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Continuously pumped Nd^{3+}:YAG laser operating on two locked frequencies

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Abstract. Experimental and theoretical study of locking of two mutually orthogonal polarisation modes in a cw flash-lamp-pumped Nd^{3+} : YAG laser is reported. The possibility of locking polarisation modes by a radio signal is shown theoretically. The limiting detuning allowing for the existence of locking is determined. Locking at 23 MHz is experimentally studied.

1. Introduction

The development of solid-state lasers pumped by laser diodes has quickened interest in two-frequency lasers with frequency difference lying in the radio-frequency region. Interest in such lasers is associated with the possibility of increasing accuracy and sensitivity of various optical measurements, such as optical ranging, remote atmospheric sensing, optical gyroscopy, etc.

Two-frequency oscillation has been studied in gas [1, 2] and solid-state lasers [3 – 6]. As noted in these papers, the main problem in obtaining stationary two-frequency lasing is the competition of lasing modes due to their nonlinear interaction in an active medium. To suppress mode competition, it was proposed to use either spatial separation (both longitudinal and transverse) of modes [7] or lasing on two orthogonally polarised modes [2]. The second method has been realised in [3], where the authors obtained deviation of the difference frequency in two-frequency lasing using anisotropy controlled by mechanical stress. Note also paper [8] in which two-frequency lasing in an anisotropic cavity was stabilised using nonlinear mode interaction upon intracavity SHG.

Note that an increase in the difference-frequency stability offers a considerable enhancement of potentialities of two-frequency lasers in optical measurements. It is evident that the absolute frequency stabilisation of lasing modes is a considerably more complicated problem than the stabilisation of their frequency difference. The latter problem can be solved to a certain extent simply by stabilising cavity and pump parameters and by purely radio engineering means, namely, by locking the difference frequency to an external radio-frequency signal using nonlinear interaction in an active medium. Here, we study this method of stabilisation of the difference frequency of lasing modes.

2. Theoretical analysis of two-frequency oscillations under conditions of their locking at the difference frequency

Consider a continuously pumped Nd^{3+} : YAG laser with an anisotropic cavity. It is assumed that anisotropy is produced by a lumped element (a thin uniaxial crystal) so that the path difference for o- and e-waves provides the desired frequency interval for modes with mutually orthogonal polarisations. We also assume that only one axial mode is excited in the laser for each polarisation. Under these assumptions, the competition of lasing modes associated with spatial inhomogeneity of inverse population because of intermode interference is reduced to a minimum.

To lock the difference frequency, we introduced into the cavity an additional element, which provides intermode interaction in the following way. Polarisation of a portion of radiation of one electromagnetic wave is changed to the orthogonal one, and its frequency is shifted up or down by Ω using an external signal. A similar operation is made for radiation with another polarisation. The frequency shift Ω is assumed to be close to the intermode interval $|\omega_1 - \omega_2|$, i.e., $\Delta = \Omega - |\omega_1 - \omega_2|$ satisfies the condition $|\Delta| \ll \Omega$. Devices that are able to perform this operation will be discussed below.

For a qualitative description of lasing dynamics, we use the system of equations [9] for the inverse population N and the mode fields E_1 and E_2 in the approximation of a harmonic oscillator with a weak nonlinearity

$$\ddot{E}_{1,2} + 2\left[\delta - \frac{\alpha}{1 + \left(E_1^2 + E_2^2\right)/E_s^2}\right]\dot{E}_{1,2} + \omega_{1,2}^2 E_{1,2} = 2\mu\omega_{1,2}^2 \hat{E}_{1,2}. \qquad (1)$$

Here, $\omega_{1,2}$ are the natural resonance frequencies of polarisation modes; $\hat{E}$ is the field whose frequency is shifted by Ω with respect to E; δ is the mode damping parameter, which is related to the Q factor of the passive cavity; α is the parameter proportional to the pump power [9]; E_s is the saturation field amplitude for the laser transition [10]; $\mu = \xi\Xi/\omega_0$ is the mode coupling factor; ξ is the coefficient of radiation power transfer from one polarisation mode to another; Ξ is the frequency interval between two nearest axial modes with the same polarisation; and $\omega_0 \approx \omega_1 \approx \omega_2$.

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For simplicity, both modes are assumed to have the same values of parameters μ,δ,α and β.

The solution of system (1) in the approximation of slowly varying amplitudes is sought in the form

$$E_1(t) = x(t)\cos(\omega_1 t + \varphi(t)),$$

$$E_2(t) = y(t)\cos(\omega_2 t + \psi(t)).$$

Because the system of equations for the amplitudes $x(t)$, $y(t)$ and phases $\varphi(t), \psi(t)$ and the analysis of this system for the presence of stationary lasing on modes with a locked frequency difference are cumbersome, we do not present them here and report only some results of the analytical and numerical analysis.

Our analysis and numerical calculations showed that stable lasing on locked modes is possible only for the detuning $|\Delta| < \omega_0\mu\sqrt{2}/8$. In the case of $\Delta = 0$, polarisation modes have the same amplitude, and the phase difference between two modes shifted in frequency by Ω vanishes. If $\Delta \neq 0$, these two oscillations have a nonzero phase shift, and modes differ in amplitude. It is evident that this fact is detrimental from the viewpoint of obtaining locked lasing. However, using a minimum phase shift as a criterion, one can realise electronic feedback that automatically tunes a laser cavity to the state with $\omega_1 - \omega_2 = \Omega$.

3. Experimental results

The locking method under consideration was tested using a cw Nd^{3+} : YAG laser operating at 1.06 μm (Fig. 1). In the experiments, we used a K-301V 'Kvantron' laser head *1*, which had a laser crystal 100 mm long pumped by one flashlamp. The cavity was formed by a plane mirror *2* with reflectivity not less than 98 % and an optical stack *3* consisting of five plates made of fused quartz. The cavity optical thickness was close to 280 mm, which corresponded to the intermode interval $\Xi = 576$ MHz. Selectors of axial (the stack) and transverse modes (an aperture *4* 1 – 2 mm in diameter) provided reliable single-mode and single-frequency lasing in an anisotropic cavity at a pump level of up to 10 % above the threshold.

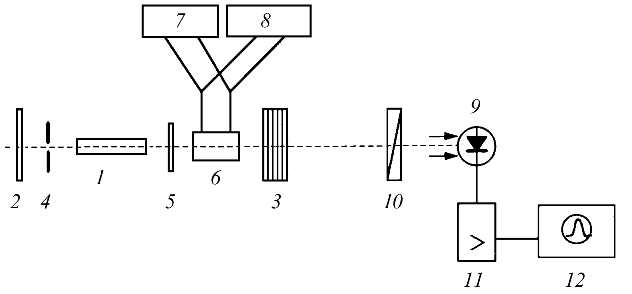

Figure 1. Experimental setup: (*1*) laser head with an active element; (*2*) totally reflecting cavity mirror; (*3*) optical stack (output mirror); (*4*) selecting aperture; (*5*) anisotropic plate; (*6*) electrooptic modulator; (*7*) low-frequency (50 Hz) modulator power supply; (*8*) high-frequency (23 MHz) power supply; (*9*) photodiode; (*10*) rotatable polariser; (*11*) resonance amplifier; (*12*) oscilloscope.

Anisotropy was produced by an intracavity LiNbO$_3$ plate *5* 0.3 mm thick, which had antireflection coatings for 1.06 μm and whose optic axis was in the plane of the plate. To obtain the desired effective thickness, the plate was rotated about its optic axis in order that the optical path difference for o- and e-polarisations be an integer of $\lambda/2$. When the path difference is exactly equal to this quantity, two polarisation modes should have the same frequency. The study of polarisation properties of laser radiation produced in this case showed that the intensity of radiation polarised along the optic axis of the plate *5* and perpendicular to it depended on the position of the aperture *4* relative to the optic axis of the active element. Choosing its position, we were able to equalise intensities of polarisation components with an accuracy of 70 – 80% or even better.

To produce dynamic coupling between modes with different polarisations, we introduced into the cavity a modulator *6*, which was made of a LiNbO$_3$ crystal 12 mm thick. The crystal was accurately aligned so that its optic axis coincided with the optic axis of the laser cavity. It was oriented so that the angle between the axis of birefringence induced by the electric field and the axis of the plate *5* was equal to 10 – 15°.

The modulator was driven by two ac power supplies. The first source *7* operated at 50 Hz. It was used for tuning and slow scanning of natural frequencies of polarisation modes. The dc voltage and the 50-Hz voltage amplitude were chosen so that the difference of natural frequencies of polarisation modes $|\omega_1 - \omega_2|$ be close to the frequency of external modulation, and it was scanned near this frequency (see below). The second power supply represented a radio-frequency generator *8* operating at the frequency $\Omega = 23$ MHz.

The output radiation was analysed by an avalanche photodiode *9* with an analyser *10* placed in front of it. The photodiode signal was fed to a 23-MHz resonance amplifier 11 with transmission band of about 500 kHz, detected with a time constant of 1.5 μs, and fed to a digital oscilloscope *12*.

The experiment on frequency locking of polarisation modes was carried out in the following way. The modulator *6* was driven by a 50-Hz signal whose amplitude produced an additional path difference of about $\sim \lambda/4$ for one of polarisation modes, which provided the coincidence of the difference frequency with the frequency Ω. The modulator was simultaneously with the power supply and before the appearance of a signal at the output of the amplifier *11* driven by a high-frequency 23-MHz voltage.

The signal at the modulation frequency was optimised in the following way. We decreased the amplitude of low-frequency voltage applied to the modulator, which caused a decrease in frequency deviation $|\omega_1 - \omega_2|$, and its coincidence with Ω was provided by the tilt of the plate *5*. To make sure that the signal observed in the experiment was indeed caused by intermode beats at the frequency Ω, we rotated the polariser *10* placed in front of the photodetector *9*. We obtained four polariser orientations giving the minimum output signal. This fact suggests that the output laser radiation contained two waves with mutually orthogonal polarisations, each of them having no modulation at the frequency Ω.

The time of existence of the signal at the frequency Ω (the detuning $\Delta = |\omega_1 - \omega_2| - \Omega$ allowable for locking) could be increased by choosing the amplitude of the modulation voltage at the frequency Ω and the optimum angle between the optic axis of the plate *5* and the axis of induced birefringence in the crystal of the modulator *6*. A typical oscillogram of the signal observed for the polariser *10* oriented at an angle of 45°, which corresponds to the maximum amplitude of intermode beats, is presented in Fig. 2. In this case, the amplitude of beats at the photodiode output reached 1.7 – 1.8 of the amplitude of the signal in each of polarisation modes. The statement that our laser operated on two modes locked at the difference frequency is supported by the fact that the signal at the output of the resonance amplifier decreased in duration with decreasing amplitude of the modulating signal at the frequency Ω. In the case of switched-off modulation, the signal decreased down to the noise level. It is likely that this fact is associated with the absence of two-frequency lasing, at least for close (in comparison with the intermode interval) frequencies of waves with mutually orthogonal polarisations.

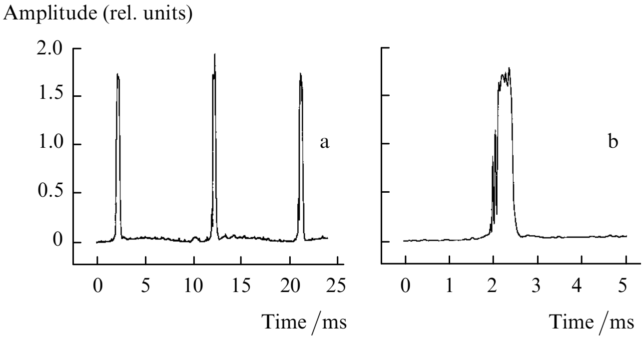

Figure 2. Oscillograms of the output signal at 23 MHz recorded with different sweep speeds.

Note that an attempt to obtain steady-state lasing by decreasing the amplitude of scanning voltage down to zero, with constant voltage tuned in the appropriate way, failed. It is likely that locking ceased because of the action of parasitic acoustic vibrations on the cavity.

Thus, the method described here is capable of procuring lasing on two locked modes with the given intermode frequency interval. However, it makes sense to use monolithic cavities, pumping of an active element by laser diodes, and automatic tuning of the cavity anisotropy, which minimises the detuning $\Delta = |\omega_1 - \omega_2| - \Omega$, for improving the locking stability.

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