lasers pulse duration cannot be shorter than the polarization relaxation time T_2 of the active medium. If the absorber operates in the regime of coherent light-matter interactions (pulse duration is shorter than T_2) the relaxation times of the medium will not impose restrictions on the duration of the generation pulse, which can reach the value in one cycle of light oscillations [2]. In this case, the so-called 2π pulse of the self-induced transparency (SIT) can occur in the laser cavity when pulse propagates in the absorber without losses as 2π pulse [3]. Mode-locking based on SIT phenomenon is called coherent mode-locking or SIT mode-locking [4-6]. To date there is no experimental demonstration of mode-locking in lasers arising due to SIT. CML was studied only theoretically in the situation when both absorber and gain operates in the coherent regime [2, 4-6]. In the situation when mode-locking arises in the laser with a coherent absorber (gain medium remains in the incoherent regime) due to SIT phenomenon was studied theoretically in [7].

In this paper, we report the peculiarities of experimental demonstration of SIT based mode-locking in Ti:sapphire laser with rubidium absorbing cell placed in the cavity, which arises only due to SIT in rubidium vapor. A detailed study of this regime is described in Refs. [8-9] and review [10].

2. Experimental setup

The setup is shown in Fig. 1. Ti:Sa laser with several cavity designs was assembled on an optical table using the standard components of a laser of the company «Technoscan». To these components belong a sapphire crystal (1) and spherical and plane mirrors (M1-M6). For the wavelength tuning a Lio filter and Fabry-Perot etalon were used. The output of the pump laser VERDI V10 (Coherent) was focused, using the lens (L), through the mirror M1 into the Ti:Sa crystal (1). The Rb vapor cell with the natural mixture of isotopes and high quality windows oriented at the Brewster angle to the beam path to minimize the losses. The cell was placed before the output mirror of the cavity M5, and could be warmed and cooled.



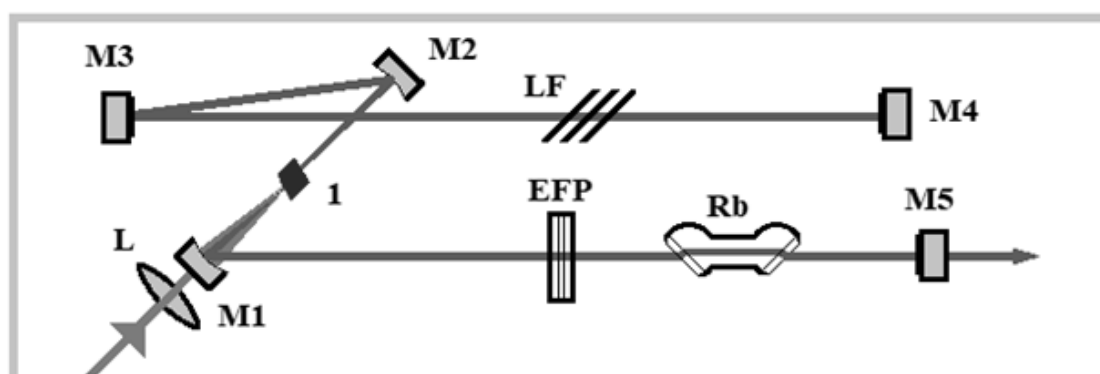


Figure 1. Ti:Sa laser with a Rb vapor cell in a cavity 1 Ti:Sa crystal, M1,2 are the confocal mirrors of the cavity, M3 is an auxiliary plane mirror, M4,5 are the fully reflecting plane mirror and the output mirror (transparency around 8%), L is a focusing lens. LF is the Lio filter, and EFP is the Fabry-Perot etalon for tuning the lasing wavelength.

Laser intensity in dependence on time was registered using a high speed photodiode and an oscilloscope DSO 9104A (Agilent Technologies) with the temporal resolution near 300 ps. The wavelength was determined by a spectrometer, the power was measured by the power meter «Maestro» (Standa). To estimate the pulse durations we used an interferometric autocorrelator based on the Michelson interferometer, as well as the Fabry Perot interferometer with variable base.

3. Results

In the experiment several regimes were observed. In the first case, there was a regular mode-locking. The amplitude of the pulses was stable during long time. An example of such a mode-locking regime is shown in Fig. 2.

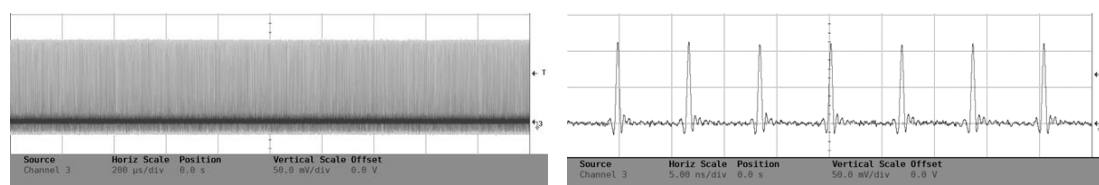


Figure 2. Examples of mode-locking oscillogram due to the effect of self-induced transparency on the DII line of rubidium. On the left oscillogram the time scale is 200 $\mu\text{s}/\text{div}$, on the right 5 ns/div.

In such regime [8-10] the generation pulse duration was obtained from 2 ns to 60 ps. It is shown that the pulse duration is determined only by the generation power. Generated pulse duration decreases with increase of generation power and the pulse area determined according to McCall and Hanh as integral on the pulse envelope over the time [3] remains constant and equals 2π . Our analysis revealed that pulses in the cavity are pulses of self-induced transparency [8-10]. All observed pulse durations were shorter than the polarization relaxation time T_2 of rubidium vapors. The minimum duration achieved was less than T_2 by two orders of magnitude.

The second regime was with pronounced irregular pulses. An example of arising such regime from regular mode-locking below in Fig. 3. The fragment with a duration of 0.325 ms is shown in Fig. 3 (a). Waveforms of pulses in places marked with numbers 1, 2, 3, 4, 5 in fig. 3 (b) - (f).

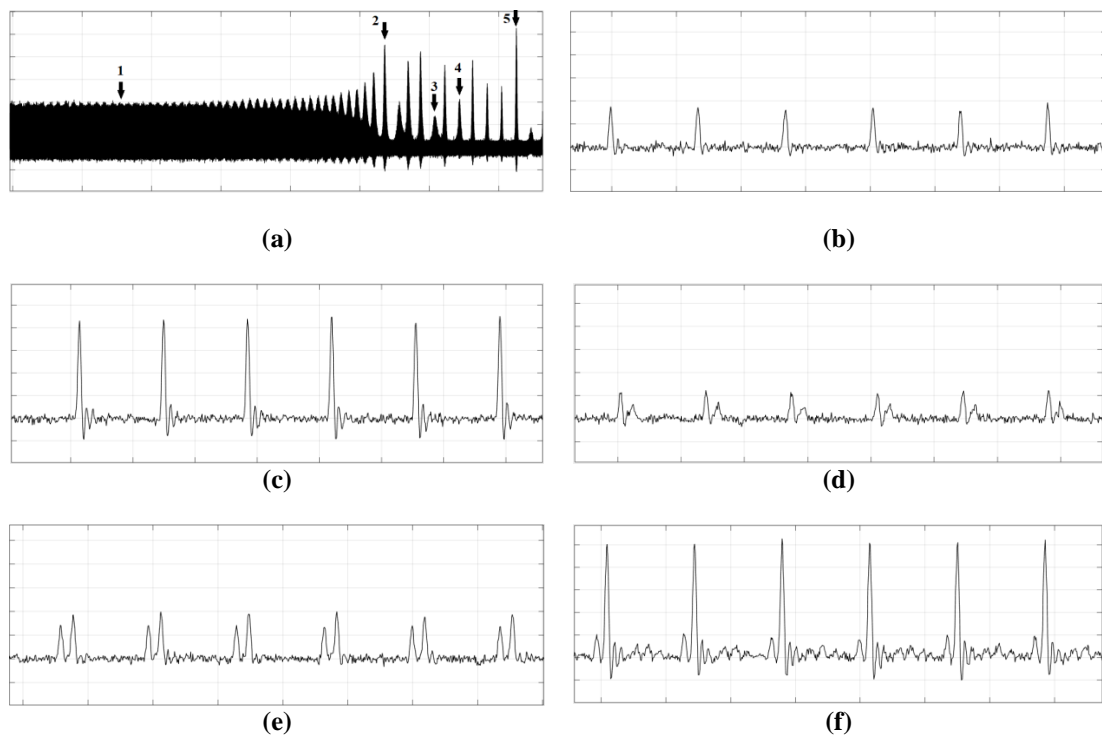


Figure 3. Examples of arising irregular regime. (a) – time scale 50 $\mu\text{s}/\text{div}$. (b)-(f) time scale 5 ns/div. Oscillations at the trailing edge of the pulses occurred due to transients in the input electrical circuit photodetector - oscilloscope.

In the third regime, there were switching between longtime quasi-stable fragments with different pulse parameters. The example is given in Fig. 4.

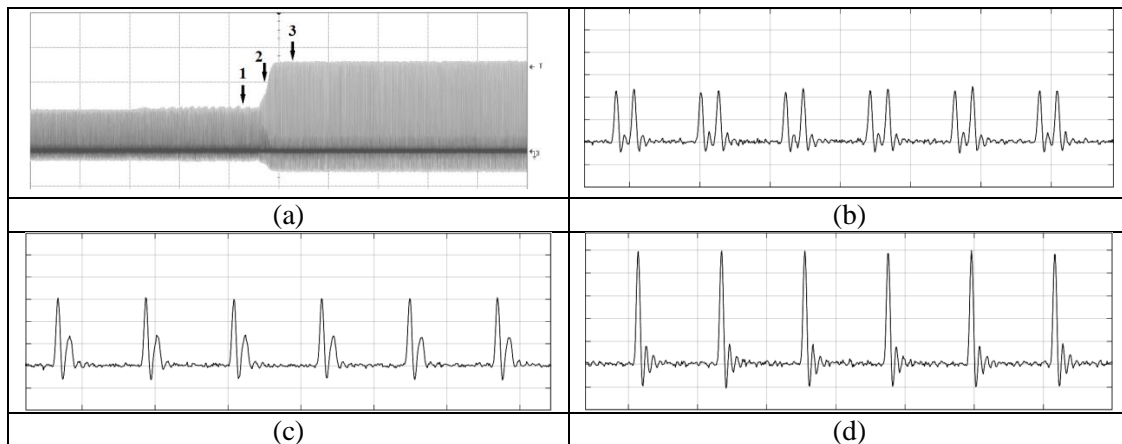


Figure 4. Examples of mode-locking with switching between quasi-stable regimes. Waveforms of pulses in places marked on (a) with numbers 1, 2, 3 are in (b) - (d). (a) – time scale 200 $\mu\text{s}/\text{div}$. (b)-(d) time scale 5 ns/div. Oscillations at the trailing edge of the pulses occurred due to transients in the input electrical circuit photodetector - oscilloscope.

The existence of such irregular and switching regimes raises the question of their nature. Here it is necessary to take into account one important circumstance. To implement SIT mode locking, it is necessary

that the pulse area is 2π . If the beam cross-section into absorber changes, this condition cannot be satisfied. Coherent absorber creates losses. Laser generation at the transition frequency in rubidium becomes impossible. The reasons of these regimes may be any change in the beam cross section due to the configuration of the resonator and the self-action of the beam in the absorber, which also creates a change in the beam cross section. In this case, the area of the pulses will vary. Then it can be assumed that the only option in which there are minimum losses in a coherently absorbing medium is the case of propagation of a zero-area pulse. During the experiments, we noted that the transitions between the regular and irregular regimes could be obtained by changing the tuning of the cavity mirrors. This partially confirms the assumption made above. When changing the installation angles of the cavity mirrors, the beam shape in the absorber changes, which can lead to the specified effects. There are either fast or slow switching between generation modes.

Note that in our experiments 0π pulses with a zero area were observed. Below in Fig.5 is an example of such pulses. They have two maxima, which are characteristic of such pulses. The spectrum has a dip in the center. These dips were recorded on interferograms, which were obtained using a Fabry-Perot interferometer.

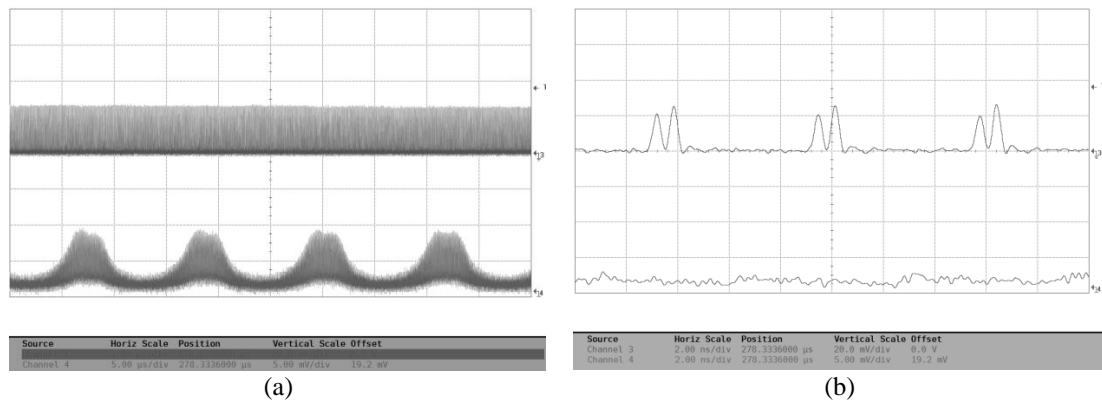


Figure 5. Examples of mode-locking with 0π pulses. (a) – generation waveform on upper trace, interferogram with deep in center on low trace. (b) – part of (a) data, upper line 0π pulses with two maxima

In the case of stable SIT pulses generation it was possible to obtain the harmonic mode locking. In the cavity there was not one pulse, but several pulses were observed. The maximum number of pulses that we observed was seven. We received this when we placed the rubidium cell in the resonator of the commercial laser of the Mira Optima 900 D (Coherent). In this laser, the output power generation reached 1.4 watts with cell in cavity. This is 10 times more than in the experiments described in our publications [8, 9]. The high lasing output power and long cavity length made possible to exist several SIT pulses in the cavity simultaneously. Examples of waveforms are given in Fig. 6

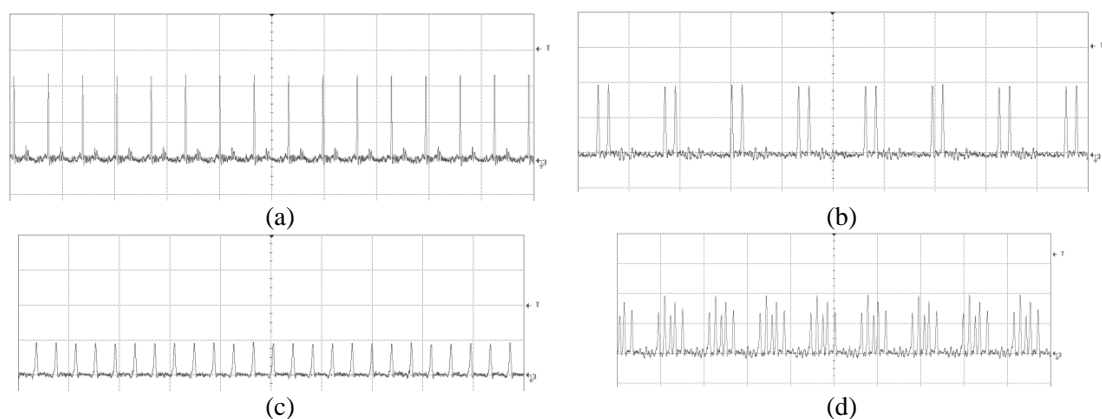


Figure 6. Examples of SIT harmonic mode-locking in Ti:Sa laser Mira Optima (Coherent). (a) fundamental mode-locking, cavity round trip time 17 ns, time scale 20 ns/div. (b) – two pulses in cavity, cavity round trip time 17 ns, time scale 10 ns/div. (c) – three pulses in cavity, cavity round trip time 12 ns, time scale 10 ns/div (d) – five pulses in cavity, cavity round trip time 12 ns. Time scale 10 ns /div.

4. Conclusions

In the presence of a coherent absorber in a Ti: Sa laser and tuning of the generation wavelength to the absorption line, different regimes can occur: regular SIT coherent mode locking, regimes with irregular pulsation, switching between quasi-stationary mode-locking regimes. Regime of zero-area pulses was also observed. In the case of SIT, the existence of harmonic mode locking is shown. Simultaneously, from one to seven pulses were observed in the cavity. Note that the listed regimes (harmonic mode-locking, chaotic and switching regimes) with the exception of the zero-area pulses case are also observed in lasers with saturable absorbers.

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Acknowledgments

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