ISSN 0021-3640, JETP Letters, 2019, Vol. 109, No. 10, pp. 634–637. © Pleiades Publishing, Inc., 2019.
Russian Text © The Author(s), 2019, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2019, Vol. 109, No. 10, pp. 657–661.

OPTICS
AND LASER PHYSICS

Mode Locking in a Ti:Sapphire Laser by Means of a Coherent Absorber

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Received April 4, 2019; revised April 4, 2019; accepted April 5, 2019

The regime of passive mode locking in a Ti:sapphire laser with a coherent absorber resulting in the emission of pulses with a duration considerably shorter than the absorber relaxation times is demonstrated experimentally. A cell filled with rubidium vapor placed in the laser cavity serves as a coherent absorber. Mode locking arises when the laser oscillation frequency is tuned to the resonance transitions in rubidium. In our opinion, 2π pulses of self-induced transparency appear in the cavity, and the reported results represent the first experimental demonstration of passive mode locking caused by the effect of self-induced transparency, which has previously been discussed only theoretically.

DOI: 10.1134/S0021364019100059

INTRODUCTION

The regime of passive mode locking in lasers occurs when, apart from the gain medium, the laser cavity contains an absorbing medium characterized by a nonlinear dependence of transmission on the intensity, for example, because of saturation of absorption [1–3]. The saturation of absorption, along with the saturation of the amplifier gain, ensures the conditions for the onset of mode locking without active external modulation of the cavity parameters. This is widely used in lasers [2, 3]. We note that saturation effects have a resonance character and the recovery of absorption after each pulse takes time. The minimum pulse duration in such lasers is limited by the relaxation time T_2 of the medium. Obtaining very short pulses requires "fast" nonlinearities, such as the nearly instantaneous Kerr nonlinearity. In this case, owing to the extremely fast change in the refractive index of a transparent medium, which depends on the square of the electric-field strength, the partial self-focusing of the beam takes place, whereby losses for high-power short light pulses are reduced, and the regime of passive mode locking ("Kerr lens mode locking") sets in [2, 4].

Note that resonant absorbers working in the regime of coherent light–matter interaction can also be used to obtain passive mode locking [5–15]. In this case, the relaxation times of the medium will not limit the duration of the generated pulses, which, in principle, can become as short as one light oscillation cycle [9, 10]. Coherent light–matter interaction occurs when laser pulses are shorter than the population-difference relaxation time T_1 and polarization relaxation time T_2 [16, 17]. In this situation, pulses can propagate without damping in a resonantly absorbing medium in the regime of a 2π pulse of self-induced transparency (SIT) [18, 19]. Passive mode locking that arises owing to the effect of SIT is commonly called coherent mode locking (CML) [5, 8–14]. We again emphasize that this type of mode locking is due to the effect of SIT, meaning that the pulse interacts with the absorbing medium in the coherent regime. This makes CML significantly different from laser systems using the conventional passive mode locking mechanism, which relies on incoherent absorption saturation [8–14]. Although the CML regime has long been analyzed theoretically by different authors [5–11, 13, 14], it has not been demonstrated experimentally. The authors of [12, 15] argued that they obtained mode locking with a resonant coherent absorber working in the regime of generation of so-called zero-area pulses (0π pulses) [20]. In such pulses, the sign reversal of the envelope of the field takes place, so that generated radiation has the form of two coupled pulses with slowly varying amplitudes [15]. Mode locking that results from the appearance of a 2π SIT pulse in the absorbing medium

has not been obtained experimentally. Self-induced transparency in a cell with rubidium isotope vapor placed inside a laser cavity was obtained for the first time in [21]. For this purpose, a Ti:sapphire laser containing the cell with rubidium vapor was brought into the regime of passive mode locking with the help of a semiconductor saturable absorber mirror (SESAM). By tuning the lasing wavelength by a spectral selector within the cavity to the resonance transition in rubidium vapor, the authors of [21] observed an increase in the pulse duration, the reduction of the lasing stability, and an increase in the pulse repetition period with an increase in the concentration of rubidium in the intracavity cell. The authors of [21] presented calculations and estimates that, in their opinion, give evidence of the emergence of SIT at the resonance transitions of rubidium. They do not mention whether they were able to obtain the SIT regime without achieving mode locking by a SESAM element. Thus, it has remained unclear whether a cell with rubidium vapor, where optical transitions have a long relaxation time T_2, can induce mode locking, and whether pulses arising in this case will be SIT pulses. Here, we use a layout based on a Ti:sapphire laser with an intracavity cell with rubidium vapor to experimentally demonstrate the occurrence of self-started mode locking that emerges solely owing to the effect of SIT in rubidium vapor.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The Ti:sapphire laser was assembled on an optical breadboard using a set of standard laser parts from TECHNOSCAN. Laser wavelength tuning was carried out by a Lyot filter (LF). For the additional narrowing of the laser line, an etalon Fabry–Perot interferometer (EFP) could be introduced inside the cavity. Radiation from a VERDI V10 pump laser (Coherent) was focused into the Ti:sapphire crystal 1 using mirror M and lens L. The cell with rubidium vapor (the natural mixture of isotopes) was placed in front of the output mirror M5 of the cavity. The cell windows were oriented at the Brewster angle to minimize losses. The length of the cell was 8 cm. The cell could be introduced into or removed from the cavity, heated, or cooled. The time dependence of the laser emission intensity was recorded using a fast photodiode and a DSO 9104A oscilloscope (Agilent Technologies), the laser wavelength was determined by a spectrometer, and the laser output power was monitored by a MAESTRO power meter (Standa).

EXPERIMENTAL RESULTS

When the rubidium vapor cell was placed in the Ti:sapphire laser cavity and the oscillation wavelength was tuned to the region of resonance absorption of Rb, laser mode locking set in, accompanied by luminescence in the cell. Figure 2 shows the waveforms of the pulses.

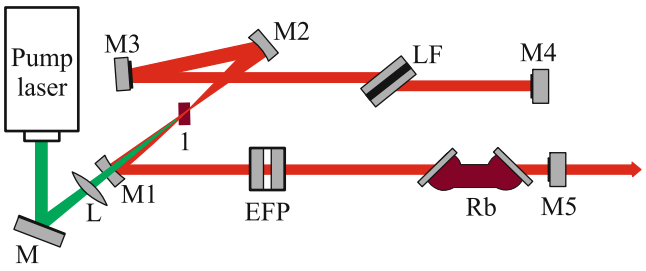

Fig. 1. (Color online) Layout of the Ti:sapphire laser with a cell containing rubidium vapor in the cavity: (1) Ti:sapphire crystal; (M1, M2) spherical mirrors; (M3) auxiliary mirror; (M4, M5) cavity high reflector and output coupler with a transmission coefficient of about 8%, respectively; (M) pump mirror; (L) pump focusing lens; (LF) Lyot filter; and (EFP) Fabry–Perot etalon.

Mode locking occurred when wavelength tuning was performed by the Lyot filter both without a Fabry–Perot etalon and with one. When the cell was cooled with cotton wool soaked with liquid nitrogen, mode locking disappeared. As nitrogen evaporated and the cell heated to a temperature of 24°C, mode locking was restored. When the cell was heated from 24 to 70°C, mode locking persisted. It should be noted that mode locking started spontaneously when the lasing wavelength was tuned to the rubidium absorption line. No additional action was required. The mode locking regime persisted for a long time (tens of minutes), although no special measures were taken to stabilize the cavity in the experimental setup. It is known that Ti:sapphire lasers can operate in the self-mode-locking regime owing to the nonlinear Kerr lens in the active element. By applying an external stimulus, short-term mode locking for a period of a dozen microseconds could be obtained at much higher lasing powers of 0.4–0.8 W when the rubidium cell and the selective elements were removed from the cavity. In our experiments, the highest output power did not exceed 0.15 W, and the power inside the cavity was also fairly low. Self-mode-locking was not observed at wavelengths beyond the absorption lines of rubidium even upon the application of such stimuli as using a mechanical impact to initiate vibrations of the mirrors and the breadboard hosting the laser cavity or upon the introduction of diaphragms. In this situation, rubidium vapor could not provoke self-mode-locking owing to the Kerr nonlinearity. Taking into account that, under the implemented experimental conditions, $T_2 = 2T_1$, where $T_1 = 27$ ns [21, 22], and the laser pulse duration is shorter than this value, the interaction of radiation with transitions in rubidium vapor has a coherent character. The single pulse generation per roundtrip time suggests that these pulses should be of SIT nature: initially, the pulse excites the absorbing medium, and then the energy from the medium

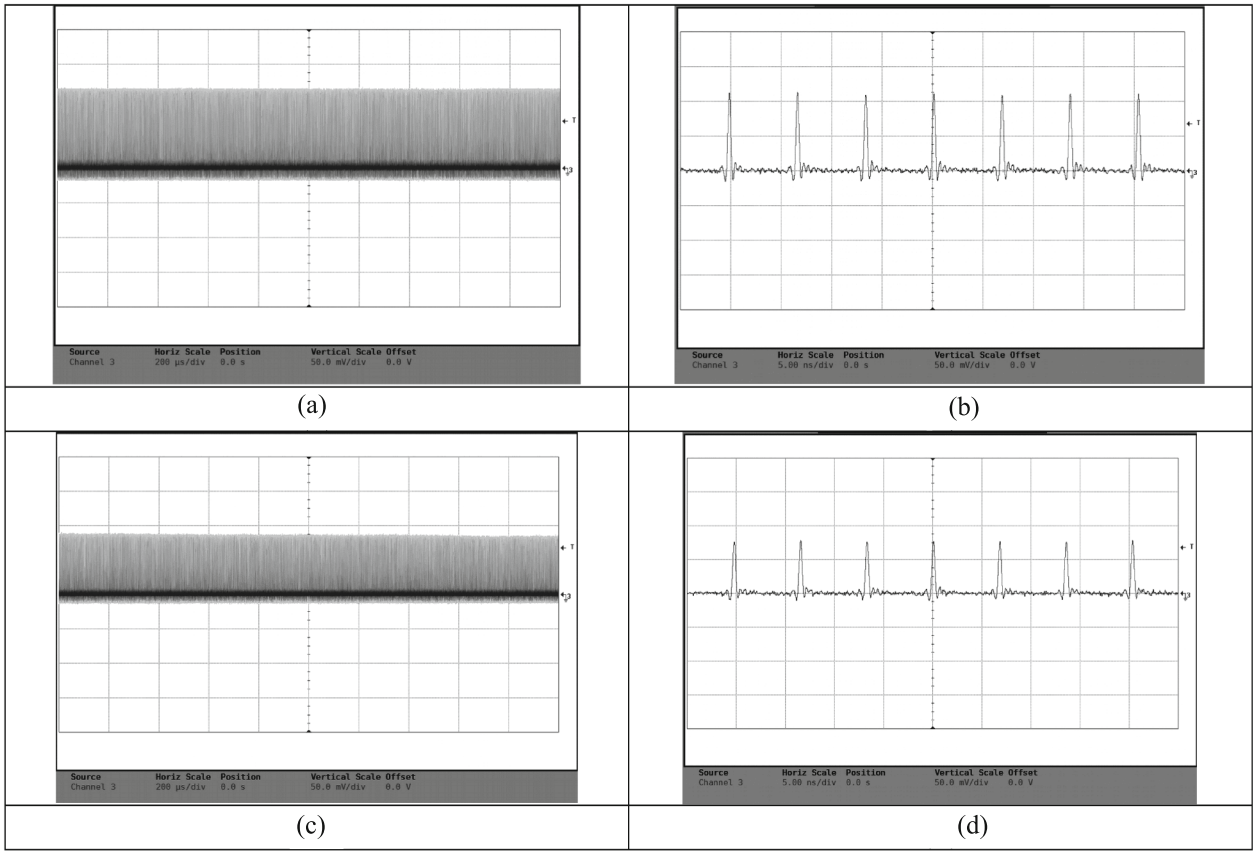

Fig. 2. Waveforms of pulse trains emitted by the Ti:sapphire laser with a cell containing rubidium vapor at a temperature of 24°C. The laser wavelength is tuned in resonance with (a, b) 780-nm DII and (c, d) 795-nm DI lines. The horizontal axis scale is (a, c) 200 μs/division and (b, d) 5 ns/division.

returns back to the pulse. After the passage of the pulse, the medium should remain in the initial unexcited state, and the energy losses are minimal. If the SIT regime is established in the cavity, the area of the pulse envelope will be 2π and will remain unchanged when the pulse energy changes. This means that, with an increase in the laser output power, the pulse duration will decrease.

Let us derive a relation for estimating the pulse duration as a function of the laser output power. The duration should correspond to the Rabi period $T_{\text{Rabi}} = \dfrac{2\pi}{\Omega_{\text{Rabi}}}$. The Rabi frequency is $\Omega_{\text{Rabi}} = \dfrac{d_{12}E}{\hbar}$, where E is the electric field strength, d_{12} is the dipole moment of the transition (equal to 7.5 D in Rb [22]), and $\hbar$ is the reduced Planck constant. The field strength can be expressed in terms of the power density W in the pulse. In electrostatic units, the relation is $E(\text{ESU}) = 27\sqrt{\left(W\left(\dfrac{\text{W}}{\text{cm}^2}\right)\right)\Big/300}$ [23]. The power density can be written as $W = \dfrac{P_{\text{out}}T_{\text{cav}}}{T_r\tau\pi(D/2)^2}$, where P_{out} is the measured power, T_r is the transmission coefficient of the cavity output coupler, T_{cav} is the time taken by a pulse to make a round trip of the linear cavity, τ is the pulse duration, and D is the diameter of the beam in the cavity in the region of the rubidium cell. For further estimation, we assume that the pulse has a rectangular shape, in which case $\tau = T_{\text{Rabi}}$. Then, the pulse duration τ can be expressed in terms of the measured power as

$$\tau = \left(\frac{22\pi h}{d_{12}}\right)^2 \frac{T_r\pi\left(\dfrac{D}{2}\right)^2}{T_{\text{cav}}}\frac{1}{P_{\text{out}}}. \qquad (1)$$

One can see that the duration of SIT pulses is inversely proportional to the output power P_{out}.

The pulse duration τ calculated by Eq. (1) is compared with the experimental values in Fig. 3. The shortest pulse duration of 80 ps was obtained for an output power of 0.094 W and measured by an interferometric autocorrelator. The theoretical estimates are in good agreement with the experimentally determined pulse durations.

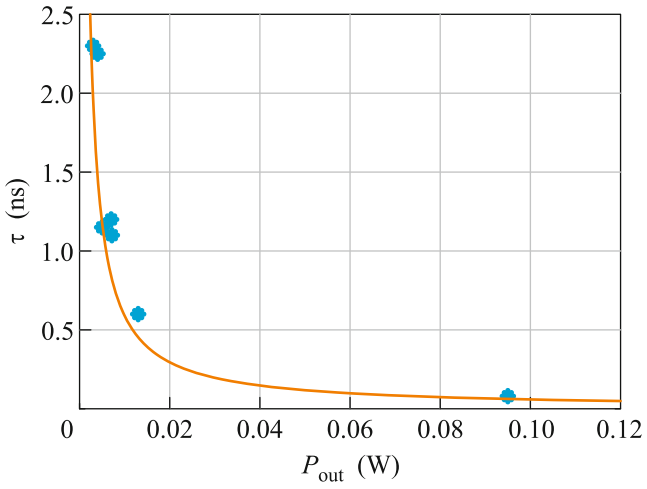

Fig. 3. (Color online) Laser pulse duration versus the output power. Symbols show the measured values of the pulse duration and the solid line shows the result of calculation by Eq. (1).

CONCLUSIONS

The body of experimental results along with theoretical estimates allows us to conclude that laser mode locking observed in the described experiments occurred owing to the formation of SIT pulses in rubidium vapor. No conditions for self-mode-locking in the regime of saturable absorber existed in the laser, since the pulse durations were significantly shorter than the relaxation time T_2. The pulse duration corresponded to pulses with an area of 2π.

To summarize, we have, to the best of our knowledge, for the first time demonstrated experimentally the regime of passive mode locking that emerges owing to the presence of a coherent absorber where SIT pulses are formed, rather than as a result of absorption saturation. This regime is promising for generating extremely short laser pulses.

The study was carried out using the equipment of the Resource Center for Optical and Laser Methods of Materials Research, Scientific Park of St. Petersburg State University. This study is included in the work plan of the project application no. 19-72-00012 for the Russian Science Foundation.

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Translated by M. Skorikov