Paper

Nonlinear optics of the thin-film quasiwaveguide amplifier: applications to directional switching in the optical communication systems

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Abstract — We examine nonlinear optical effects in the active medium of the thin-film quasiwaveguide amplifier-oscillator with injection of the external signal. The injection locking has been obtained in the case when both the frequency and the direction of propagation of the injected signal differ from those for a free-running thin-film laser which offers a possibility for the frequency and directional switching of the output of the thin-film laser. The effects of four wave mixing and phase conjugation have been discussed in the active medium of the thin-film laser when additional mirrors forming an external resonator have been used.

Keywords — thin-film laser, directoral switching, four-wave mixing, optical communication systems.

Introduction

The injection of an external reference signal into the laser cavity when the injected signal frequency differs from that of the free-running laser is of significant practical interest and is being extensively used as an effective tool for frequency stabilization, increasing the output power and spectral brightness of different types of oscillators, (see for example, [1-3]). As a rule, alone the frequency of the injected signal differs from that of the free-running oscillator in the applications reported earlear. A question arises, what will be the response of a free-running laser on injection of an external signal, which differs not only by the frequency but by the direction of propagation as well from the free-running mode of the laser. The answer on this question is important from the practical point of view for spacially extended laser-active systems, for example, waveguide lasers [4], or surface emitting semiconductor lasers [5].

This paper deals with a thin-film quasiwaveguide (TQ) amplifier-oscillator, which consists of a plane thin film laser-active medium of refractive index n_2 and gain factor α, bounded by two passive dielectric media of refractive indicies n_1 and n_2 under the condition $n_2 < n_1, n_3$, see Fig. 1. Due to this condition, this system has only leaky modes. Because of the large gain factor of the laser-active medium (a dye solutions or polymers with laser pumping are usually used) and the structural peculiarities (the layer thickness is of order of a wavelength), operation of TQ with comparatively large spectral-angular dispersion is possible [6,7].

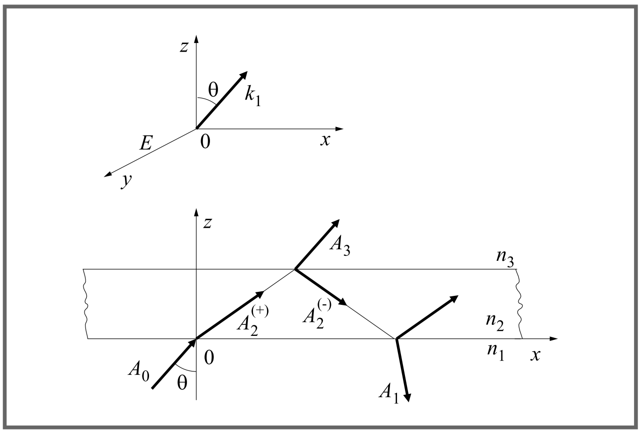

Fig. 1. Schematic diagram of the thin-film amplifier-oscillator

There is a possibility in this system for the injected signal to differ not only by the frequency but also by the direction of propagation from the free-running TQ laser output, in contrast with the ordinary laser systems. We consider the interaction between a plane monochromatic electromagnetic wave and the TQ amplifier taking into account the amplification saturation. We show that the injection locking takes place at sufficiently high intensity of the injected signal. This injection locking differs from the well known ordinary one. Namely, not only the frequency of the free-running TQ is being locked by the injected signal, but the direction of propagation of the TQ's output radiation also coincides with that of the injected signal.

The effects of four-wave mixing and phase conjugation in the active medium of TQ laser with two additional mirrors making an external resonator for the output radiation are briefly discussed as well.

A two-level homogeneously broadened amplifying medium of resonant frequency ω_0 has been assumed in this paper. We have the following equations for the electric field strength in the steady-state interaction regime under consideration (see Fig. 1)

$$\left(\Delta + \frac{\omega^2}{c^2} n_j^2\right) E_j = i\,\frac{\omega}{c}\,\frac{\alpha}{1+\gamma^2|E|^2}\,\delta_{j2} E_j\,, \qquad (1)$$

where Δ is the Laplace operator, ω is the frequency, n_j is the refractive index of the j-th medium and δ_{ij} is the

Kronecker's delta (i, $j=1,2,3$). $\alpha = \frac{8\pi}{\mathrm{ch}}\omega|d|^2\frac{\Delta_0}{\Gamma}$ is the gain coefficient describing the amplification properties of the medium, with d being the dipole moment, and Γ being the linewidth of the active transition, Δ_0 is the initial population inversion density, $\gamma = \frac{8T_1|d|^2}{\mathrm{h}^2\Gamma}$ is the saturation parameter with T_1 being the longitudinal relaxation time.

The case of a symmetric system, where $n_1 = n_3 = n$, ($n_2 < n$) is discussed in this paper for the sake of simplicity.

We consider here the case of signal amplification with a wave vector lying in the plane $X0Z$ and the electric field strength polarized along the y axis, as in Fig. 1. The electric field strengths in the three media are given by

$$E_1(x,y,z) = \frac{1}{2}\left[A_0\exp(ik_1z)+A_1\exp(-ik_1z)\right]\times \times\exp\left[i(q_1x-\omega t)\right]+c.c. \quad (2)$$

$$E_2(x,y,z) = \frac{1}{2}\left[A_2^{(+)}(z)\exp(ik_2z)+A_1\exp(-ik_2z)\right]\times \times\exp\left[i(q_2x-\omega t)\right]+c.c.$$

$$E_3(x,y,z) = \frac{1}{2}A_3\exp\left[i(k_3z+q_3x-\omega t)\right]+c.c., \quad (3)$$

where $k_1 = k_3 = \frac{\omega}{c}n\cos(\Theta)$, and Θ is the incident angle, as in Fig. 1.

The condition of the system homogeneity along the x axis leads to the relation:

$$q_1 = q_2 = q_3 = \frac{\omega}{c}\, n\, \sin(\Theta).$$

In Eqs (2), A_0 is a given amplitude of the incident wave, A_1 is the amplitude of the wave reflected from the active film, $A_2^{(+)}(z)$ and $A_2^{(-)}(z)$ are the amplitudes of the waves propagating in the active film with positive and negative projections of the wave vector on the z axis, respectively, and A_3 is the amplitude of the transmitted wave.

Our aim here is to obtain and analyse the intensities of the reflected $I_r = |A_1|^2$ and transmitted $I_{tr} = |A_3|^2$ waves as functions of the incident wave intensity $I_0 = |A_0|^2$.

We obtain the following set of equations in the amplifying medium ($j=2$) for the normalized amplitudes $a^{(+)} = \sqrt{\gamma/2}A_2^{(+)}$ and $a^{(+)} = \sqrt{\gamma/2}A_2^{(+)}$ using the slowly varying envelope approximation:

$$\frac{\mathrm{d}}{\mathrm{d}z}\,a^{(+)} - \exp(-2ik_2z)\,\frac{\mathrm{d}}{\mathrm{d}z}\,a^{(+)} = \frac{\beta}{2}\,f(z), \quad (4)$$

where

$$f(z) = \frac{a^{(+)}(z)+a^{(-)}(z)\exp(-2ik_2z)}{1+\left|a^{(+)}(z)\right|^2+\left|a^{(-)}(z)\right|^2+a^{(+)*}(z)a^{(-)}(z)\exp(-2ik_2z)+a^{(+)}(z)a^{(-)*}(z)\exp(2ik_2z)},$$

and

$$\beta = \frac{\omega}{c}\,\frac{n_2\alpha}{k_2}.$$

It is important to note, that $f(z)$ is a periodic function with period π/k_2. It means that we can represent the function $f(z)$ in the form of a Fourier series

$$f(z) = \sum_{m=-\infty}^{\infty} C_m\exp(-2imk_2z)$$

with

$$C_m = \frac{k_2}{\pi}\int_{-p/k_2}^{p/k_2} f(z)\exp(-2imk_2z)\mathrm{d}z. \quad (5)$$

We obtain the following equations for the normalized amplitudes by equating the coefficients of exponentials with equal indicies:

$$\frac{\mathrm{d}}{\mathrm{d}z}\,a^{(+)} = \frac{\beta}{2}\,C_0\,,$$

$$-\frac{\mathrm{d}}{\mathrm{d}z}\,a^{(-)} = \frac{\beta}{2}\,C_{-1}\,.$$

We have the following set of equations from the last one after substitution of the C_0 and C_{-1} calculated from Eq. (4):

$$\frac{\mathrm{d}}{\mathrm{d}z}\,a^{(\pm)} = \pm\frac{\beta}{2}\,\frac{1}{a^{(\pm)*}}\cdot \cdot\frac{|a^{(\pm)}|^2 - \frac{d}{2}\left[1-(1-4|a^{(+)}|^2|a^{(-)}|^2/d^2)^{1/2}\right]}{d(1-4|a^{(+)}|^2|a^{(-)}|^2/d^2)^{1/2}}, \quad (6)$$

where

$$d = 1+|a^{(+)}|^2+|a^{(-)}|^2.$$

We have from Eq. (5) for intensities of the counter-propagating waves in the active medium of TQ in the case of week saturation when $\eta = 2|a^{(+)}|^2+|a^{(-)}|^2/d \ll 1$, keeping terms up to second order of η:

$$\frac{\mathrm{d}}{\mathrm{d}z}\,I^{(+)} = \beta\,\frac{I^{(+)}}{1+I^{(+)}+I^{(-)}} - \left[1-\frac{I^{(-)}}{1+I^{(+)}+I^{(-)}}\right]'$$
$$\frac{\mathrm{d}}{\mathrm{d}z}\,I^{(-)} = \beta\,\frac{I^{(-)}}{1+I^{(+)}+I^{(-)}} - \left[1-\frac{I^{(+)}}{1+I^{(+)}+I^{(-)}}\right] \quad (7)$$

with $I^{(\pm)} = |a^{(\pm)}|^2$.

These equation have the following motion integral

$$\frac{I^{(+)}(z)I^{(-)}(z)}{\left[1+I^{(+)}(z)\right]\left[1+I^{(-)}(z)\right]} = = \frac{I^{(+)}(z=0,L)I^{(-)}(z=0,L)}{\left[1+I^{(+)}(0,L)\right]\left[1+I^{(-)}(0,L)\right]} = K = \mathrm{const}. \quad (8)$$

The boundary conditions of the problem under consideration are the continuity conditions of the tangential components of the electric and magnetic vectors of the waves on the interfaces of the laser-active and the passive dielectric media at $z=0$ and $z=L$.

We integrate the Eqs. (6) by introducing the amplification parameter $\xi = I^{(+)}(L)/I^{(+)}(0) = I^{(-)}(0)/I^{(-)}(L)$ (which describes the wave amplification during one pass through the film) and using the boundary conditions. The equation for the parameter ξ has the following form

$$\frac{(1-K)^2}{(1+K)^2}\left\{(1+K)I^{(+)}(L)(1-1/\xi)+\right.$$
$$+\frac{K}{K+I^{(+)}(L)(1+K)}\left[1-\frac{K+I^{(+)}(L)(1+K)}{K+(1+K)I^{(+)}(L)/\xi}\right]+$$
$$\left.+(1-K)\ln\left[\frac{K+I^{(+)}(L)(1+K)}{K+(1+K)I^{(+)}\{L\}/\xi}\right]\right\}=\beta L\,,$$

$$a^{(+)}(L)=a^{(+)}(0)\xi^{\frac{1}{2}}\,;$$

$$a^{(-)}(0)=a^{(-)}(L)\sqrt{\frac{\xi+I^{(+)}(L)}{\left[1+I^{(+)}(L)\right]\left[1+I^{(-)}(L)\right]-I^{(-)}(L)\left[\xi+I^{(+)}(L)\right]}},$$

where $K=\frac{I^{(+)}(L)I^{(-)}(L)}{\left[1+I^{(+)}(L)\right]\left[1+I^{(-)}(L)\right]}$.

The intensities $I(L)$ may be expressed through the intensity I_{tr} of the wave transmitted through the TQ using the boundary conditions at the interface $z=L$:

$$I^{(\pm)}(L)=\frac{1}{4}\left(1\pm\frac{k_1}{k_2}\right)^2 I_{tr}\,.$$

We obtain the following expressions for the normalized intensities of the transmitted $I_{tr}=\frac{\gamma}{2}|A_3|^2$ and the reflected $I_r=\frac{\gamma}{2}|A_1|^2$ waves using boundary conditions on the interface $z=0$ and Eq. 9), and assuming that the parameter $K\ll 1$:

$$I_{tr}=I_0\,\frac{\xi(1-P)^2}{\xi^2P^2-2\xi P\cos(2k_2L)+1}\,,$$

$$I_r=\frac{1}{\xi}\,I_{tr}\left(\frac{k_2^2-k_1^2}{4k_1k_2}\right)\left[1+\xi^2-2\xi\cos(2k_2L)\right],\quad (9)$$

where $I_0=\gamma/2|A_0|^2$ is the normalized intensity of the incident wave, and $P=(k_1-k_2)^2/(k_1+k_2)^2$.

The oscillation regime of the TQ laser corresponds to the zero denominator condition in Eq. (10). Using this condition, we can determine the eigenvalue of the wave vector k_2, the threshold value α_{th} and the amplification parameter ξ_{th} in the oscillating regime:

$$k_2L=m\pi,(m=\pm1,\pm2...);\ \xi_{th}=1/P\,;$$

$$\alpha_{th}=\frac{2}{\beta}\,\ln(1/\sqrt{P})\,.$$

The dependencies of I_{th} and I_r on I_0 calculated using Eqs. (8, 10) are plotted in Fig. 2.

It should be noted that the nonsingle-valued dependencies in Fig. 2 are observed only when the gain coefficient exceeds the threshold value $\alpha_{th}:\alpha\ \geq\ \alpha_{th}$.

These dependencies are single-valued when $\alpha<\alpha_{th}$, see Fig. 3.

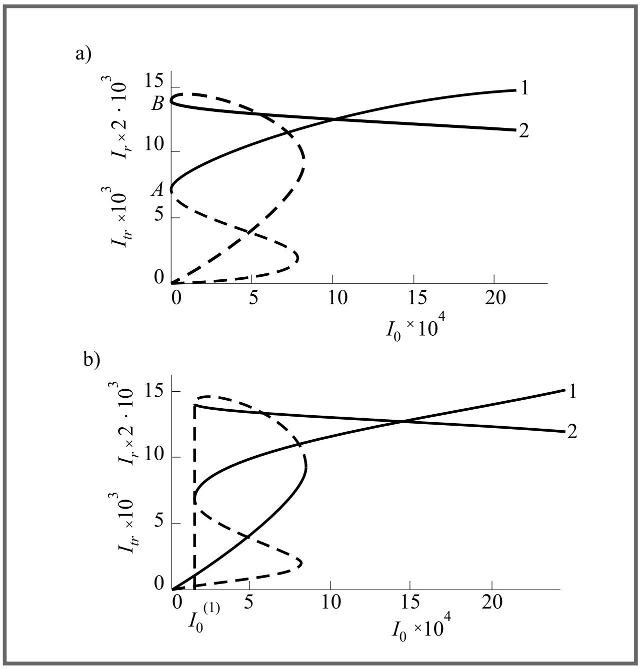

Fig. 2. Dependence of the normalized intensity of the transmitted I_{tr} (curve 1) and reflected I_r (curve 2) waves on the normalized intensity I_0 of the injected signal, at $\alpha=10\ \mathrm{cm}^{-1}$, and $\lambda=2\pi c/\omega=5.7\times10^{-5}$ cm, and in (a) $k_2L=\pi$, $A=B=I_G$; and in (b) $k_2L=(1+5\times10^{-3})\pi$. The unstable parts of the curves are marked by dashed lines.

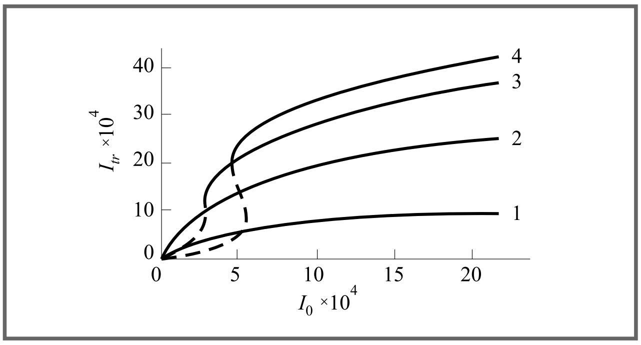

Fig. 3. Dependence of the normalized intensity I_{tr} of the transmitted wave on the normalized intensity I_0 of the injected signal at different values of the gain factor $\alpha:\alpha=4\ \mathrm{cm}^{-1}$ (1), $\alpha=5\ \mathrm{cm}^{-1}$ (2), $\alpha=6\ \mathrm{cm}^{-1}$ (3), $\alpha=6.5\ \mathrm{cm}^{-1}$ (4), at $k_2L=(1+5\times10^{-3})\pi$, $L=10^{-3}$ cm, $\lambda=5.7\times10^{-5}$ cm. The unstable parts of the curves are plotted by dashed lines.

Conclusions

In conclusion, the injection locking effect in the TQ laser has been studied in this paper. The possibility of the frequency and directional switching of the TQ output radiation by means of external signal injection has been shown.

The saturation effects and the nonlinearity of the refractive index of the laser-active medium of TQ may lead to the nonlinear interaction between the eigenmodes of TQ. This interaction is strong in the case when an additional external resonator has been performed by a pair of external mirrors.

The analysis shows that the interference between the eigenmodes of TQ with an external resonator leads to generation of light-induced gratings of the complex refractive index in the laser-active medium. The scattering from these gratings of the modes of TQ which are nonresonant in respect to the external resonator results in four wave parametric mixing and phase conjugation effects in the laser-active medium of TQ.

The features of the TQ laser-amplifyer presented in this paper allow one to propose this system as a promising laser-active element with tunable frequency for directional and frequency switching in the optical communication systems.

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