Melting and freezing of light pulses and modes in mode-locked lasers

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Abstract: We present a first experimental demonstration of melting of light pulses and freezing of lightwave modes by applying external noise which acts like temperature, verifying our recent theoretical prediction (Gordon and Fischer [1]). The experiment was performed in a fiber laser passively mode-locked by nonlinear rotation of polarization. The first order phase transition was observed directly in time domain and also by measurement of the quartic order parameter (RF power).

OCIS codes: (140.4050) Mode-locked lasers, (000.6590) Statistical mechanics

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When a saturable absorber element is inserted into a laser cavity, a remarkable phenomenon of passive mode-locking (PML) that gives short light pulses, occurs [2]. This has led to one of the most important and studied branches in laser physics and related technologies, now enabling light pulses as short as a few femto-seconds. Yet there are a few puzzling and less understood features of such lasers, as described below, which shed light on a unique aspect of these lasers: They present an interesting many body (many mode) system when many modes, with interaction between them due to various nonlinearities, are excited. The number of modes can reach $\sim 10^7 - 10^9$ in long fiber lasers that have broad gain bandwidths. The mode interaction induced by the saturable absorber in the laser cavity aligns (synchronizes) the temporal phases of all of the modes, compared to the random phase nature of the modes without the locking (see Fig. 1).

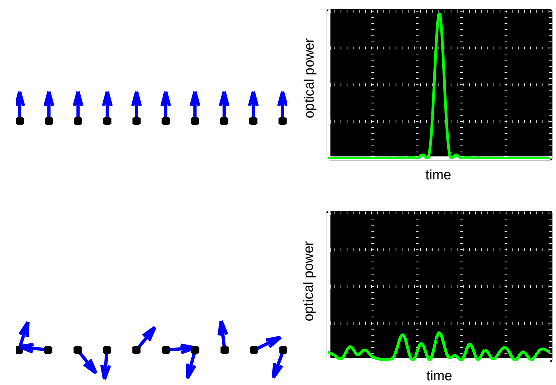

Fig. 1. Two regimes of a many-mode laser, illustrated in the spectral domain (on the left, where the length and angle of the arrow represent amplitudes and phases (phasors) of the electric field of the optical modes ("particles") respectively) and in the time domain (on the right). In the ordered state (phase) the modes are correlated (locked), and add up to form a pulse (upper pictures). In the disordered state (lower pictures) the non-correlated modes add up to a noisy "continuous" light.

The onset of pulses in such lasers is of a very intriguing nature [3] - [14] : When one turns the laser on, it usually produces "ordinary" continuous light rather than pulses. But when the laser pumping power is increased to reach a certain threshold, the laser falls abruptly into a highly ordered state, where a vast number of modes suddenly become correlated, and thus starts pulsating.

The above described threshold phenomenon is known for about 30 years, and the traditional theoretical approach to its study is dynamical ("mechanical") one: Over the years different kinds of nonlinear equations of motion have been analyzed [3] - [11] for the dynamical stability of their solutions against perturbations. It was found that various equations of motion have stable CW solutions for some range of parameters of the equations (often the population inversion or the laser power), but when one or several of the parameters exceed certain values, the CW solution loses stability and the system switches to a pulsed (mode locked) regime, which is stable at that range. This type of theories has provided models for various discontinuities in the operation of lasers, some of which are the lasing threshold and the mode locking threshold.

In a recent work [1] we presented a theory that provides a different basic understanding of the operation of such lasers: In contrast to the mechanical (dynamical) theories, we approached the problem from a statistical-mechanical (thermodynamic) point of view. We have shown that a dynamically stable solution, such as a mode locked (ordered) configuration, can collapse and give way to a disordered state when noise above a certain critical value is applied.

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Mechanical stability is not the only factor in shaping the behavior of PML lasers: entropy considerations should also be taken into account. This is a common situation in thermodynamics, where ordered phases such as solids or ordered ferromagnets, which are the minima of the energy, suddenly become *thermodynamically unstable* at high enough temperatures. This loss of thermodynamic stability at high temperature is where a phase transition occurs.

Resemblance between discontinuities in lasers and phase transitions was discussed in several classical works [6,15]. However these works also perform *dynamical stability analysis*, and therefore the analogy to phase transitions is only formal. Although Langevin noise terms are sometimes added, they are not identified as a source of the discontinuities, which exist also with zero noise. Noise has only been thought to smooth the discontinuities [6, 15] or induce fluctuations in the pulse train [16]. According to the theory we have presented [1], *noise is the cause of the discontinuity*, just like temperature in phase transition theory: Upon gradual variation of the noise intensity the order parameter of the system exhibits a discontinuity (a jump), reflecting the transition between pulsed and CW regimes. We therefore consider this analogy between lasers and phase transitions to be more profound and essential than the traditional ones.

The close resemblance between pulse formation and "freezing" may seem surprising in view of the fact that lasers are not in thermal equilibrium. The root of this resemblance is that PML lasers are governed by a statistical distribution which has the structure of the Gibbs distribution [1]

$$e^{-\mathscr{H}/T},$$

where $\mathscr{H}$ is the generator of the PML equations of motion and T is half the spectral power of noise in the system. An interesting aspect of PML lasers is therefore that they are a physical realization of a one dimensional many interacting particle system which obeys the Gibbs distribution and undergoes a phase transition, resembling the traditional interacting systems like ferromagnets [17].

Here we report on the first experimental demonstration of the noise-induced phase transition

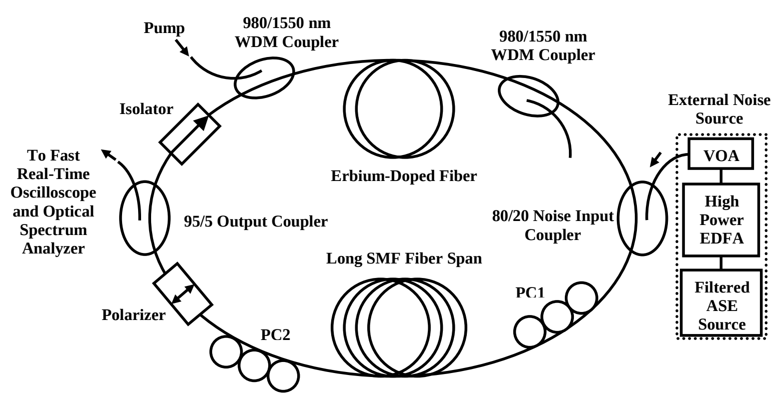

Fig. 2. Experimental configuration of the PML fiber laser system. It consists of an Erbium doped fiber amplifier (EDFA) pumped by a 980 nm laser source through a WDM coupler, an isolator that assures oscillations in one direction only, while the polarization controllers (PC), long fiber span (SMF) and the polarizer provide the saturable absorber [2]. The external noise source for the tunable noise ("temperature") is constructed from filtered amplified spontaneous emission (ASE) source, high power EDFA and variable optical attenuator (VOA).

of the first kind we have predicted. We demonstrate the "melting-freezing" process for pulses and modes in PML lasers, and we verify the order-disorder phase transition nature, with its inherent "latent heat," as the "temperature" (noise) is varied. This is shown in the time domain and also via a direct measurement of the order parameter of the laser mode system. It provides a clear experimental confirmation of the statistical-mechanics theory of pulses formation in PML lasers.

The experiment was conducted in a polarization-locked fiber ring laser [2] depicted in Fig. 2. The gain was provided by a 5-m long erbium doped fiber with small signal gain of 6.2 dB/m. The intracavity light-wave roundtrip time was 0.83 μs, corresponding to total length of roughly 170 meters. To the existing unavoidable amplified spontaneous emission (ASE) noise in the laser we have added (through 20/80 coupler) external noise from high power EDFA. The power of this external noise could be directly tuned by variable optical attenuator (VOA). For fixed intracavity power of the laser we gradually varied the level of the external noise, observing the abrupt disappearance or appearance of the pulses.

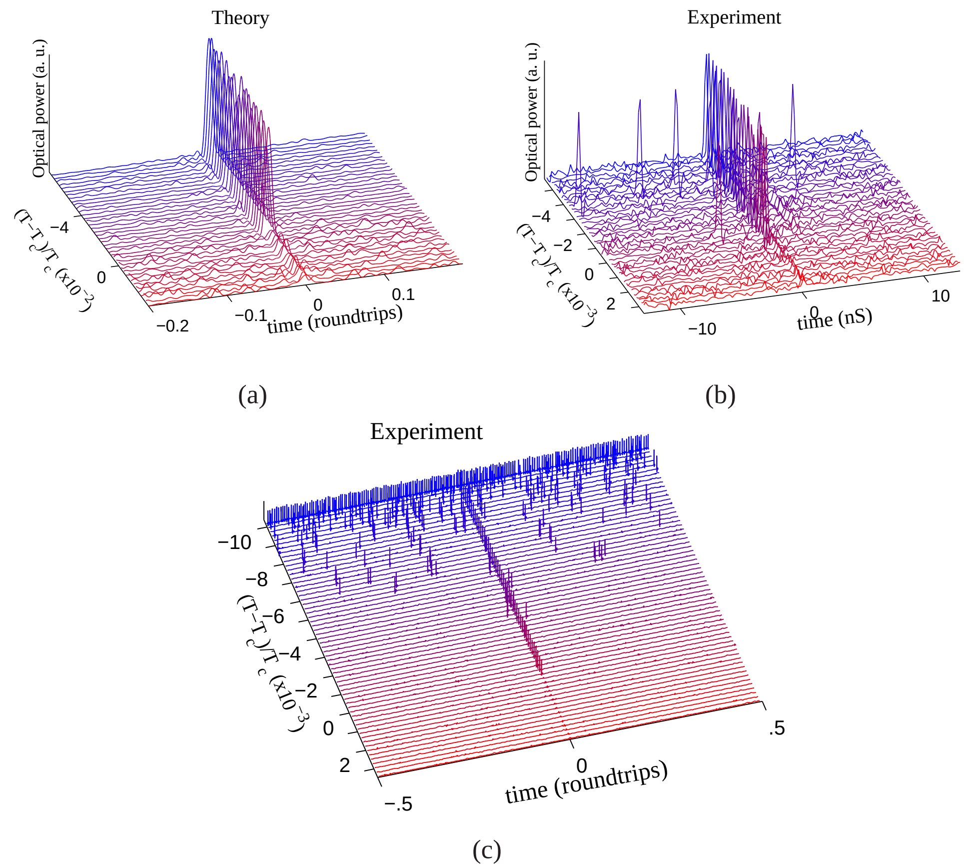

Fig. 3. The temporal waveform (light intensity as a function of time) of the laser as a function of the "temperature" (noise) showing the melting of pulses as the temperature is increased and passes the transition temperature T_c. Numerical simulation (a) and experiment (b, c) shown in a small range (b) and a larger range (c) of time and tempetature. In the experiment, in addition to the clear phase transition, one can witness in (c) the gradual disappearance of additional pulses per period upon "heating".

The confirmation of the very idea of the noise-induced phase transition and thermodynamic stability of pulses can be easily seen by observing the waveforms at the output of the laser using

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a photodiode connected to a fast real-time oscilloscope. Plots of the slowly varying intensity of the laser field as function of time for different "temperatures" are shown in Fig. 3. The discontinuity as a function of "temperature" predicted in Ref. [1] is illustrated on a theoretical (numerical) plot (Fig. 3(a)) of the temporal waveform of the laser as a function of the "temperature". For "temperatures" below the phase transition the laser modes form a pulse, while right above that value the laser produces a fluctuating continuous wave. The experimental plot shown in Fig. 3(b) demonstrates the same discontinuity. For lower "temperatures" the buildup of multiple pulses per roundtrip time can be seen in (Fig. 3(c)), a phenomenon characteristic of such soliton lasers pumped well above PML threshold [2].

The transition in Fig. 3 occurred at the noise level of $0.25\frac{mW}{nm}$. The intracavity power was about $7.6mW$. Comparison between the noise power and the signal is not straight forward, since they are measured in different units. What can be compared is, for example, the peak power density of the spectrum of the pulses, which was about $8\frac{mW}{nm}$, by about 40 larger than the noise power density.

The second way we studied the phase transition is by measuring an order parameter of the system as a function of the "temperature". A useful dimensionless order parameter is [1]

$$\bar{\mathscr{Q}} = \frac{\tau}{2}\frac{\int_0^\tau |\psi(t)|^4 dt}{(\int_0^\tau |\psi(t)|^2 dt)^2} = \frac{\sum_{j-k+l-m} a_j a_k^* a_l a_m^*}{(\sum_m |a_m|^2)^2},$$

where $\psi(t)$ is the envelope of the electric field at a certain point in the laser cavity, τ is the cavity roundtrip time and a_m are the slowly varying amplitude of the longitudinal modes of the laser. It is easy to show that if $\psi(t)$ consists of N locked modes (Fourier components of equal phases), $\bar{\mathscr{Q}} \propto N$, while at a single mode configuration or at a disordered configuration of the modes $\bar{\mathscr{Q}}$ is of order one. We have shown theoretically [1] that this parameter exhibits a discontinuity as a function of "temperature". This parameter can be experimentally measured by a fast photodiode attached to a RF power meter, since the current produced by the photodiode is proportional to the light power, and hence the RF power carried by this current is proportional to $\bar{\mathscr{Q}}$. It is easy to see that $\bar{\mathscr{Q}}$ is also inversely proportional to the pulsewidth.

In Fig. 4 we show theoretical and experimental curves of the order parameter as a function of "temperature". One can clearly see in the figure the discontinuous jump at a certain point T_c. The experiment in the laser systems with different operational parameters (of the laser pumping power, and the polarization conditions) consistently showed the phase transition picture (Figs. 4(b), 5(a), 5(b)). In addition, in some cases the experiment revealed some more fine structures and secondary discontinuities in $\bar{\mathscr{Q}}$, (one in Fig. 5(c) and many in Fig. 5(d)), as the "temperature" was decreased to low values. It can be attributed to the build-up of additional pulses oscillating in the PML laser cavity (seen in Fig. 3(c)): the moment the number of pulses per roundtrip changed, the RF power exhibited a discontinuity. When such a process of pulse number increase occurred, we obtained a gradual order-disorder transition and even a diffused phase transition, as seen in Fig. 5(d). For suitable experimental parameters, the built-up pulses are solitons. We have shown theoretically [1, 18, 19] that the order-disorder phase transition nature holds for soliton lasers, and also for the more general cases that include dispersion and Kerr nonlinearities.

The phase transition with the discontinuity shown in our experiment as we varied the "temperature" (noise) can be equivalently obtained by varying the light power in the laser [1]. This is manifested in the power threshold and the abruptness of the pulses emergence in PML lasers.

There are many aspects of phase transitions that can be studied in the presented optical pulsed laser system. Examples are hysteresis – supercooling and superheating, which were both observed in the experiment but need further study. On supercooling, we can comment that according to theory [1, 19] the high "temperature" disordered phase persists as a metastable

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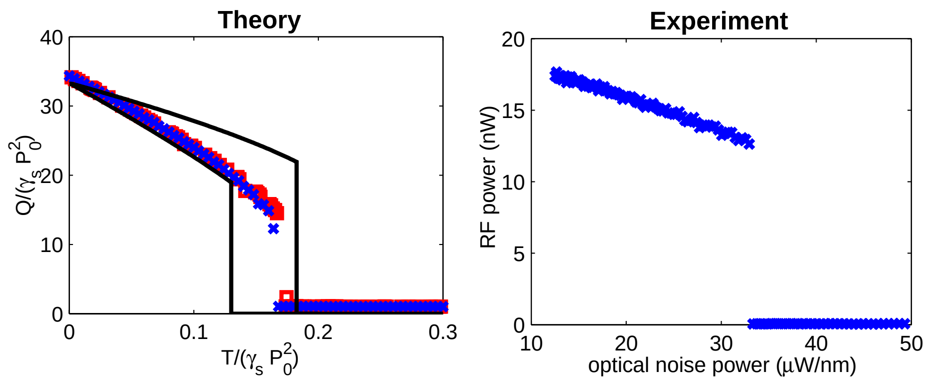
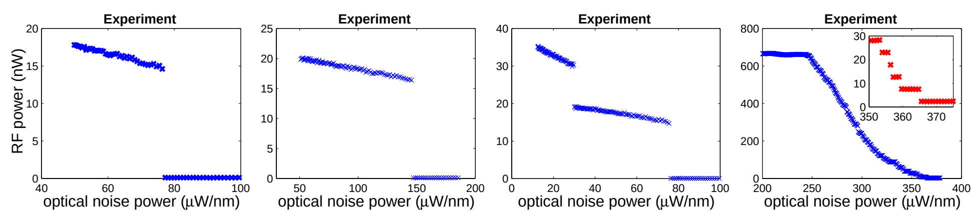


(a) (b)

Fig. 4. Theoretical and experimental plots of the order parameter $\mathcal{Q}$ vs. the optical noise T ("temperature"). The theoretical curve (a) was obtained by a Monte-Carlo simulation of the Gibbs distribution (squares), by a direct simulation of the equations of motion (crosses) and by mean field theory (lines) [1]. Here the temperature is normalized by the square of the light power P. The experimental results in (b) were measured by an RF power meter (for a pumping current of 30mA). One can see the discontinuity ("latent heat") in the order parameter with the predicted phase transition of the first kind.



(a) (b) (c) (d)

Fig. 5. More experimental plots of the order parameter $\mathcal{Q}$ vs. the optical noise T ("temperature") measured by an RF power meter. In (a-b) we find again the typical discontinuity in the order parameter for different laser pumping currents (of 40 and 70 mA, respectively). In (c) there is a second large discontinuity, and in (d) a gradual (diffused) transition that is actually a cascade of small discontinuities (its lower part is seen in the zoomed inset), associated with the build-up of additional pulses in the cavity.

state upon cooling the system below the phase transition "temperature" (noise), down to zero. (This supercooling feature might explain the often need of a slight physical shake to start the pulsation of PML lasers, in order to push it out from the metastable state to the frozen state that matches the cold environmental "temperature"). We expect these and many other interesting features to be found in the light pulse world, with meaning for their basic understanding and significance to future technological uses. In addition, since the relation between PML lasers and phase transition theory goes as deep as to the level of the Gibbs distribution itself, these lasers can provide a very convenient platform for studying phase transitions. A major advantage of lasers is the rare ability to follow each degree of freedom (mode) of the complex system directly and in real time.

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