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SPATIOTEMPORAL CHAOS AND ORDER IN FIBER LASERS

CAOS Y ORDEN ESPACIOTEMPORAL EN LÁSERES DE FIBRA

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We introduce a model that permits the unified description of the emergence of different regimes of complex temporal structures in noise-like or quasi-CW fiber lasers. The model is based on the vector Ginzburg-Landau equation that also permits to reproduce the experimentally observed polarization antiphase behavior and the synchronization of spatiotemporal turbulence into polarizations domain wall solitons.

Se introduce un modelo que permite la descripción unificada de la emergencia de diferentes regímenes de estructuras complejas temporales en láseres de fibra noise-like o cuasi CW. El modelo está basado en la ecuación vectorial de Ginzburg-Landau, que también permite reproducir el comportamiento experimentalmente observado de polarización antifase y la sincronización de la turbulencia espacio temporal en el dominio de polarizaciones de la barrera de solitones.

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I. INTRODUCTION

Fiber lasers have been widely studied as stable sources of ultrashort mode-locked pulses [1]. In recent years, novel regimes of operation of fiber lasers leading to complex temporal dynamics have been experimentally explored. Consider for example noise-like pulse emission [2], antiphase polarization temporal structures [3] and quasi-CW Raman fiber lasers [4]. In this work, we provide a unified theoretical description of how modulation instabilities in quasi-CW locked fiber lasers may evolve into the different regimes of turbulent or noise-like pulse emission.

II. SCALAR GLE

We discuss first the phase transition diagram that rules the different regimes of stable, intermittent or spatiotemporal chaotic emission for fiber ring lasers, passively mode locked by nonlinear polarization rotation (see Fig.1). In this diagram, the two free parameters of the ruling Ginzburg-Landau equation (GLE) that describes the cavity-averaged slow temporal evolution of the field in the laser are the cavity dispersion and nonlinearity, respectively [5]. In Fig. 1, phase transition curves separate domains that are associated to different statistical states of the light field: amplitude turbulence (AT), phase turbulence (PT), spatiotemporal intermittency (STI), bi-chaos (BC) that is intermediate between amplitude and phase turbulence, and non chaotic (NC) emission.

III. VECTOR GLE

Next we introduce nonlinear polarization coupling in a vector fiber ring laser, that is, without polarization selective components. In this case, it is remarkable that (complex) nonlinear polarization coupling may lead to the anti-synchronization of spatiotemporal chaos into ordered ultrashort pulse or soliton trains, and polarization domains.

As we shall see, nonlinear polarization coupling also leads to vector rogue waves in long-cavity Raman fiber lasers. Complex temporal light pattern dynamics in vector fiber lasers may be phenomenologically described in terms of the coupled GLEs [6],

$$\begin{aligned} \partial_t U &= U + (1+i\beta)\,\partial_\tau^2 U - (1-i\gamma)\,|U|^2 U - (\eta - i\rho)\,|V|^2 U \\ \partial_t V &= V + (1+i\beta)\,\partial_\tau^2 V - (1-i\gamma)\,|V|^2 V - (\eta - i\rho)\,|U|^2 V. \end{aligned} \quad (1)$$

Here the time coordinates t and τ denote a slow time (measuring the number of circulations in the cavity) and a fast time (measuring the intra-cavity pulse structures), and U, V are the complex amplitudes of ortogonal polarizations.

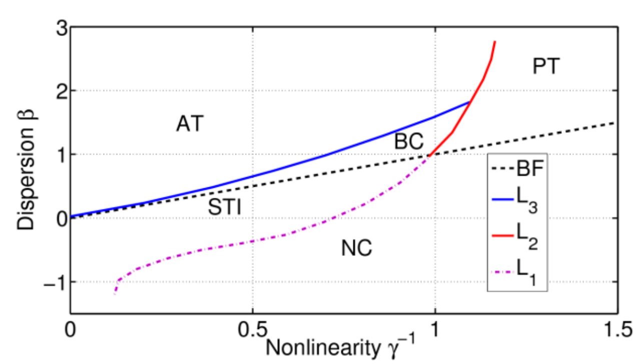

Figure 1. Phase diagram of transition curves between different light emission states from a scalar fiber laser [1].

Next β measures cavity dispersion ($\beta > 0$ for anomalous dispersion), γ is the self-phase modulation (SPM), η is the cross-gain saturation, and ρ is the cross-phase modulation (XPM) coefficient, respectively.

Let us describe now some characteristic regimes of stable or unstable light emission when the parameters of the coupled GLEs (eq. 1) are varied. In Fig. 2, we set $\beta = 0.2$, $\gamma = 2$, $\eta = 1.05$, and $\rho = 2.1$.

As can be seen, although in the uncoupled (or scalar) case described by Fig.1 laser emission exhibits STI, a nonlinear cross-gain saturation coefficient larger than unity leads to stabilization of the field in alternating domains of constant polarization, separated by sharp switching regions or domain walls [6]. Polarization domains and domain walls were indeed recently experimentally observed in a vector fiber laser [6].

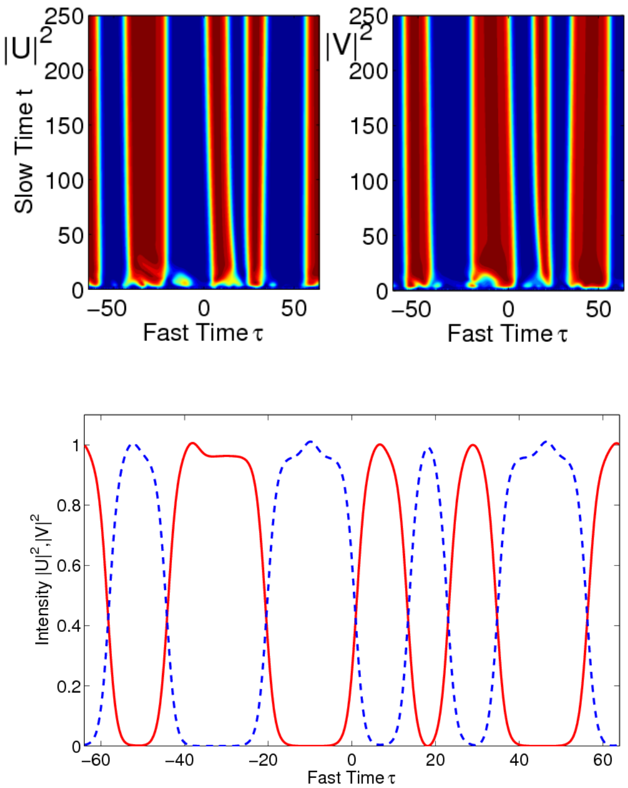

Figure 2. Polarization domain emission. Top (a): evolution of intensities from the laser; bottom (b): snapshot of intensities vs fast time τ after a large number of circulations.

Let us consider laser dynamics in the normal dispersion regime: in the top panels of Fig.3, we set $\beta = -0.5$, $\gamma = 1.5$, and $\eta = \rho = 0$ (no nonlinear polarization coupling). Here uncorrelated STI occurs: laminar regions of CW emission are separated by the emission of black holes at the collision of dark soliton pulses with opposite speed.

In the middle panels of Fig.3, we increased γ up to 4: as can be seen, the laminar regions are much reduced in size, and the black holes exhibit a relatively long lifetime.

The bottom panels of Fig.3 show that the presence of XPM ($\rho = \gamma = 4$) dramatically changes the nature of the field evolution that exhibits now a fully developed turbulence.

By further increasing the strength of both SPM and XPM up to $\gamma = \rho = 25$, and introducing also a finite cross-gain saturation $\eta = 0.4$, one observes a rarefaction of the high-intensity peaks that emerge from a sea of low level intensity fluctuations (see Fig.4).

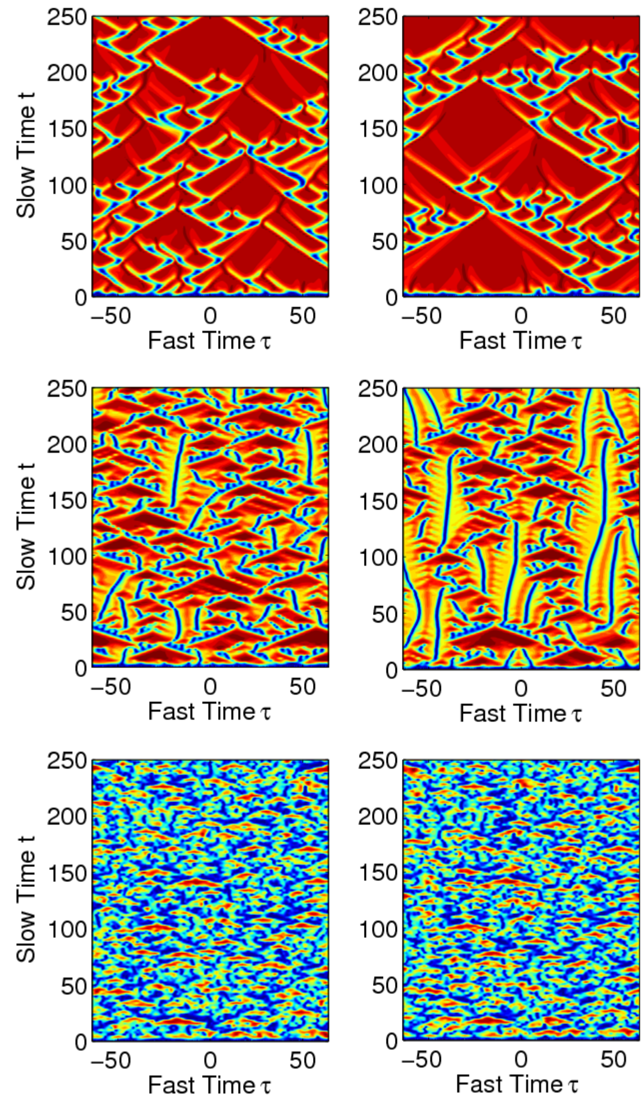

Figure 3. Transition from vector STI (top) to coexhisting STI and dark solitons (middle) and fully developed AT (bottom).

In the top panel of Fig.4 we show the irregular evolution of the total laser intensity as a function of both fast and slow time coordinates. Whereas in the middle panel of Fig.4 we illustrate a zoom of the intensities of the two orthogonal polarization components, showing a single extreme event. The corresponding shapshot of the polarization resolved intensities is reported in the bottom panel of Fig.4.

We may call the dynamics that is shown in Fig.4 as "near-conservative turbulence": in this case Eqs.(1) are close to perturbed coupled nonlinear Schroedinger equations (CNLSEs) since SPM and XPM terms are much larger than nonlinear self and cross-gain saturation terms.

It is interesting to note that the irregular dynamics in Fig.4 is qualitatively close to the chaotic emission that is experimentally observed in a quasi-CW long Raman fiber laser, which also exhibits extreme high-intensity peaks that have a complex polarization sub-structure [7].

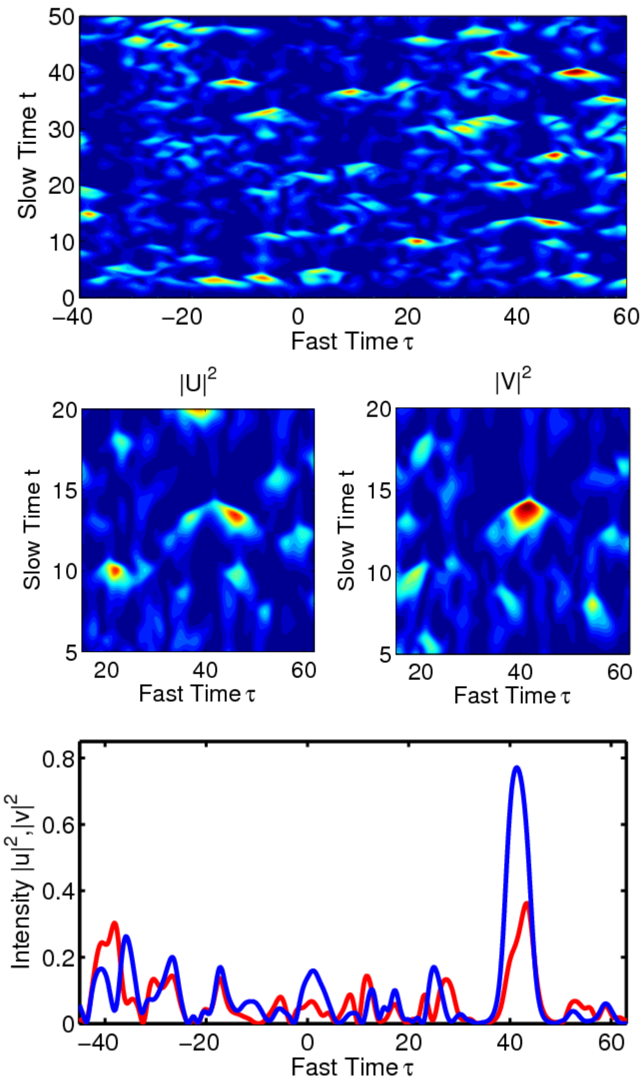

Figure 4. Near-conservative turbulence in a Raman fiber laser.

In vector fiber ring lasers operating in the normal dispersion regime, it has also been observed that the spatiotemporal dynamics can be modeled by means of a purely conservative set of CNLSEs, by supposing that linear gain and loss exactly balance each other, and that the presence of nonlinear gain saturation terms can be neglected [8]. Quite remarkably, even in the conservative limit the CNLSEs exhibit polarization domain and domain wall solutions that correspond well to the experimentally observed antiphase dynamics of the two orthogonal modes of polarization [8].

IV. CONCLUSIONS

In conclusion, we discussed how a simple universal phenomenological model, provided by the scalar or the vector complex GLE with cubic nonlinearity and with nonlinear gain saturation (as opposed to nonlinear gain for describing stable short pulse emission from passively mode-locked lasers [1]), may be able to qualitatively describe a wide range of complex temporal dynamics in fiber lasers. Specific examples of quasi-CW, high intensity laser sources of importance for several applications are: noise-like lasers, polarization antiphase domain lasers, and ultralong Raman fiber lasers.

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