STABILIZATION OF VCSEL RADIATION USING EXTERNAL OPTICAL INJECTION WITH CONSIDERATION OF NONLINEAR GAIN EFFECTS

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Introduction

A free-running broad-area surface-emitting laser with a vertical resonator (VCSEL) emits irregular dynamics because it is subject to modulation instabilities. It is known that additional external optical injection of weak amplitude can suppress the instabilities and obtain spatially uniform radiation. For a qualitative assessment of the efficiency of the method, it is necessary to take into account the effects of nonlinear amplification for population inversion. It is shown that the consideration of nonlinear amplification does not destroy the stabilization effect, but only slightly increases the threshold value of the amplitude of optical injection necessary for stabilization.

Mathematical model

To describe the dynamics of vertical cavity lasers, we use the system of equations:

$$\begin{cases} \dfrac{\partial E}{\partial t} = [E_{inj} - (1+i\theta) + (1-i\alpha) f(N)]E + i\Delta_\perp E, \\ \dfrac{\partial N}{\partial t} = \gamma\left[I_p - N - |E|^2 f(N)\right], \end{cases}$$

E, D *dimensionless envelopes of the electric field and population inversion, respectively,* $\boldsymbol{I}$ *the pump current ,* $\boldsymbol{\gamma = \tau_p/\tau_N}$*, where* $\boldsymbol{\tau_p}$ *is the photon lifetime,* $\boldsymbol{\tau_N}$ *is the nonradiative carrier recombination time,*$\boldsymbol{\alpha}$ *is the linewidth enhancement factor,* ***d*** *the diffusion coefficient,* $\boldsymbol{E_{inj}}$ *is the normalized injected field,* $\boldsymbol{\theta}$ *represents the detuning between the cavity and the injected field frequencies.* ***T*** *is the transmission coefficient of the mirrors,* $\boldsymbol{v = c/n}$*, and* ***n*** *is the refractive index of the medium,* ***L*** *is the length of the cavity of the resonator.* $f(N) = N$

Homogeneous nontrivial solution

$$E_0 = \sqrt{\frac{I_0 - N_0}{N_0 - 1}} \qquad N_0 = 1 + \frac{1}{2C} \qquad \boxed{\theta = -\alpha}$$

Standard linear analysis

$$E = E_0 + \delta E_0 e^{(\lambda t + i(q_x x + q_y y))}, \quad N = N_0 + \delta N_0 e^{(\lambda t + i(q_x x + q_y y))}$$

$$\lambda^3 + a_1\lambda^2 + a_2\lambda + a_3 = 0$$

Modulation instability (MI) $\lambda = \Lambda_3$

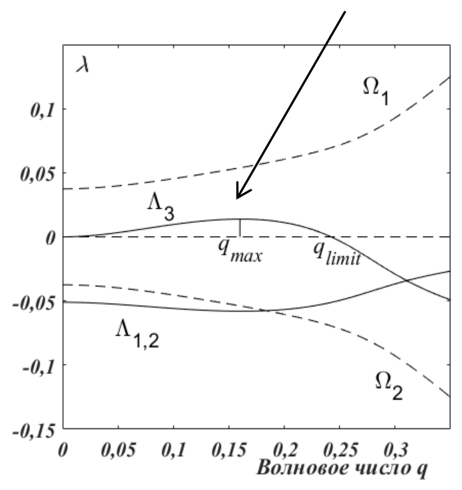


Fig.1 Dispersion curves

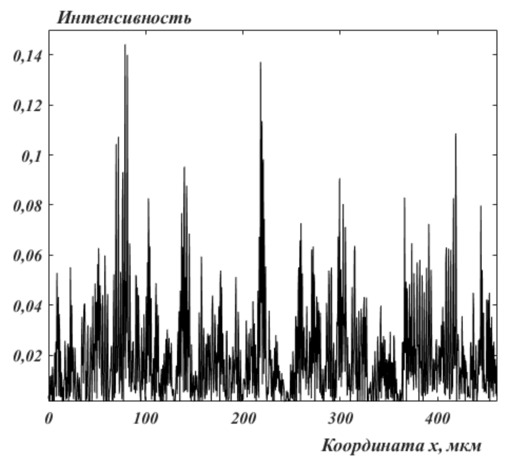
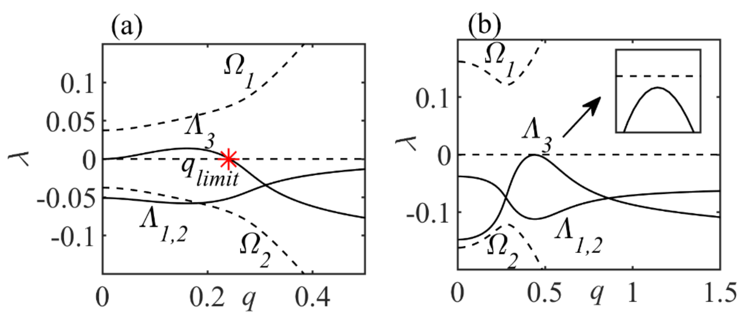


Fig.2 Distribution of the generation intensity in the transverse profile

Suppression of modulation instability by weak external optical injection



$$\boxed{|E_{inj}|^2 / |E_0|^2 \approx 0.011}$$

Fig. 5. Dispersion curves for (a) $E_{inj} = 0$ and (b) $E_{inj} = 0{,}03$

<u>*The addition of external optical radiation leads to a new stationary value $|E_s|$, which is defined by the implicit expression:*</u> $|E_{inj}|^2 = |E_s|^2\left[\left(\theta + 2C\alpha(N_s - 1)\right)^2 + \left(1 - 2C(N_s - 1)\right)^2\right], \quad N_s = \dfrac{I + |E_s|^2}{|E_s|^2 + 1}$

MI and Andronov-Hopf instability domains

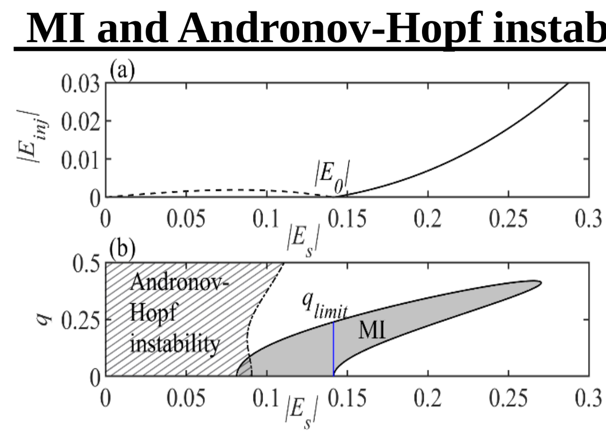


Fig. 3. (a) Steady-state curve of the homogeneous solution $|E_s|$ depending on $|E_{inj}|$, where the stationary states of the dashed branch undergo subcritical bifurcations, and the solution abruptly switches to the branch of stationary states, which we depicted with a solid line; (b) MI and Andronov-Hopf instability domains. Unshaded area corresponds to the stability domain.

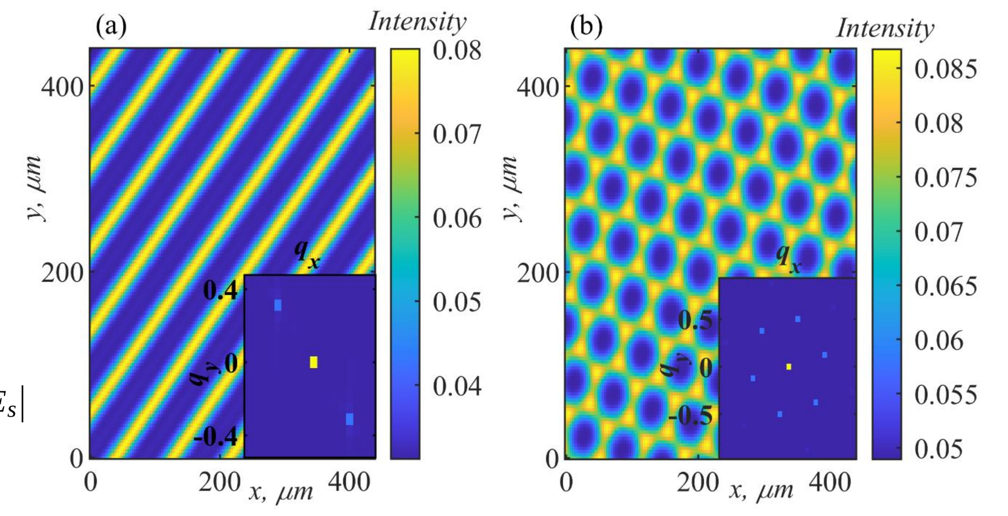


Fig. 4. Snapshots of the intensity profile and the far-field Fourier spectrum for (a) stationary stripe pattern with $|E_{inj}| = 0.01$ $|E_s| = 0.21$ (b) stationary hexagonal pattern with $|E_{inj}| = 0.02$ $|E_s| = 0.25$

where $f(N)$ the function contains the dependence of the gain on the carrier density. Earlier we made the simplification that $f(N)$ =N. The linear stability analysis performed earlier showed that the pro-spatial homogeneous generation mode is subject to modulation instability. As a result, such a device generates radiation with poor spatial and temporal coherence (Fig. 2). To improve the quality of the radiation, a method of external optical emission has already been proposed, which allows a weak amplitude of the master laser to stabilize the dynamics of the slave laser (fig. 3, fig. 4, fig.5)

Earlier studies did not take into account the effects of nonlinear gain. In fact, the maximum gain curve is better approximated under the assumption of a quadratic dependence on the carrier density, which leads to $f(N)$ =N(1-β)N. Numerical calculations have shown that taking into account the nonlinear amplification factor does not destroy the stabilization effect, while only slightly increasing the value of the external radiation amplitude up to 2% of the generated one. In Fig.6(b) and (c) the damping of the increments is clearly visible, indicating stabilization. Taking into account the nonlinear amplification in the future may affect the determination of the area of formation of spatial structures, which requires further study.

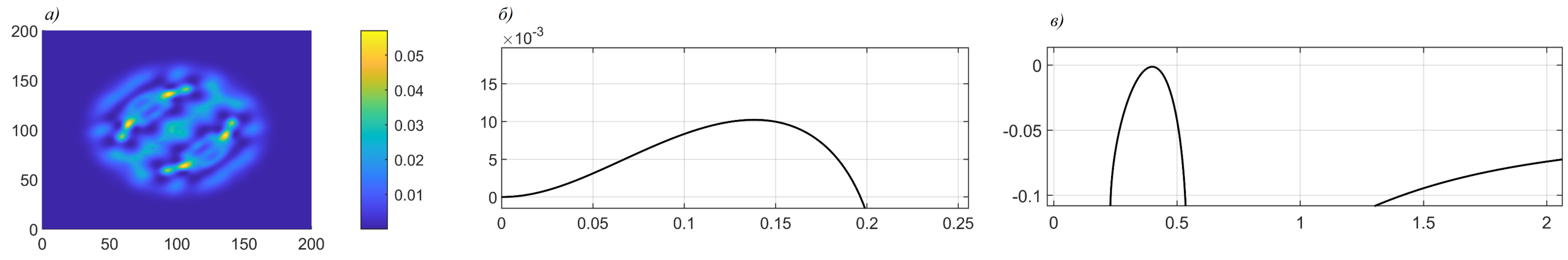


Fig.6 a) Distribution of the generation intensity in the transverse profile b) Dispersion curves for $E_{inj} = 0, \beta = 0.125$ and (c) $E_{inj} = 0.04, \beta = 0.125$

Conclusions

- *Low-amplitude resonant injection can suppress irregular filamentations and instead lead to stationary optical patterns (stripes and hexagons).*
- *Optical injection is effective in completely suppressing modulation instability. It is important that this effect has a threshold character.*
- *We obtain the critical value of the uniform stationary solution, which makes it possible to calculate the required threshold value of the external optical radiation amplitude in order to obtain a highly coherent non-filament output beam.*

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