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Solid-state laser with self-stabilized or linearly chirped output frequency

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Abstract. The specific regimes of the linear tuning and the frequency self-stabilization were proposed and analyzed theoretically in a diode pumped solid-state laser with a thin-film metallic selector.

Keywords: diode pumped solid-state laser, single-frequency laser, frequency self-stabilization, thin-film selector.

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1. Introduction

Today, construction of highly stable optical standards of the fundamental laser parameters, such as energy, power or frequency is a problem. During the last decade diode-pumped solid-state lasers achieved fantastically high frequency stability. The electronically stabilized system demonstrated relative stability about several hundred mHz [1]. However, such system is quite complex and non-transportable. For operation in the hospital, in the plant, or in the airport one needs the standard of minor stability but simple, small and relatively cheap. To our mind, the best candidate for this role is the solid-state diode-pumped laser with the thin-film absorbing selector [2, 3].

In the single-frequency regime laser line width is about six orders of magnitude less than that at a free running mode. This laser has extremely narrow spectral width (~10^4 Hz). It is very sensitive to thermal disturbances (~10^9 Hz/K) [4]. A solid-state laser with a thin-film absorbing selector may be designed to be quite insensitive to mechanical noise. At the same time it has to provide both the stable single-frequency mode and a wide range of tunable frequency. Unfortunately, simultaneous satisfaction of such requirements is opposite in their nature.

The principle idea of the absorbing thin-film operation is the following [5]. The metallic film with a thickness significantly smaller than the standing wave period is placed into the linear cavity. If the thin film is adjusted to the node phase surface area of a mode, the losses for this mode become very low and the single longitudinal mode starts to operate. It is well known, that phase characteristics of interferometers with an absorbing mirror depend strongly on layer thickness and its composition [5]. Due to the high value of the absorption coefficient the thin film introduces strong distortion into the phase of the laser radiation. This phase shift depends on the position of the film relative to the standing wave structure inside the laser cavity and on the film properties. In this communication we demonstrate how to make this dependency predictable and controllable.

2. Basic principles

The phase of a wave that interacts with a metal mirror interferometer is given by expression [5]:

$$\Psi(\varphi) = -arctg\,[\frac{2(H - B\cdot tg\varphi)tg\varphi}{(H - B\cdot tg\varphi)^2 + (G^2 - 1)\cdot tg^2\varphi}] \qquad (1)$$

where $\varphi = 2\pi l/\lambda = \lambda\omega/c$ is the interferometer phase, ω is the radiation frequency, c is the velocity of light, l is the interferometer base length, l is the wavelength of radiation, $B = \xi''/n_1$; $G = \xi'/n_1$; $H = n_2/n_1$, n_1 is the index of refraction of the substrate, n_2 is the index of refraction of the material inside the interferometer, $\xi = \xi' + i\xi''$ is the surface conductivity with real and imaginary parts connected with the mass material parameters as:

$$\xi' = 2n\chi\, 2\pi\delta d/\lambda,\;\; \xi'' = (n^2 - \chi^2) 2\pi\delta d/\lambda, \tag{2}$$

where χ and n are the absorption coefficient and the index of refraction of the film mass material, respectively, δd is the film thickness.

The frequency of an electromagnetic wave can be calculated as a time derivative of the phase:

$$\frac{d\Psi(\varphi)}{d\varphi} = \frac{d\Psi}{dt}\frac{dt}{d\varphi} = \frac{d\Psi}{dt} / \frac{d\varphi}{dt} = \frac{F_{out}}{F_{in}} \tag{3}$$

For an interferometer located in a laser cavity the parameter F_{in} is a frequency, which corresponds to the number of half-wave lengths along the interferometer base, and F_{out} is the real frequency of oscillation. Thus, the derivative $d\Psi(\varphi)/\delta\varphi$ demonstrates the output radiation frequency normalized to "geometrical" frequency (connected with an integer of the half-waves in the cavity). Combination of the different parameters B, G, H results in specific behavior of $d\Psi(\varphi)/\delta\varphi$ function. Gathering up the appropriate B, G, H values (among experimentally achieved), one can predict the laser output frequency behavior. Let us consider two examples of such analyses.

3. Linear chirp of frequency

The laser with frequency chirping can be used as a range finder on middle (some km) distances. In such systems the radiated frequency has to vary linearly versus the time, although in laser with a thin-film selector the frequency changes non-linearly and, sometimes, even by a non-monotone mode, depending on the position of the selector. The interferometers, which were considered before [2, 3] were intended for a single mode selection. Therefore, principal attention was paid to achieve a maximum sharp reflection peak with this interferometer. It is evident, that the presence of a narrow peak of reflection indicates the presence of a strong phase shift of the reflected signal. It means that even at minor variations of the position of the selector in a resonator, owing to the thermal, mechanical, or piezodriver feeding voltage perturbations, the frequency changes of the radiation can rather noticeably differ from linear, though the oscillation remains permanently a single-frequency one. In elaboration of the laser for the Doppler range finding purposes an actual problem is control of the frequency changes rate.

Any profile of a reflection coefficient of an interferometer takes place at changes of an interferometer base (l) (scanning an interferometer), or with a constant base, but variable frequency of a radiation (classical interferometer Fabry-Perot). The phase of the radiation, which has interacted with the interferometer has both frequency and spatial components. If the phase of a reflected signal by a non-linear mode reacts to the linear selector shift it means that the additional phase modifications are connected with frequency shift. If the space modifications of a position of a mirror linearly correspond to the phase changes of an echo, the resonance frequency of a mode is shifted proportionally to shifts of a mirror position. Such case has to be realised in the laser with linear frequency tuning. In case of film absence $B = G = 0$, $H = 1$. The expression (1) is transformed to that one, which demonstrates a linear phase change at double pass by the field of the distance to a mirror and back.

$$\Psi(\varphi) = -arctg\;\frac{2tg\,\varphi}{1 - tg^2\varphi} = -arctg\;(tg\,2\varphi) = -2\varphi \tag{5}$$

In the case when $\xi' \neq 0$, $\xi'' \neq 0$, but $\Psi(\varphi) = -2\varphi$, there are no phase variations connected with a frequency change. In other words, it is possible to ask: whether there is an actual set of parameters H, G, B, R, that in the definite range of the parameter variations the following equality is valid:

$$\frac{2(H - B\cdot tg\,\varphi)tg\,\varphi}{(H - B\cdot tg\,\varphi)^2 + (G^2 - 1)\cdot tg^2\varphi} = tg\,2\varphi = \frac{2tg\,\varphi}{1 - tg^2\varphi} \tag{6}$$

Under these circumstances $d\Psi/d\varphi = -2$, that is the ratio of oscillation frequency to frequency of set-up is a constant. From expression (6) one can obtain the following equations:

$$\begin{aligned} Y0 &= (H - B\cdot tg\varphi)(1 - tg^2\varphi) = \\ &= (H - B\cdot tg\varphi)^2 + (G^2 - 1)tg^2\varphi = Y1 \end{aligned} \tag{7}$$

If there is a solution of the equation above, the graphs of the left and right parts should coincide. It correlates with the experimental conditions, when the changes of the output frequency are proportional to frequency variations connected with the selector relocation. And, as it will be shown below, the velocity tuning can be controlled due to the definite selection both of the film and the substrate parameters. So, the frequency velocity chirp can be controlled in the definite limits but remains a linear one.

For testing we substitute values of the film parameters close to those that were observed in the experiment [2, 3], namely $\xi' = 0.6$, $\xi'' = 0.01$, $R = 0.95$, $n_1 = 1.46$, $n_2 = 1$. In Fig. 1a the graphs of functions $Y(\varphi)$ and $Y1(\varphi)$, and in Fig. 1b, accordingly, distribution of reflection coefficient $r(\varphi)$, linear (spatial) phase change $\Psi 1(\varphi) = -2\varphi$ and the actual phases of an reflected signal are depicted. It is evident that the functions $Y(\varphi)$ and $Y1(\varphi)$ have no common points, so the equation (7) has no solution. In such case the frequency of output reacts on the selector set-up of. In Fig. 1b and 2b the function $\Psi(\varphi) = -2\varphi$ is marked as $\Psi 1$.

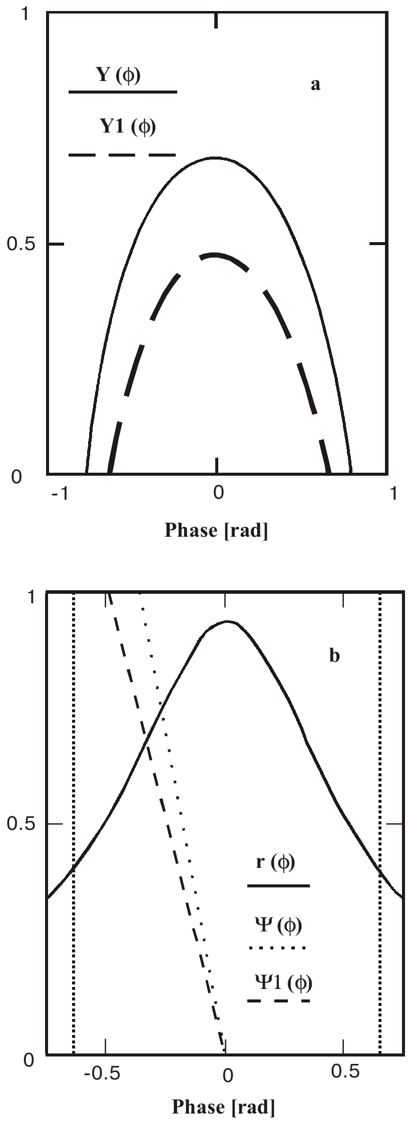

Fig. 1 (a) Graphs of left and right parts of an expression (7) at $\xi' = 0.6$, $\xi'' = 0.01$, $R = 0.95$, $n_1 = 1.46$, $n_2 = 1$. (b) Reflection coefficient and an output phase versus the input phase.

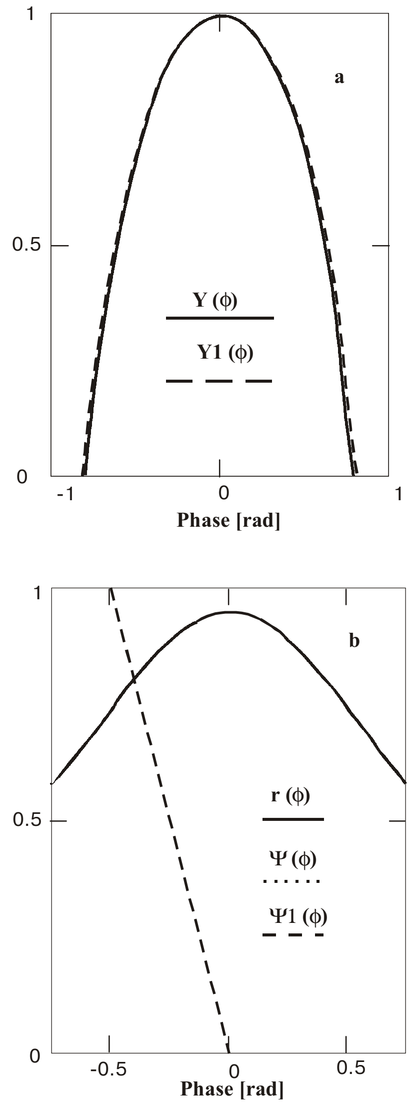

Fig. 2 (a) Graphs of left and right parts of an expression (7) at $\xi' = 0.4$, $\xi'' = 0$, $R = 0.95$, $n_1 = n_2 = 1.46$. (b) Reflection coefficient and an output phase versus input phase.

The following graphs (Fig. 2) demonstrate the above-mentioned functions at $\xi' = 0.4$ and $n_1 = n_2 = 1.46$. That corresponds to the metallic thin film (6-7 nm thick) located between two quartz plates. Thus, $Y(\varphi)$ and $Y1(\varphi)$ as well as, accordingly, $\Psi 1(\varphi)$ and $\Psi(\varphi)$ coincide within a rather broad interval of values. Practically, to realize conditions $n_1 = n_2$, it is possible when using a deposition of a SiO_2-film on a metal film, or the dielectric layers deposited on a metal film, which match the necessary values n_1 and n_2. Such a multilayer selector may provide the single-frequency operation and linear tuning inside the range of several GHz.

4. Frequency control

Owing to the voltage instability of the power supply, the piezodriver moves the selector chaotically. At piezodriver sensitivity of 18 nm/V and at a voltage of, for example, 100 V and with a typical voltage instability about 1%, twitching of the selector is possible, within an order of magnitude, of the typical internode space in the place of a selector position in a linear cavity. With length of a resonator of about 10 cm and coefficient of the linear expansion of a cavity material of about 10^{-5}/K, the variation of the cavity length is 100 nm per a degree. It means that at variations of temperature about 1K the hopping between several longitudinal modes is possible. Let's consider the problem: whether to fix such parameters of a film so that the frequency of oscillation would not depend on a selecting interferometer phase. Mathematically it means satisfaction of the equality $d^2\Psi/d\varphi^2 = 0$ or absence of the frequency shift versus the selector shift. The second derivative from expression (1) has an extremely complex view and practically does not yield to the analytical analysis at variations of the parameters both of

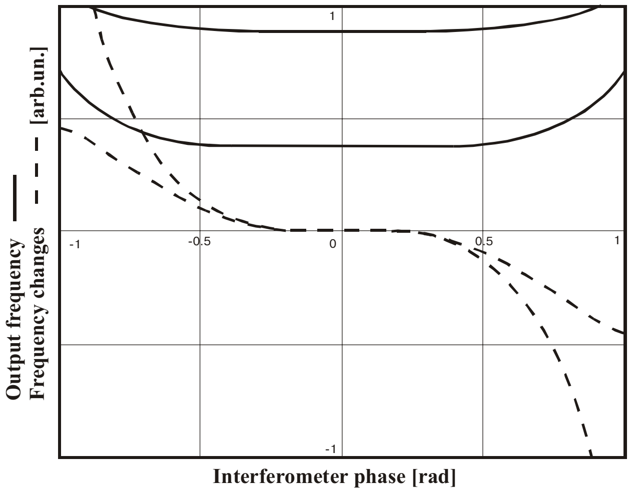

Fig. 3. Oscillation frequency dependences (solid curves) and frequency changes (dash curves) versus the phase of selecting interferometer for the sets of the parameters: a) $\xi' = 0.625$, $\xi'' = 0$, $n_1 = 1$, $n_2 = 1.46$; b) $\xi' = 0.295$, $\xi'' = 0$, $n_1 = 1.37$, $n_2 = 1.46$.

the film and the substrate. In Fig. 3 the examples of the computer evaluation of the phase curves that make possible versions of the construction of a laser with self-stabilization are demonstrated. At such combinations of the parameters the output frequency is independent on the phase of the selecting interferometer within limits of approximately ±0.3 rads. The period of a standing wave for the neodymium laser is 530 nm. The phase change of about one radian corresponds to a 100 nm space shift of a selector position that exceeds many times the typical space between the nodes of the modes around a location of the selector. It means that in the limits of an intermode space the output frequency would not depend on the position of the thin-film selector. It is necessary to note, that these conditions are possible with the film faced to an active medium (or a substrate to an output mirror) that is the inverse orientation as compare with the single-frequency operation design [2, 3]. In this case, the reflection peak is more wide and smooth and, probably, for sure mode selection it would be necessary to keep the length of an active medium shorter than that used in [2, 3].

4. Conclusion

We propose the new specific regimes of the linear tuning and the frequency self-stabilization provided with the thin-film metallic selector in the diode pumped solid-state laser.

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