Self-organizing And Filamentary Behaviour in Broad-area Lasers

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Abstract— Presented work is concerned with analytical and numerical investigation of broad-area lasers dynamical regimes resulting from the stability loss of the steady lasing. It is shown that depending on the type of spatio-temporal instability filamentary and pattern forming behaviour may be observed in the system. Main principles and formation concepts of these dynamical regimes in the transverse section of the broad-area laser emission were considered and elaborated.

1. INTRODUCTION

Broad-area lasers are often necessary for high-power laser applications since increasing of transverse sizes of pumping region entails increasing the output power. However, for pumping levels well above the lasing threshold broad-area lasers exhibit complicated spatio-temporal dynamics. This is caused by the development of steady lasing instabilities that turn to be especially complex in broad-area lasers as transverse space-coupling processes and corresponding nonlinearities become involved. As a result related laser operation leads to degradation of brightness of these devices and coherence reduction of emitted beam. That is why these dynamical regimes deserve more detailed investigation.

On the other hand, complex spatio-temporal dynamics makes broad-area laser an interesting object to explore the general aspects of behaviour in nonlinear spatially-extended systems. Such systems are known to exhibit spontaneous pattern formation, chaotic and turbulent regimes that turns out to be very similar regardless the particular model under investigation. Thanks to laser being a very practically relevant device experimental observation of different nonlinear spatio-temporal regimes seems to be most feasible just in the laser systems.

In presented paper we report on detailed investigation of spatio-temporal instabilities emergence for steady stationary operation in broad-area lasers. We have shown that free-running broad-area laser can demonstrate both filamentary behaviour accompanied by nonregular pulsations of optical field and self-organization phenomena when different regular patterns can be observed. We found the bifurcation mechanisms responsible for each dynamical regime and model parameters regions for their implementing.

2. THEORETICAL MODEL

Our analysis was based on Maxwell-Bloch equations for frequency detuned cavity along with transversely distributed two-level lasing media [1, 2]:

$$\left\{ \begin{array}{l} \frac{\partial E}{\partial t} = \sigma \left(P - E \left(1 - i\delta \right) \right) + ia\Delta_{\perp} E \\ \frac{\partial P}{\partial t} = - \left(1 + i\delta \right) P + DE \\ \frac{\partial D}{\partial t} = -\gamma \left[D - r + \frac{1}{2} \left(E^{*} P + E P^{*} \right) \right], \end{array} \right. \tag{1}$$

where E, P, D are slowly varying dimensionless envelopes of electric field, polarization and population inversion; $\gamma = \gamma_{II}/\gamma_{\perp}$, $\sigma = k/\gamma_{\perp}$, where $\gamma_{\perp}$, γ_{II} and k are the decay rates of polarization, population inversion and electric field respectively. r is the pump parameter, $\delta = (\omega_0 - \omega_{cav})/(\gamma_{\perp} + k)$ stands for the normalized frequency detuning between the centre of gain line ω_0 and cavity frequency ω_{cav} scaled to the line half-width. Diffraction of the field is described by Laplace operator $\Delta_{\perp}$ acting in the transverse directions with $\Delta_{\perp}$ as the diffraction parameter. Electric field in model (1) is scaled to the amplitude of the transparency field and population inversion is scaled to the threshold value. Time is normalized to the coherence time.

This model considers a single-longitudinal-mode operation thus neglecting the nonlinear effects in longitudinal dimension in favor of the transverse dynamics. We restricted our analysis to the case of $\delta \leq 0$ when laser naturally selects spatially homogeneous steady operation as the first lasing solution [3]:

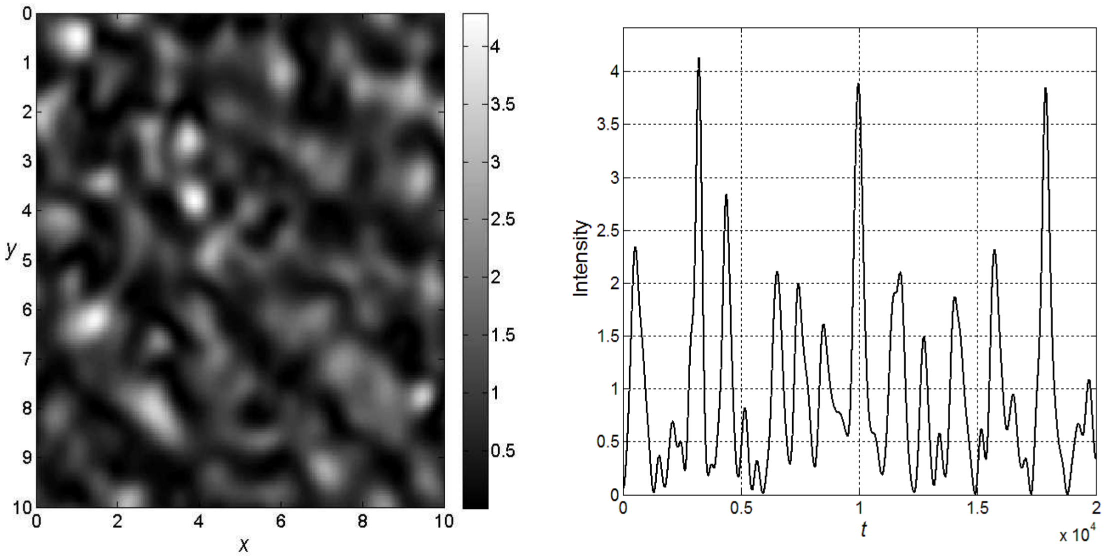
$$D_{st} = 1 + \delta^2; \quad |E_{st}|^2 = r - D_{st}; \quad P_{st} = (1 - i\delta)\, E_{st}. \tag{2}$$

Since pump r and frequency detuning δ are variable control parameters in system (1) principal importance is related to the ratios between the intracavity field and active medium decay rates described by parameters σ and γ. Stability analysis of solution (2) together with numerical modeling demonstrated several separable dynamical regimes depending on the latter ratios. Principally, it allowed distinguishing filamentary instability from pattern forming instability.

3. FILAMENTARY DYNAMICS

Filamentary behaviour is shown to emerge for incoherent light-media interaction when medium polarization instantaneously follows the intracavity field. It corresponds to the ratios $\gamma \ll \sigma \ll 1$. Such values are typical, for example, for solid-state and semiconductor laser systems. This filamentary dynamical regime is found to be induced by modulation-type instability as steady lasing (2) loses its stability against small perturbation with finite wavelength. Steady lasing is preserved for non-detuned cavity but inclusion of nonzero detuning results in its breakup.

Figure 1 shows typical image for this regime. Intensity profile (Fig. 1(a)) has very nonregular view with the temporal series (Fig. 1(b)) in the form of complex sustained oscillations.



(a) (b)

Figure 1: Filamentary pattern for $\sigma = 0.05$, $\gamma = 0.0001$, $\delta = -0.5$, $r = 2$; (a) instantaneous intensity profile; (b) intensity time series.

A number of mechanisms that can contribute to filamentation are known. First of all according to the seminal paper [4] the influence of Kerr self-focusing nonlinearity is defining in the case of strongly nonlinear light-matter interaction that is relevant for both passive and active systems. Another important mechanism is concerned with the strong gain-index coupling in semiconductor materials [5].

Our results show possibility of such dynamics in active system without gain-index coupling for even low electromagnetic field intensity just above the threshold. Indeed, when the instability is fully developed, the observed dynamics are similar to filamentary behaviour what is accompanied with both temporal and spatial nonregular dynamics although our model does not explicitly include gain-index coupling. Hence we expect this instability to be one of the possible routes to filamentation and light threads formation in numerous active optical systems when extending the transverse section like semiconductor and solid-state lasers and amplifiers.

4. SELF-ORGANIZING BEHAVIOUR

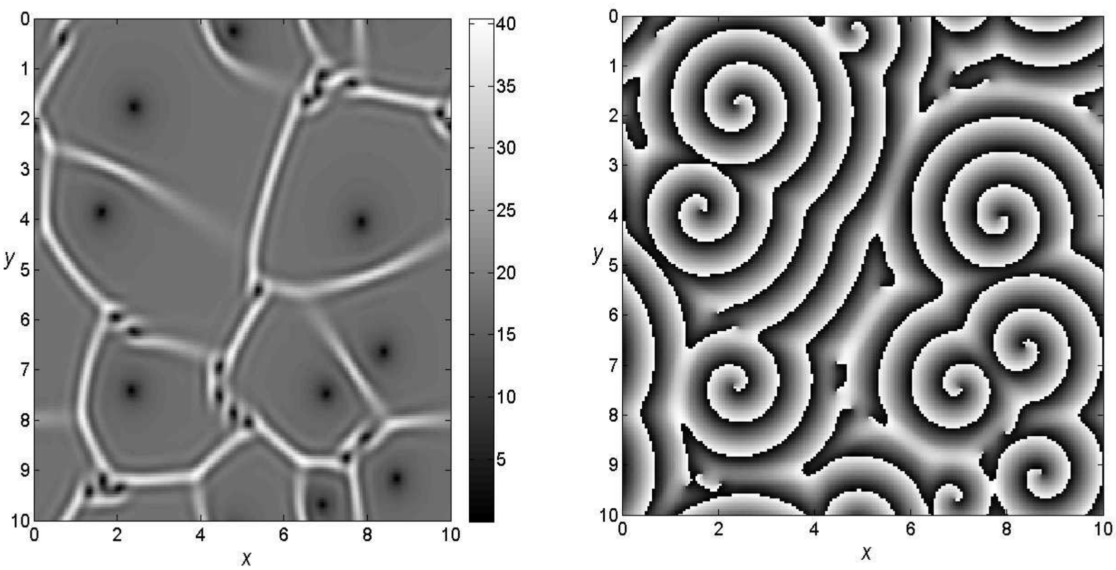
Some aspects of self-organization in broad-area lasers were reported earlier [6–8] and described the generation of tilted waves, localized solitons and optical vortices.

In our problem statement pattern formation is found to evolve for coherent light-media interaction that is usually realized in some atomic and molecular gas active mediums and implies comparable values for the material and field decay rates ($\gamma \leq \sigma \sim 1$).

A careful analytic treatment revealed a distinct scenario for the subsequent dynamics. Steady lasing becomes unstable in favor of self-oscillating homogeneous operation when the definite threshold for pumping value is exceeded. This type of dynamics doesn't reach however a steady behaviour since it is in turn destabilizes owing to instability against small perturbations with finite wavelength. The latter instability then governs the spatio-temporal evolution of the system giving rise to diverse processes.

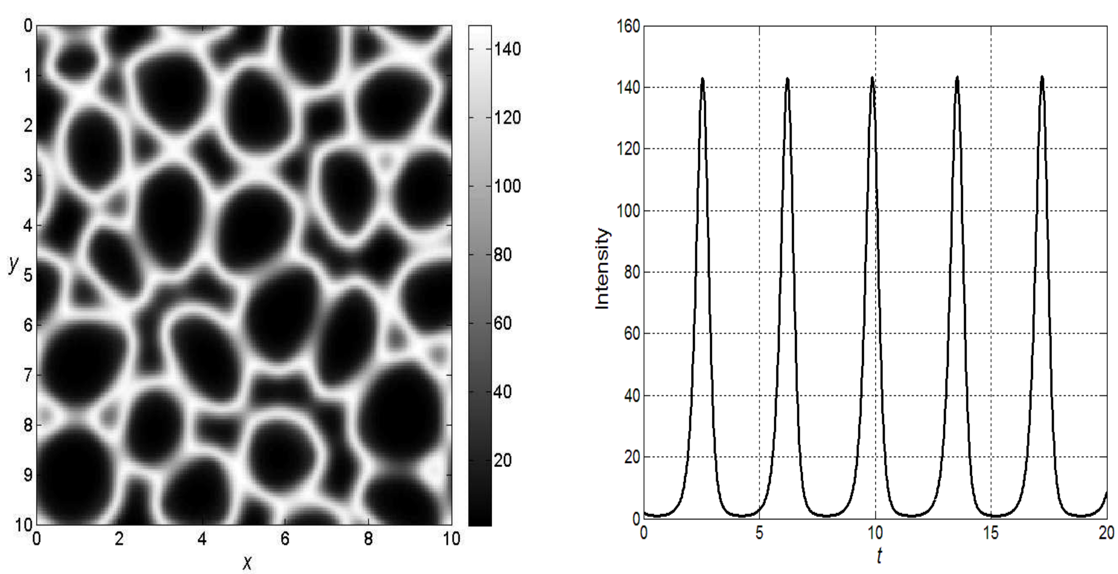
Numerical simulations showed that the development of spatial inhomogeneties can follow several ways leading to a number of spontaneously forming regular patterns.

In some cases the creation of phase singularities is observed each of them containing a zero of the electric field. Then the spiral waves eventually appear, consisting of time-periodic phase distribution with rotating movement around the spiral cores together with a stationary intensity



(a) (b)

Figure 2: Spiral pattern for $\sigma = 4$, $\gamma = 0.7$, $\delta = -0.1$, $r = 20$; (a) stationary intensity profile; (b) rotating electric field phase profile.



(a) (b)

Figure 3: Standing wave pattern for $\sigma = 5$, $\gamma = 0.1$, $\delta = -0.3$, $r = 30$; (a) instantaneous intensity profile; (b) intensity time series.

profile where each spiral core occupies some area separated from each other by the sharp shock walls. All these aspects are clearly visible in Figs. 2(a)–(b) obtained for an appropriate set of model parameters.

Otherwise the formation of oscillating inhomogeneous intensity profile was found. In this instance self-organizing processes lead to spatially modulated standing autowaves. Specific shape of intensity profile is regular enough but it doesn't demonstrate any symmetry properties (see example on Fig. 3(a)). Temporal evolution for the field intensity is the periodic one though it exhibits a definite phase shift for each pair of points in the transverse laser section (Fig. 3(b)).

Described above scenarios of pattern formation seems to be specific for nonlinear optics only as the complex character of the optical field turns out to be the defining factor. Though main aspects of the self-organizing behaviour are general regardless the physical origin of particular system broad-area laser being an active nonlinear optical system shows a peculiar variety of optical patterns.

5. CONCLUSION

To conclude, we performed stability analysis for steady stationary operation of broad-area free-running lasers. We revealed that either filamentary or self-organizing dynamics may be observed depending on character of light-medium interaction. Basically filamentation is found to evolve for the coherent interaction while otherwise more complicated pattern forming is obtained. Main principles and bifurcation mechanisms responsible for the definite transverse spatio-temporal dynamics were studied. We hope our findings to contribute to the general understanding of nonlinear dynamical regimes in broad-area lasers and to allow controlling and optimization of the characteristics of laser emission.

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