PHYSICAL REVIEW A **101**, 013803 (2020)

Self-induced-transparency mode locking in a Ti:sapphire laser with an intracavity rubidium cell

M. V. Arkhipov,[1,2] A. A. Shimko,[1] N. N. Rosanov,[2] I. Babushkin,[3,4,5] and R. M. Arkhipov[1,2,*]
[1]*St. Petersburg State University, 7/9 Universitetskaya Naberezhnaya, St. Petersburg, 199034, Russia*
[2]*ITMO University, Kronverkskiy Prospekt 49, St. Petersburg, 197101, Russia*
[3]*Institute of Quantum Optics, Welfengarten 1, 30167, Hannover, Germany*
[4]*Cluster of Excellence PhoenixD (Photonics, Optics, and Engineering—Innovation across Disciplines), 30167, Hannover, Germany*
[5]*Max Born Institute, Max-Born-Strasse 2a, Berlin, 10117, Germany*

(Received 22 July 2019; published 7 January 2020)

In self-induced-transparency (SIT) mode locking, 2π SIT solitons with a duration much smaller than the polarization relaxation time T_2 in the gain and absorber are formed in a laser cavity. This is in contrast to standard passive mode-locking schemes based on gain and absorption saturation. Despite the great promise, up to now SIT mode locking with 2π pulses was mainly studied theoretically. In this paper, a stable self-starting passive mode locking is demonstrated experimentally in a Ti:sapphire laser with a Rb vapor cell. We show that the mode locking indeed appears to be due to SIT in the Rb cell; that is, the pulse in the Rb cell is a 2π SIT soliton. We also confirm self-starting of the SIT mode locking. Self-starting takes place via a set of intermediate regimes, including the one containing zero-area pulses.

DOI: 10.1103/PhysRevA.101.013803

I. INTRODUCTION

One of the most noticeable phenomena in nonlinear optics is the self-induced transparency (SIT) described theoretically and observed experimentally by McCall and Hann in the very beginning of the laser era [1,2]. In a medium with a resonant transition having dipole moment d_{12} and relaxation times T_1, T_2 (of the population and atomic polarization, respectively), optical pulses resonant with the atomic transition can propagate without losses if the light-matter interaction is "coherent"; that is, if the pulse duration is $\tau < T_2$, and, in addition, the pulse area S of the slow envelope $\varepsilon(t)$ defined as $S = \frac{d_{12}}{\hbar} \int \varepsilon(t)dt$ (here $\hbar$ is the Planck constant) satisfies the condition $S = 2\pi$ [2]. Such pulses are called 2π pulses. Propagation without losses arises because the pulse transfers its energy to the atoms on the leading edge of the pulse, so that the atoms are excited, after which the medium transfers the energy back to the pulse on its trailing edge, fully returning to the ground state. That is, a full Rabi oscillation occurs. This process takes place on timescales less than the relaxation times; therefore the energy is not dissipated and the energy losses are absent.

There is another possibility to transmit the energy without losses on the resonant frequency, namely, if the pulse area $S = 0$ (so-called 0π pulse), and the radiation takes the form of two linked subpulses with the opposite signs of the envelope [2–5]. The spectrum of a 0π pulse consists of two peaks in the frequency space located on both sides of the resonance.

SIT can be used to modulate nonlinear losses in a cavity and thus to achieve a passive mode locking [6–15]. 0π or 2π pulses have the lowest losses in the absorber among all other pulse shapes, making them stable attractors of the system. In particular, if a small perturbation arises on the background of a 2π pulse, it is absorbed by the absorber and thus disappears. SIT-induced 2π pulses in a cavity are more preferable than 0π ones because of a more attractive temporal and spectral shape. Therefore, the "term "SIT" typically refers to 2π pulses [1–3]. Later on, we also will assume, namely, 2π pulses when speaking about SIT mode locking.

As the pump power increases, the SIT-induced pulse duration decreases [1–3]. This is an extremely attractive property of SIT mode locking since there is no lower limit on the duration of Rabi oscillations, and thus there exists a possibility to generate few-cycle pulses as was predicted theoretically in [11,12].

Despite this, a possibility to use SIT for mode locking (in the sense of producing 2π pulses) has been discussed up to now only theoretically [6–15]. One of the reasons is that, as is typically believed, SIT mode locking with 2π pulses is rather difficult to realize in practice since the experiments with the SIT effect in pulse propagation are rather cumbersome [16]. The activity in this direction was limited also because of the counterintuitive nature of the fact that narrow lines can nevertheless produce ultrashort pulses; in addition, most of the theoretical works were made in a two-level approximation which is hardly suitable for few-cycle pulses, which also certainly delayed the onset of practical interest.

Practically, to realize passive mode locking in two-section lasers (absorber and amplifier sections) resonant absorbers have been long and successfully used [17–21] but, in contrast to a SIT absorber, those absorbers work in the incoherent regime (pulse duration is larger than medium polarization relaxation time, $\tau > T_2$). For such saturable absorbers the pulse duration is fundamentally limited by the width of the transition line in the absorber. Typically, the amplifier also works in the incoherent regime, which puts additional limitations on the minimal pulse duration.

---

[*] arkhipovrostislav@gmail.com

Up to now, any attempt to obtain mode locking with SIT effects (2π pulses in absorber) and, furthermore, to show the absence of the usual pulse duration limitations, was unsuccessful. One should, however, mention the recent work [22] in which a passive mode locking in a Ti:sapphire laser with an intracavity Rb-87 cell was achieved using a semiconductor saturable absorbing mirror (SESAM). In that work the SIT pulses were indeed obtained in a Rb cell; however, they were not the cause of mode locking. In contrast, the opposite effect was observed: As the pump wavelength of the already mode-locked laser was tuned to the Rb resonance using an intracavity spectral filter, increasing of the pulse duration, decrease of the mode-locking stability, and increasing of the repetition rate were observed in [22]. In addition, in our recent experiments, we observed mode locking in a cw dye laser with a coherent absorber (cells with molecular iodine vapor) [23,24]. However, the mode locking occurred via formation of 0π pulses and not 2π SIT ones.

In a recent short communication [25], we indeed achieved, experimentally, mode locking in a Ti:sapphire laser with a coherent absorber. Here, we extend [25] and provide a detailed experimental study of coherent SIT mode locking. We use an intracavity Rb cell as a nonlinear coherent resonant absorber in a Ti:sapphire laser cavity, and probe different cavity geometries. We show that the Rb cell causes stable self-starting passive mode locking at low pump levels, much less than typically needed for Kerr mode locking. We claim that the mode locking is caused by the SIT effect in the Rb cell; that is, the resulting pulses are indeed 2π pulses in the absorber. We also study experimentally the mode-locking onset scenarios and show that it significantly differs from the ones observed in passive mode-locked lasers with a saturable absorber. In particular, we confirm the full self-starting of the SIT mode locking recently predicted theoretically in [14].

II. EXPERIMENTAL SETUP

The setup we used is shown in Fig. 1. A Ti:sapphire laser with several cavity designs was assembled on an optical table using standard components of a commercial laser (Technoscan). To these components belonged a sapphire crystal (1) and spherical and plane mirrors (M1–M6). For tuning the wavelength of the laser a Lyot filter, a Fabry-Pérot étalon, and prisms were used. The output of the pump laser Verdi V10 (Coherent) was focused, using the mirror (M) and the lens (L), through the mirror M1 into the Ti:sapphire crystal (1). A chopper was put into the pump beam path, allowing to set the pump duration from 500 μs to cw to study the self-starting of the mode locking. 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 were used. The cell was placed before the output mirror of the cavity M5 and could be warmed and cooled. Mode locking was observed in three different cavity designs, namely, the linear cavity (a), (b) and the ring cavity (c).

The wavelength tuning in the cavity design (a) was accomplished by rotating of the mirror M4, and in (b), (c) the Lyot filter LF and the Fabry-Pérot interferometer EFP were used for this goal. Laser intensity dependent on time was registered using a high-speed photodiode and an oscilloscope DSO 9104A (Agilent Technologies) with a temporal resolution of 300 ps. The wavelength was determined by a spectrometer and the power was measured by a Maestro power meter 8Standa). To estimate the pulse durations we used an interferometric autocorrelator based on the Michelson interferometer, as well as the Fabry-Pérot interferometer with a variable base.

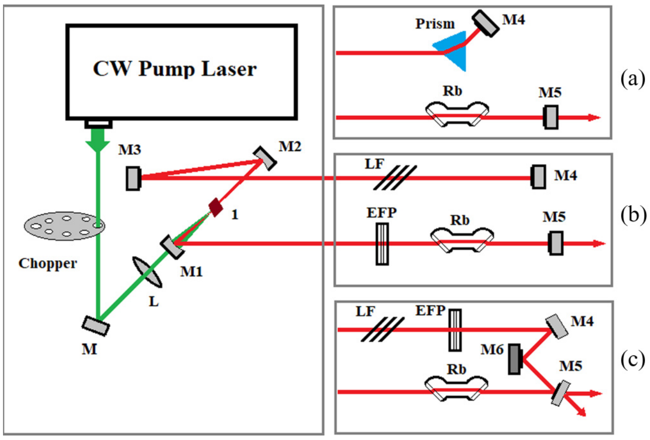

FIG. 1. Different cavity configurations of a Ti:sapphire laser with a Rb vapor cell. (a), (b): Two variants of a linear cavity with different spectrally selective elements. (c): A ring cavity. Here 1 is a Ti:sapphire crystal, M1 and M2 are the confocal mirrors of the cavity, M3 is an auxiliary mirror, M4 and M5 are the fully reflecting mirror and the output mirror (transparency around 8%), M6 is a fully reflecting auxiliary mirror, M is the mirror in the pump channel, L is a focusing lens, LF is the Lyot filter, and EFP is the Fabry-Pérot étalon, Prism is a prism for tuning the lasing wavelength.

III. RESULTS

Mode-locking did not appear if the lasing wavelength was not tuned to the Rb transitions. Therefore, intracavity spectral filters that allow tuning of the lasing wavelength were used. Only with these spectral-selective elements, by tuning the wavelength to the resonant transitions DI (794 nm) and DII (780 nm) were we able to obtain mode locking. In the linear cavity design (a) (see Fig. 1) for the wavelength, tuning a prism was used, in (b) and (c) a Lyot filter and a Fabry-Pérot étalon were applied. Since no special measures to stabilize the laser were undertaken, mechanical instabilities and air flows led, after several minutes of operation, to drift of the filters from the cavity resonance; because of this, two filters were used to make the operation more stable. In this case, mode locking was conserved for a quite extended time, from tens of minutes to 1 h, which allowed us to make measurements without tuning of the cavity [in case (b)]. The ring cavity (c) was more stable than (a) but less stable than (b). In case (c), two counterpropagating waves were possible, with switching between them; they were difficult to control.

The mode-locking regimes were always accomplished by intense luminescence of the Rb vapor in the cell. This luminescence was absent when no mode locking was present. Besides, mode locking always disappeared if we cooled the cell with liquid nitrogen. In contrast, the mode-locking operation remained stable if the cell was warmed up to 70 °C. This allowed us to identify the Rb cell as the main ingredient of the mode locking. Since the mode locking was stably observed at the room temperature, the experiments described below were made without any warming of the cell.

The stable mode locking was observed in all three cavity designs on both Rb transitions, DI and DII. In the ring cavity (c), the mode locking was observed both if two counterpropagating waves were present simultaneously and if only one of the waves were there. Examples of the oscillograms of the output pulses in the mode-locking regime for the linear (b) and ring (c) cavity are shown in Fig. 2.

It is also well known that a Ti:sapphire laser can act in a mode-locking regime induced by the so-called Kerr lens [26,27]. In our experiments, however, the power was well below the Kerr lens mode-locking threshold. In particular, the maximal output power in our experiments was not higher than 0.15 W [because of the highly transmitting output mirror (8.2%) the intracavity power was also not large]. Without the Rb cell and selective elements, one needs much higher output power of 0.4–0.8 W to obtain the mode locking (which is in this case Kerr mode locking). Importantly, in this latter case the mode locking could only be obtained using a mechanical disturbance (mechanically kicking the mirrors and/or the optical plate), and the mode locking disappeared after several tens of μs. Therefore, we believe that the Kerr mechanism was not the reason for our mode locking.

In Rb vapors at room temperature the decay rates are well known: $T_2 \approx 2T_1$, $T_1 \approx 27$ ns [28]. The repetition period (in our experiments from 4 to 7 ns) and observed pulse durations (between 2 ns and 60 ps) are both noticeably less than T_2. Therefore, interaction of the radiation with the Rb transitions is clearly coherent. Because of the coherent character of the interaction, the losses in the Rb cell are zero for the pulses with the area $2\pi n$ with $n = 0, 1, \ldots$, in which case the energy after the pulse is fully returned back to the medium. The case of $n = 0$ (zero-area pulse) is excluded by the single-peak character of the pulses observed in experiments (zero-area pulses must have a double-peak structure as discussed before). On the other hand, it is known that the pulses with $n > 1$ are unstable and split into several 2π ones [1,2]. Hence, we see that the most probable pulse configuration is a pulse with the area $= 2\pi$ in the cell.

This fact can be checked experimentally. On the one hand, we can obtain the pulse duration from the intensity oscillograms or, when the duration is less than the resolution of the oscilloscope, we can use an autocorrelator and a scanning Fabry-Pérot interferometer. On the other hand, the duration of a 2π pulse can be estimated independently from the measured output power as follows: The Rabi period $T_{\rm Rabi} = \frac{2\pi}{\Omega_{\rm Rabi}}$ and Rabi frequency $\Omega_{\rm Rabi} = \frac{d_{12}E_0}{\hbar}$ (here E_0 is the peak field strength; the values of d_{12} for Rb are given in [28]) can be related to the output power $P_{\rm out}$ via the expression $W = \frac{P_{\rm out}T_{\rm cav}}{T_r\tau\pi(D/2)^2} = \frac{c\varepsilon_0}{2}E_0^2$, where T_r is the transmittivity of the cavity mirror, $T_{\rm cav}$ is the round-trip time, τ is the pulse duration, D is the diameter of the beam in the cell, c is the speed of light, and ε_0 is the vacuum permittivity. If, for simplicity, we assume a rectangular pulse shape, for a 2π pulse we have $\tau = T_{\rm Rabi}$. Combining the above expressions we will obtain

$$\tau = \left(\frac{2\pi\hbar}{d_{12}}\right)^2 \frac{c\varepsilon_0 T_r \pi \left(\frac{D}{2}\right)^2}{2T_{\rm cav}} \frac{1}{P_{\rm out}}. \qquad (1)$$

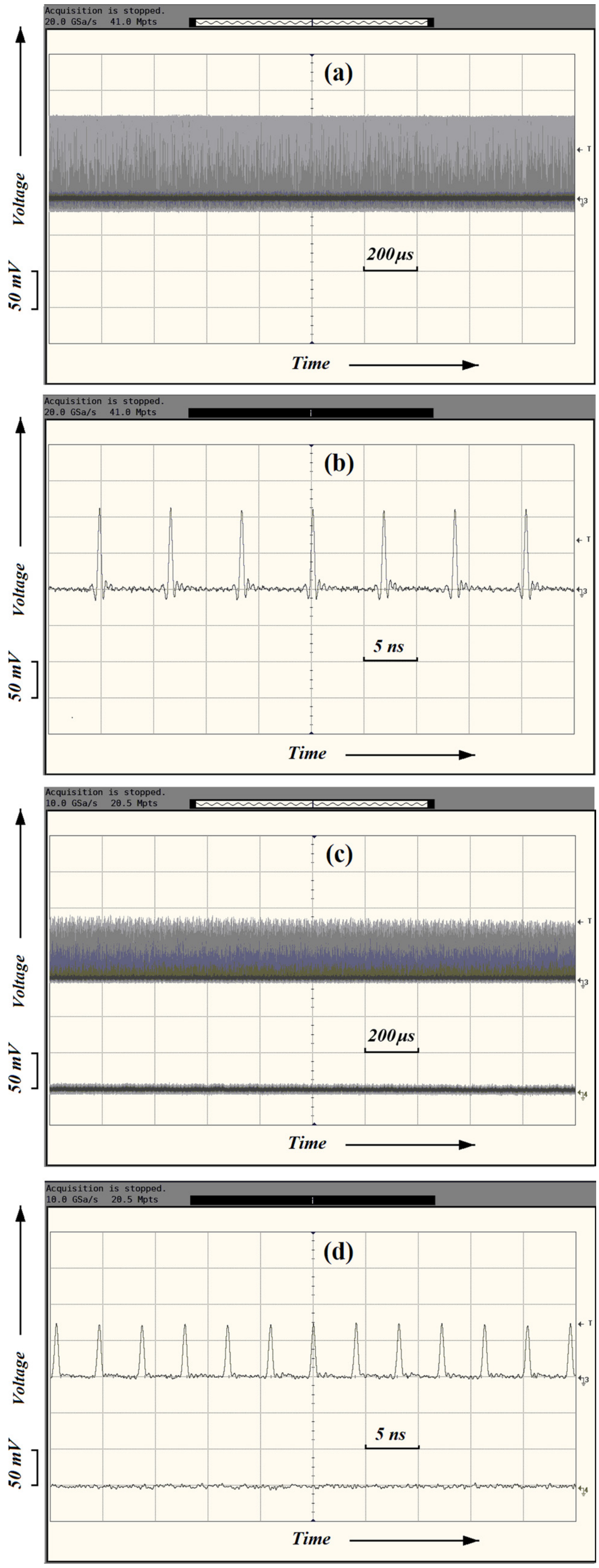

FIG. 2. Oscilloscope screenshots of mode-locking regimes in a Ti:sapphire laser with linear (a,b) and ring (c,d) cavity geometries, with the wavelength tuned to the transitions DII (a,b) and DI (c,d) of Rb. In (c,d), the upper (lower) line shows the clockwise- (anticlockwise-) propagating wave.

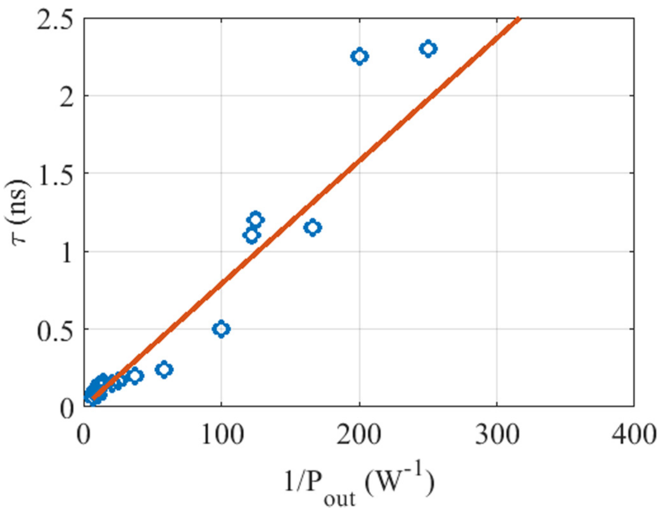

FIG. 3. Dependence of the mode-locked pulse duration for transition D1 in Rb on the inverse output power. Points show the measurements whereas the line depicts the prediction of Eq. (1).

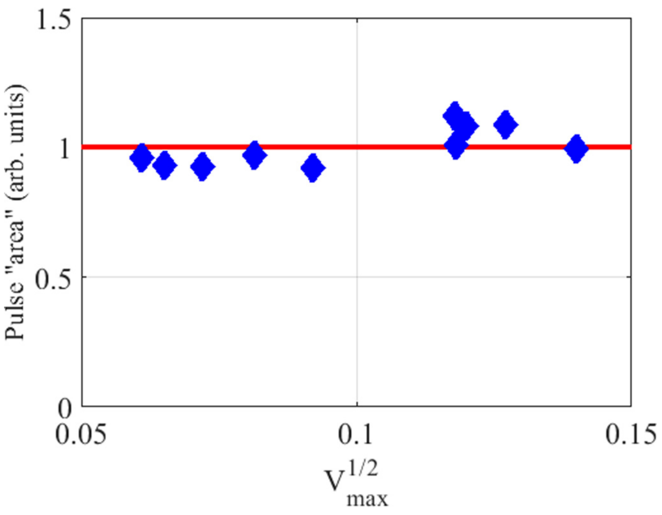

FIG. 4. Dependence of the pulse area (in arbitrary units) on the square root of the peak voltage (representing the peak field strength) for the mode-locked regime.

Equation (1) relates the duration of 2π pulses with the parameters, all of which are accessible from our measurements with a good precision (except the pulse diameter, which was not constantly monitored even though it could slightly vary with the pulse power). In Fig. 3 we show the pulse durations τ obtained using Eq. (1) for the line DI with the direct experimental measurements of P_{out}.

The results of Fig. 3 demonstrate rather good agreement between the pulse durations expected for 2π pulses and measured in our experiment, which confirms the SIT character of the pulses. As seen, in this case the pulse duration is inversely proportional to the output power.

Figure 3 clearly illustrates the decrease of the pulse duration with increase of power. This feature is typical for the SIT phenomenon [1–3]. This fact makes SIT mode locking significantly different from the standard passively mode-locked lasers where incoherent saturation of absorption takes place. Indeed, it was shown experimentally that the pulse duration in standard passively mode-locked lasers increases with increase of power; see, e.g., [29–32]. Physically this means that as the power increases, the absorber becomes more saturated and transparent for the coming pulse, and thus cannot play the role of a discriminator for the pulse anymore [33,34].

Another property of 2π pulses which can be experimentally checked is independence of the pulse area on the peak intensity. In Fig. 4 we show the dependence of the pulse area obtained directly from the pulse shape given by the oscillograms on the square root of the peak voltage (representing the peak field strength). It can be seen that, despite the peak voltage (intensity) changing about one order of magnitude, no significant change of the pulse area is observed.

An important peculiarity of the SIT mode locking is its possibility to self-start as was recently suggested theoretically [14]. Here we confirm the self-starting of our experimental scheme using a chopper which periodically breaks the pump beam, allowing us to study how the mode-locking regimes set up. The chopper was installed at the path of the pump beam allowing us to record the whole pulse train inside of every chopper cycle. We observed that the mode locking is stable and reestablishes reliably in the beginning of every cycle. An example of a typical pulse train is given in Fig. 5. It is quite different from a passive saturable absorber mode locking, where, according to the fluctuation model [33], the pulse develops from intensity fluctuations that arise at the initial lasing stage from a broadband radiation. The saturable absorber plays the role of a discriminator [34] of weak short pulses, which, combined with amplification, isolate and form a single fluctuation spike turning into a mode-locked pulse.

In a sharp contrast, a coherent absorber does not play a role of a discriminator. The scenario of the mode-locking emergence is rather complicated and is quite different from the one of the standard passive saturable absorber mode locking (see Fig. 5).

As is seen in Fig. 5, at the initial stage, several low-amplitude zero-area pulses are formed per round trip [Fig. 5(b)]. During further evolution, a single zero-area pulse survives [Fig. 5(c)]. This pulse has significantly higher amplitude than the initial pulses. As was already mentioned before, zero-area pulses have the form of two coupled pulses with the spectrum containing a valley at the transition frequency. This valley was also observed in the interferograms (not shown). At the final stage [Fig. 5(d)], a zero-area pulse turns into a single 2π one. This 2π pulse finally remains stable up to the point when the chopper breaks the pump. Our oscillograms are able to clearly distinguish the main peak in the 2π pulse. The oscillations observed at the trailing edge of the pulses we attribute to transients in the photodetector circuit and oscilloscope. The transition sequence remained the same from one pulse train to another, although exact transition time varied from train to train, and the whole transition to the stable mode locking took some time. Nevertheless, the final state with a single 2π pulse per round trip was achieved at every chopper cycle. Thus, the transition to the mode-locking state shows a reach intriguing dynamics with the stable mode locking as the final stage. Detailed study of the transient dynamics is interesting but beyond the scope of this article.

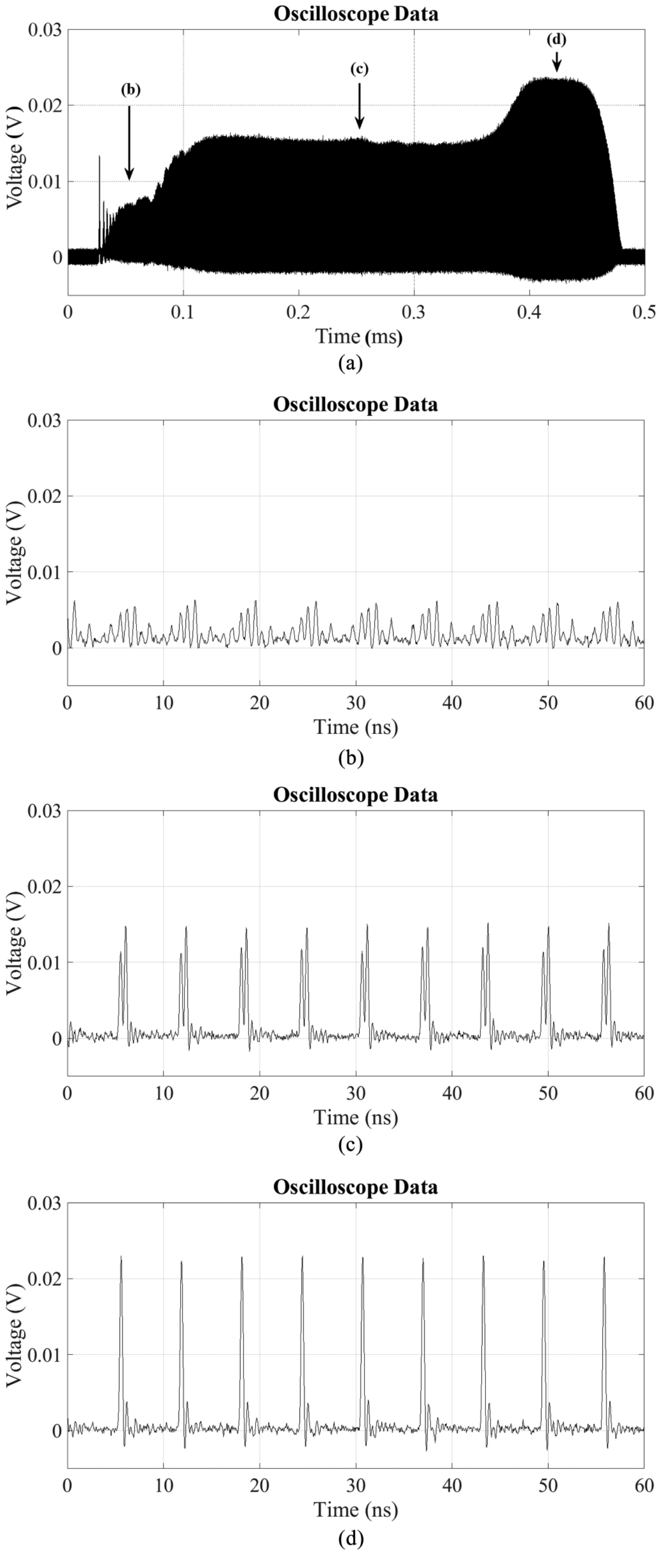

FIG. 5. Typical oscillograms of the mode-locked lasing from the moment when the chopper opens the pump to the moment when the pump is closed again, showing a reliable self-start of the mode locking at the Rb DII transition. (a) The lasing in the whole interval of the open pump. (b–d) Transition from several zero-area pulses per round trip (b) to a single zero-area pulse (c), and then to a single 2π SIT pulse (d).

IV. DISCUSSION

As is known, experiments with self-induced transparency (SIT) in atomic media in a propagation geometry are typically rather complex. Therefore, it was widely believed up to now that the SIT-based mode locking should be even more complicated in realization. However, as we see here, very stable mode locking can be quite easily obtained using rather standard techniques.

Nevertheless, a few points require care: Requirements of the optical quality of the cell windows are quite high. In our experiments we oriented them at the Brewster angle. Besides, rubidium vapor may settle on the windows thereby creating a thin metallic film invisible to the eye. It creates losses and thus prevents the laser from lasing. Therefore, it is necessary to ensure that Rb is absent on the cell windows, and remove it by heating if necessary. Finally, the beam cross section in the cell must be as constant as possible; otherwise the pulse will not have the same area across the cell. The losses grow dramatically and it becomes impossible to obtain the mode locking.

If these requirements are satisfied, it is not difficult at all to obtain the SIT mode locking: A Rb cell at room temperature is to be placed in the cavity of an arbitrary Ti:sapphire laser near the output mirror, and the mirror must be adjusted to produce lasing. After that, spectral intracavity filters are to be tuned to the transition of rubidium. Mode locking is accompanied by heavy luminescence in the cell, which is easy to see with the help of an IR visualizer. Besides the regular mode locking it is possible also to observe chaotic spiking.

In our experiments, we also placed the cell inside the cavity of a commercial Mira Optima 900-D (Coherent) laser, made readjustments and obtained mode locking at rubidium transitions. The maximum output power was 1.2 W. We used a natural mixture of rubidium isotopes.

Note that the wavelength range of the Ti:sapphire laser allows one to reproduce coherent mode locking not only in rubidium but also in cesium or potassium vapors.

V. CONCLUSIONS

We have demonstrated passive self-induced-transparency (SIT) mode locking in a Ti:sapphire laser, that is, mode locking arising due to coherent interaction of radiation with resonant transitions in an intracavity rubidium vapor cell, which in this case played the role of a coherent absorber. We have shown that the area S of the pulses, regardless of their power, is constant and is indeed equal to 2π; that is, pulses of self-induced transparency in the Rb cell take place.

Furthermore, we have demonstrated that the mode locking self-starts very stably, nevertheless demonstrating reach dynamics in transition from a nonlasing to mode-locking state. The minimal duration of the mode-locked pulses was two orders of magnitude shorter than the time T_2 of the absorber. That is, the relaxation time T_2 of the absorber does not limit the pulse duration. Finally, our mode locking was obtained at the input powers which are an order of magnitude less than needed for Kerr mode locking. Our experimental results show that, importantly, the pulse duration decreases with increase of the lasing power, in contrast to standard passive mode-locked lasers with a saturable absorber. Although our pulses have picosecond duration, here we make a step towards realization of the mode locking producing ultrashort pulses which are not limited by the absorber and amplifier linewidths.

Finally, we investigated experimentally the onset of the SIT mode locking. We found that at the initial stage zero-area pulse formation takes place, which afterwards approaches a stable 2π SIT pulse. This scenario differs dramatically from the one taking place in standard passively mode-locked lasers.

ACKNOWLEDGMENTS

R.M.A. thanks the Russian Science Foundation (Project No. 19-72-00012) for the financial support. I.B. is thankful to the DFG (Deutsche Forschungsgemeinschaft) for the financial support (Project No. BA 4156/4-2) as well as Germany's Excellence Strategy within the Cluster of Excellence PhoenixD (EXC 2122, Project ID 390833453). The investigations were performed at the Center for Optical and Laser Materials Research, Research Park, St. Petersburg State University.

[1] S. L. McCall and E. L. Hahn, Self-Induced Transparency by Pulsed Coherent Light, Phys. Rev. Lett. **18**, 908 (1967).

[2] S. L. McCall and E. L. Mahn, Self-induced transparency, Phys. Rev. **183**, 457 (1969).

[3] L. Allen and J. H. Eberly, *Optical Resonance and Two-Level Atoms* (Wiley, New York, 1975).

[4] M. D. Crisp, Propagation of small-area pulses of coherent light through a resonant medium, Phys. Rev. A **1**, 1604 (1970).

[5] J. E. Rothenberg, D. Grischkowsky, and A. C. Balant, Observation of the Formation of the 0π Pulse, Phys Rev. Lett. **53**, 552 (1984).

[6] V. V. Kozlov, Self-induced transparency soliton laser via coherent mode locking, Phys. Rev. A **56**, 1607 (1997).

[7] V. P. Kalosha, M. Müller, and J. Herrmann, Coherent-absorber mode locking of solid-state lasers, Opt. Lett. **23**, 117 (1998).

[8] V. P. Kalosha, M. Müller, and J. Herrmann, Theory of solid-state laser mode locking by coherent semiconductor quantum-well absorbers, J. Opt. Soc. Am. B **16**, 323 (1999).

[9] C. R. Menyuk and M. A. Talukder, Self-Induced Transparency Modelocking of Quantum Cascade Lasers, Phys. Rev. Lett. **102**, 023903 (2009).

[10] M. A. Talukder and C. R. Menyuk, Analytical and computational study of self-induced transparency mode locking in quantum cascade lasers, Phys. Rev. A **79**, 063841 (2009).

[11] V. V. Kozlov, N. N. Rosanov, and S. Wabnitz, Obtaining single-cycle pulses from a mode-locked laser, Phys. Rev. A **84**, 053810 (2011).

[12] V. V. Kozlov and N. N. Rosanov, Single-cycle-pulse passively-mode-locked laser with inhomogeneously broadened active medium, Phys. Rev. A **87**, 043836 (2013).

[13] R. M. Arkhipov, M. V. Arkhipov, and I. V. Babushkin, On coherent mode-locking in a two-section laser, JETP Lett. **101**, 149 (2015).

[14] R. M. Arkhipov, M. V. Arkhipov, and I. Babushkin, Self-starting stable coherent mode-locking in a two-section laser, Opt. Commun. **361**, 73 (2016).

[15] R. M. Arkhipov, M. V. Arkhipov, I. Babushkin, and N. N. Rosanov, Self-induced transparency mode locking, and area theorem, Opt. Lett. **41**, 737 (2016).

[16] R. E. Slusher and H. M. Gibbs, Self-induced transparency in atomic rubidium, Phys. Rev. A **5**, 1634 (1972).

[17] H. A. Haus, Mode-locking of lasers, IEEE J. Sel. Top. Quantum Electron. **6**, 1173 (2000).

[18] U. Keller, Recent developments in compact ultrafast lasers, Nature **424**, 831 (2003).

[19] E. U. Rafailov, M. A. Cataluna, and W. Sibbett, Mode-locked quantum-dot lasers, Nat. Photonics **1**, 395 (2007).

[20] U. Keller, Ultrafast solid-state laser oscillators: A success story for the last 20 years with no end in sight, Appl. Phys. B **100**, 15 (2010).

[21] J. C. Diels and W. Rudolph, *Ultrashort Laser Pulse Phenomena* (Elsevier, Amsterdam, 2006).

[22] K. Masuda, C. Affolderbach, G. Mileti, J. C. Diels, and L. Arissian, Self-induced transparency and coherent population trapping of ^{87}Rb vapor in a mode-locked laser, Opt. Lett. **40**, 2146 (2015).

[23] M. V. Arkhipov, R. M. Arckhipov, A. A. Shimko, and I. Babushkin, Mode-locking in a laser with a coherent absorber, JETP Lett. **101**, 232 (2015).

[24] M. V. Arkhipov, A. A. Shimko, R. M. Arkhipov, I. Babushkin, A. A. Kalinichev, A. Demircan, U. Morgner, and N. N. Rosanov, Mode-locking based on zero-area pulse formation in a laser with a coherent absorber, Laser Phys. Lett. **15**, 075003 (2018).

[25] M. V. Arkhipov, R. M. Arkhipov, A. A. Shimko, I. Babushkin, and N. N. Rosanov, Mode locking in a Ti:sapphire laser by means of a coherent absorber, JETP Lett. **109**, 634 (2019).

[26] D. E. Spence, P. N. Kean, and W. Sibbett, 60-fsec pulse generation from a self-mode-locked Ti:sapphire laser, Opt. Lett. **16**, 42 (1991).

[27] U. Morgner, F. X. Kartner, S. H. Cho, Y. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, and T. Tschudi, Sub-two-cycle pulses from a Kerr-lens mode-locked Ti:sapphire laser, Opt. Lett. **24**, 411 (1999).

[28] D. A. Steck, Rubidium 87 *D* line data, available at http://steck.us/alkalidata (rev. 2.1.1) (2009).

[29] A. Kovsh, A. Gubenko, I. Krestnikov, D. Livshits, S. Mikhrin, A. Zhukov, and E. Portnoi, Quantum dot mode-locked and broad-band lasers for optical interconnect solutions, in *2006 IEEE 20th International Semiconductor Laser Conference, 2006, Conference Digest* (IEEE, New York, 2007), pp. 147–148.

[30] Y. C. Xin, V. Kovanis, Y. Li, A. L. Gray, L. Zhang, and L. F. Lester, 1.3-μm quantum dot monolithic multi-section passively mode-locked lasers, in *LEOS 2006—Proceedings of the 19th Annual Meeting of the IEEE Lasers and Electro-Optics Society* (IEEE, New York, 2007), pp. 872–873.

[31] M. G. Thompson, A. R. Rae, M. Xia, R. V. Penty, and I. H. White, InGaAs quantum-dot mode-locked laser diodes, IEEE J. Sel. Top. Quantum Electron. **15**, 661 (2009).

[32] D. I. Nikitichev, Y. Ding, M. A. Cataluna, E. U. Rafailov, L. Drzewietzki, S. Breuer, W. Elsaesser, M. Rossetti, P. Bardella, T. Xu *et al.*, High peak power and sub-picosecond Fourier-limited pulse generation from passively mode-locked monolithic two-section gain-guided tapered InGaAs quantum-dot lasers, Laser Phys. **22**, 715 (2012).

[33] P. G. Kryukov and V. S. Letokhov, Fluctuation mechanism of ultrashort pulse generation by laser with saturable absorber, IEEE J. Quantum Electron. **8**, 766 (1972).

[34] P. G. Kryukov, Continuous-wave femtosecond lasers, Phys. Usp. **56**, 849 (2013).