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Self-starting stable coherent mode-locking in a two-section laser

R.M. Arkhipov [a], M.V. Arkhipov [b], I. Babushkin [c,d,*]

[a] Saint-Petersburg State University of Information Technologies, Mechanics and Optics, St.Petersburg, Russia
[b] Faculty of Physics, St. Petersburg State University, Ulyanovskaya 1, Petrodvoretz, St. Petersburg 198504, Russia
[c] Institute of Quantum Optics, Leibniz University of Hannover, Germany
[d] Max Born Institute, Max Born Str. 2a, 12489 Berlin, Germany

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ABSTRACT

Coherent mode-locking (CML) uses self-induced transparency (SIT) soliton formation to achieve, in contrast to conventional schemes based on absorption saturation, the pulse durations below the limit allowed by the gain line width. Despite the great promise it is difficult to realize it experimentally because a complicated setup is required. In all previous theoretical considerations CML is believed to be non-self-starting. In this paper we show that if the cavity length is selected properly, a very stable (CML) regime can be realized in an elementary two-section ring-cavity geometry, and this regime is self-developing from the non-lasing state. The stability of the pulsed regime is the result of a dynamical stabilization mechanism arising due to finite-cavity-size effects.

1. Introduction

Development of ultrashort laser pulse sources with high repetition rates and peak power is an area of principal interest in optics. Such lasers have applications in a high-bit-rate optical communications, real time-monitoring of ultrafast processes in matter, etc. A well-known method for generating high power ultrashort optical pulses is a passive mode-locking (PML) [1–6]. In order to achieve PML, a nonlinear saturable absorbing medium is placed into the laser cavity. In the most of existing passively mode-locked lasers generation of ultrashort pulses arises due to the absorption/gain saturation in the gain and absorber sections [7–9,1]. Thus, in the most schemes the ultimate limit on the pulse duration τ_p is set by the medium polarization relaxation time T_2, that is, $\tau_p \gtrsim T_2$. The interaction of the pulse with resonant gain and absorber media is not coherent in the sense that the medium polarization just follows the field and thus can be adiabatically eliminated [1,7–14]. This is valid also in the case when the absorber enters the coherent regime (see below) whereas the gain medium is still in the usual regime of the gain saturation [15–19].

Another new way to achieve ultrashort pulse generation was proposed theoretically in [20,21] [see Fig. 1(a)] where it was named "coherent mode-locking" (CML), or self-induced-transparency (SIT) mode-locking, as it is called sometimes [22,23]. In this approach interaction of light with matter is so strong, that the medium polarization and inversion change significantly on the time scale of the pulse duration, and Rabi oscillations arise [24–26] (coherent regime). In this case, because the period of Rabi oscillations is not limited from below, the pulse duration can be significantly smaller than the medium coherence time, $\tau_p \ll T_2$, and the presence of the phase memory on the scale of T_2 changes the evolution of the pulse dramatically. Unlike the common passive mode-locking with a slow saturable absorber [7,1,27,28], where the absorption is just saturated near the pulse center [see Fig. 1(b)], in the case of coherent interaction it is completely inverted, so that the population inversion crosses zero and changes its sign. As a result, such pulse propagates without losses in the absorber in the regime of self-induced-transparency (SIT) (2π pulse), thus forming a soliton. In the gain section the pulse takes all the energy from the medium (π pulse), making it highly absorbing (that is, again, the population inversion changes it sign), in contrast to common lasers schemes, where the population inversion in the gain section either does not change significantly [as in Fig. 1(c)], or changes relatively slightly, without crossing zero [as in Fig. 1(b)]. Because of this, such SIT-induced solitons are fundamentally different in their dynamics from the pulses appearing in the saturable schemes [27–29].

Contrary to the conventional passively mode-locked lasers with a saturable absorber, CML lasers can generate optical pulses with a duration much shorter than T_2, i.e. with the spectrum exceeding the bandwidth of the gain medium. Moreover, it was predicted [20,21,30,31] that pulse duration from CML lasers can approach

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[*] Corresponding author at: Institute of Quantum Optics, Leibniz University Hannover, Germany.
E-mail address: ihar.babushkin@googlemail.com (I. Babushkin).

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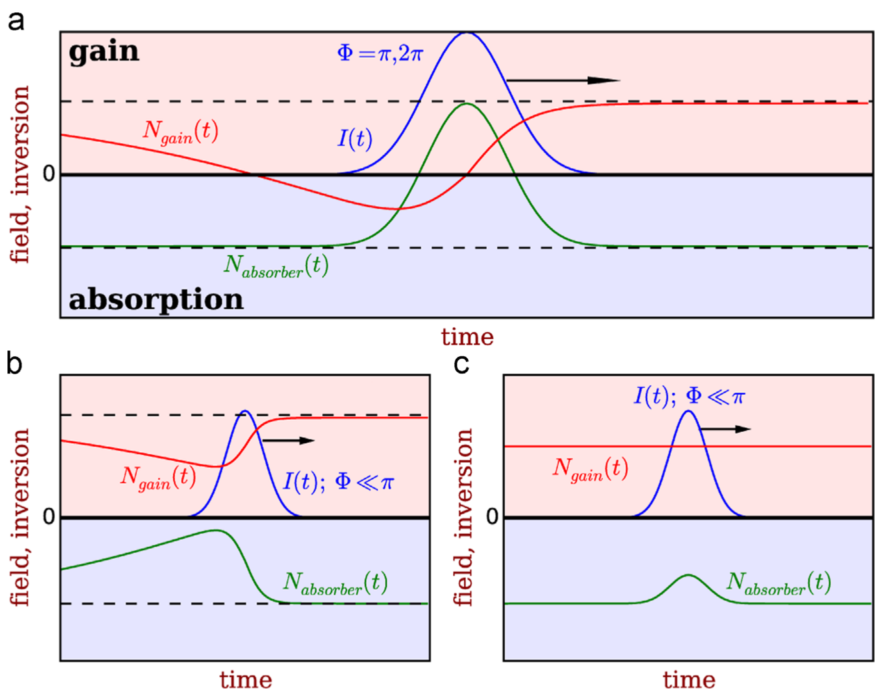

Fig. 1. Essential details of coherent mode-locking (CML) (sometimes refereed to as "SIT mode-locking"). (a) Dependence of the field intensity $I(t)$ and population inversion N_{gain}, N_{absorber} in the gain and absorber sections in the CML regime. The pulse area Φ [see Eq. (4)] is π in the gain section (a half of a Rabi oscillation) and 2π in the absorber (a whole a Rabi oscillation); in both sections the population inversion changes its sign. In the absorber, the population returns back to its equilibrium value (lower dashed line) on the pulse duration despite much slower relaxation time T_{1a} of the absorber medium. The gain section is also switched from "amplifying" to "absorbing" state and then slowly, on the time scale of the population relaxation time T_{1g}, returns back to its own equilibrium value (upper dashed line). For comparison, in (b) passive mode-locking with a slow saturable absorber and gain saturation is demonstrated with N_{gain}, N_{absorber} having different equilibrium values shown by dashed lines. In this case, both gain and absorber sections are only saturated, without onset of Rabi oscillations ($\Phi \ll \pi$). In this case, long tails of population inversion relaxing after the pulse passage appear. In (c), mode-locking with a fast absorber (such as Kerr lens) and no gain saturation is presented. Note some similarity of the absorber behavior in (a) and (c) despite fundamentally different relaxation rates of the absorber [T_{1a} in (a) and instantaneous in (c)], which is the consequence of the coherent regime.

the single optical cycle limit despite narrow-band gain and absorber, even in the presence of homogeneous line broadening [31], dispersion, and the complex level structure [32].

Unfortunately, despite the great promise, there was no experimental demonstration of CML in configuration proposed in [20,21,30,31] up to now. However, generating pulses shorter than T_2 in mode-locked argon-ion laser with active mode-locker and in self-locked He–Ne laser was demonstrated experimentally in Refs. [33,34] and [35], respectively. In our recent work [36] we have shown experimentally a mode-locking regime with a pulse duration less than T_2 in the absorber. Also, in [22,23] quantum cascade laser structures were proposed as candidates for experimental realization of CML regime.

Theoretical study of CML performed in [20–23,30,31] was carried out for a laser with the gain and absorber implemented within the same sample, that is, as a "homogeneous mixture" of the amplifying and absorbing media. Such proposals have, however, some important disadvantages. First, the pulsed regime cannot develop spontaneously from a non-lasing state. Namely, to ensure the stability of the pulse one have to suppress background fluctuations far away from it, thus automatically making the non-lasing steady state stable and the whole laser non-self-starting. That is, to initiate a soliton, one needs a seed pump pulse injected to the laser. The necessity to make CML lasers non-self-starting follows thus from a solitonic character of the coherent mode-locking. In contrast, many non-CML mode-locking lasers can indeed stably self-start even if the absorber (but not the amplifier) works in coherent regime [16,19]. Nevertheless the problem of self-starting is also actual for other existing fast mode-locking schemes such as Kerr-lens mode-locking [5]. The second important drawback is the necessity of a "homogeneous mixture" of the amplifier and absorber assumed in the works on CML up to now, which, although ensures a solitonic character of the mode-locking, makes its practical implementation rather difficult.

In this paper, we consider a simple scheme of CML-based mode-locking with the amplifying and absorbing media being well separated spatially, forming rather usual two-section geometry. A possibility of the CML is this case was shortly reported by us in [37]. In the present article we focus on the problem of self-starting of CML regime in such geometry and analyze in detail characteristic behavior of the system. We demonstrate that if the cavity length is selected properly, we can cross the point where the non-lasing state is becoming unstable, nevertheless obtaining good fundamental CML regime. That is, no need of a seed pulse is necessary anymore, in contrast to previous considerations [20–23,30,31]. The resulting pulsed attractor is stabilized globally due to finite-size effects in the cavity. We focus our attention on the gaseous media with T_2 in the range of nanoseconds, so that we have no need to approach single-cycle limit to overcome T_2, which significantly simplifies the required model. Nevertheless, this scheme is very attractive as a source of picosecond pulses with high power and high repetition rate >1 GHz.

2. The model

The ring-cavity configuration considered in this paper is shown in Fig. 2a. Between the mirrors, only one of which is assumed partially reflecting with the reflection coefficient R, and the others are "ideal" for simplicity, a gain and an absorber sections are placed. Both sections consist of resonant nonlinear medium, tuned to the same frequency. The coupling to the field, namely the dipole moment of active "atoms" is different for both sections. The media and field are described in the two-level and slowly varying