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Tunable diode-pumped single-frequency travelling-wave Nd:YAG laser operating at 1319 nm

S.M. Ignatovich, N.L. Kvashnin, M.V. Okhapkin, M.N. Skvortsov

Abstract. **A single-frequency travelling-wave Nd:YAG laser with a wide wavelength tuning range achieved due to the use of a temperature-controlled intracavity KTP filter is studied. The output laser characteristics and the frequency tuning range are presented for different operation regimes. A tuning range of 90 GHz with a tuning rate of 12 GHz °C is for the first time achieved for Nd:YAG lasers operating at a wavelength of 1319 nm. The output power in the centre of the gain line was ~ 240 mW. The laser can be used in spectroscopy and metrology.**

Keywords: *spectroscopy, travelling-wave laser, frequency tuning.*

1. Introduction

High-tech Nd^{3+}:YAG lasers have found wide application in various fields of science and technology, such as, for example, ultrahigh-resolution spectroscopy [1, 2], metrology [3, 4], and precision experiments, including measurements of the speed of light [6, 7]. Lasers with a wavelength of 532-nm stabilised by saturated absorption resonances in I_2 molecules were used to create compact sources of radiation with a relative frequency instability smaller than 10^{-14} for observation times of ~1000 s, laser spectrometers with ultrahigh resolution [2, 3, 5], and ballistic gravimeters [8]. Tunable Nd:YAG lasers with a wavelength of 946 nm are used as probe lasers to study transitions in the In^+ ion and to create optical frequency standards based on this ion [4]. One more field of application of Nd:YAG lasers is the high-resolution spectroscopy of sodium. The frequency of the sodium D2 absorption line coincides with the frequency obtained by summing the frequencies of two Nd:YAG lasers with wavelengths of 1319 and 1064 nm [9]. This type of lasers is chosen because they satisfy the conditions necessary for the precision spectroscopy, such as a small linewidth (~10 KHz) and a wide range of frequency tuning in the single-frequency generation regime.

Researchers from the Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences developed and studied a master oscillator emitting radiation at the wavelength λ = 1319 nm, which is then amplified for efficient mixing in a nonlinear crystal. This laser has an extended tuning range compared with analogous commercial lasers [10]. In addition, the frequency of this laser can be precisely tuned by changing the cavity length using piezoceramic actuators attached to the mirrors.

S.M. Ignatovich, N.L. Kvashnin, M.V. Okhapkin, M.N. Skvortsov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: sign@laser.nsc.ru, knl@laser.nsc.ru, maxok@laser.nsc.ru, skv@laser.nsc.ru

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2. Laser design

A stable single-frequency lasing regime can be obtained in lasers with both linear (when using thin amplifying media to reduce the competing longitudinal cavity modes) and ring resonators (in the travelling-wave regime). Due to the spatially uniform exhaustion of the population inversion by the travelling wave, ring lasers operate in a more stable regime.

To obtain a single-frequency regime in ring lasers, one must ensure unidirectional propagation of the beam in the cavity. As an optical diode for this purpose, we used a Nd:YAG active crystal in a magnetic field. This allowed us to decrease the number of intracavity elements, which had a positive effect on the long-term stability of the laser parameters.

The travelling-wave Nd:YAG laser was designed based on a nonplanar two-mirror cavity geometry of the cavity with an amplifying medium in the form of a prism (Fig. 1), which was previously used for 1064-nm and 946-nm Nd:YAG lasers [11, 12]. The mirror placed in point *A* is shifted from the *BCD* plane. The face *B* of the amplifying crystal is oriented at the Brewster angle θ_{Br} and rotated at an angle β with respect to the crystal axis BC to get a nonplanar geometry.

Mirror *A* in the scheme serves to couple out radiation. The pump diode laser beam (λ_{pump} = 808 nm) focused by lens *E* is coupled through mirror *D*, which has a high reflection coefficient at the laser wavelength and is antireflection coated at the pump wavelength. Both mirrors also have a high transmittance at 1064 nm in order to prevent lasing at this wavelength, at which the gain is much higher. To control the cavity length, the mirrors are mounted on piezoceramic actuators (Fig. 1). This configuration allows us to obtain the size of the beam waist in the active medium at a level of 100×200 μm for the sagittal and tangential components. The pump laser diode with an output power of 4 W and a luminous body 1×200 μm in size is equipped with a temperature stabilisation system to match the pump wavelength with the crystal absorption maximum.

The unidirectional travelling-wave regime is achieved by using an optical diode based on the Faraday effect in a Nd:YAG crystal placed in a longitudinal magnetic field (Verde constant $V \approx 1.2\times10^{-7}$ rad mm^{-1} G^{-1} at the wavelength λ = 1.3 μm). The face of the Nd:YAG crystal oriented at the Brewster angle served as a partial polariser providing a differ-

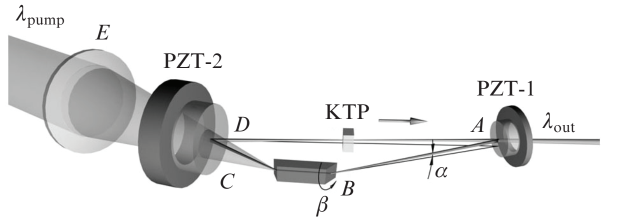

Figure 1. Optical scheme of the Nd : YAG laser cavity: (*A*) output mirror; (*B*) Nd : YAG crystal face oriented at the Brewster angle and rotated by the angle $\beta \approx 8°$ around the crystal axis so that the cavity was nonplanar; (*C*) antireflection coated face of the Nd : YAG crystal; (*D*) selective mirror transmitting the pump radiation with λ_{pump} = 808 nm and reflecting the fundamental harmonic; (*E*) focusing lens; $\alpha \approx 4°$ is the angle between the beam and the cavity plane; λ_{out} = 1064, 532 nm; (PZT-1), (PZT-2) piezoceramic actuators.

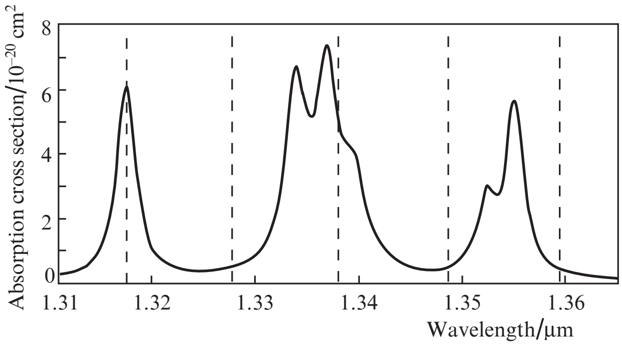

Figure 2. Calculated absorption cross sections of the Nd : YAG crystal (solid curves) and positions of the maxima of a frequency selector based on a KTP crystal 1.9 mm long (dashed curves).

ence in the losses for the counterpropagating travelling waves, which have different polarisations after passing through the Faraday rotator. The magnetic field is created by a NdFeB magnet with holes made to mount the crystal and to let the beam pass between the mirrors (*AD* line). This magnet forms a field with an average magnetic field strength of about 5.5 kG at the axis of the crystal. The formed difference in the losses for the clockwise and counter-clockwise propagating wave was ~0.25% at $\beta = 8°$ ($\alpha \approx 0.5\beta$). This turned out to be enough to achieve stable unidirectional lasing.

To extend the wavelength tuning range, we introduced a temperature-controlled birefringent filter, namely, a KTP crystal with optical surfaces normally oriented to the incident beam [13, 14]. The KTP crystal was placed inside the cavity so that the *Z* axis was directed at an angle of 45° to the fundamental beam polarisation. In this configuration, a wave with the linear polarisation controlled by the Brewster window is divided inside the crystal into the ordinary and extraordinary waves with different refractive indices.

If the phase difference between the ordinary and extraordinary waves is divisible by 2π, then the polarisation at the exit of the crystal remains linear and coincides with the polarisation at the entrance, which leads to the absence of losses at the Nd : YAG crystal surface oriented at the Brewster angle. In contrast, if the phase difference is not divisible by 2π, the polarisation after the nonlinear KTP crystal becomes elliptical, which causes intracavity losses at the partial polariser for the given laser frequency. The positions of the transmittance maxima of the birefringent filter depend on the difference in the refractive indices n_o and n_e and on the length of the nonlinear crystal.

The temperature dependence of these parameters on temperature allows one to control the positions of the filter transmittance maxima and, hence, the laser radiation frequency by changing the KTP crystal temperature. If the parameters of a birefringent filter are chosen properly, the laser can be tuned in a wide range [14]. In our case, the estimated optimal length of the KTP crystal is 1.9 mm. The period of the filter transmittance maxima is ~1.75 THz. At this length of the crystal, the filter transparency maxima lie so that the losses of the gain line at 1319 nm are minimal and the losses at the stronger lines peaked at 1337 and 1355 nm are maximal, which prevents lasing at these lines and allows one to achieve the maximum tuning range in the region of 1319 nm (Fig. 2). The wavelengths for which the losses introduced by a birefringent filter are minimal are determined by the expression

$$q\lambda = l(T)[n_e(\lambda, \varphi, \theta, T) - n_o(\lambda, \varphi, \theta, T)],$$

where q is the integer number corresponding to the selector mode number; λ is the radiation wavelength; l is the length of the birefringent crystal; φ and θ are the angles determining the beam direction in the crystal with respect to the *X* and *Z* axes, respectively, and *T* is the crystal temperature.

The temperature of the birefringent filter was controlled by the temperature of the entire resonator, which was made of brass and placed onto a thermoelectric Peltier module. The high thermal conductivity of the construction ensured efficient heat transfer to the KTP crystal. The design allowed us to change the laser temperature within a range of 15–40 °C. A system of automatic temperature control was able to keep a chosen temperature of the cavity and the KTP crystal with a stability of 10^{-2} °C.

3. Experimental study of the laser parameters

The laser parameters were studied in two operation regimes, namely, without an intracavity selector and with an intracavity birefringent filter based on a KTP crystal.

Figures 3 and 4 show the dependences of the laser wavelength and power on the resonator temperature. Without an intracavity selector, the laser wavelength was changed due to a temperature-induced shift of the gain peak of the Nd : YAG crystal. The frequency tuning range $\Delta\nu_1$ corresponding to the

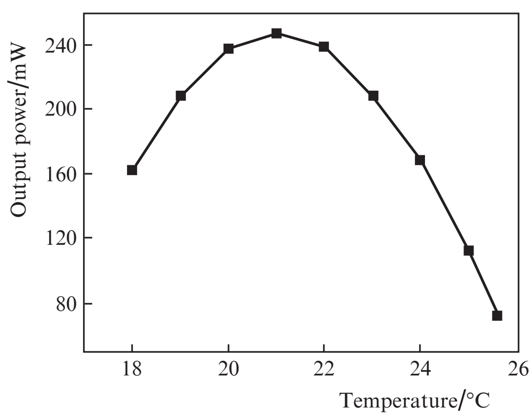

Figure 3. Dependence of the output power on the temperature of the laser with a KTP filter.

change in the temperature from 14 to 36 °C was ~28 GHz with the tuning curve slope of about –1.2 GHz °C^{-1}. The laser power in the absence of a KTP crystal was P_1 = 250 mW. Since the tuning occurred due to a shift of the centre of the gain line of the Nd:YAG crystal, the output power changed insignificantly (ΔP < 1 %).

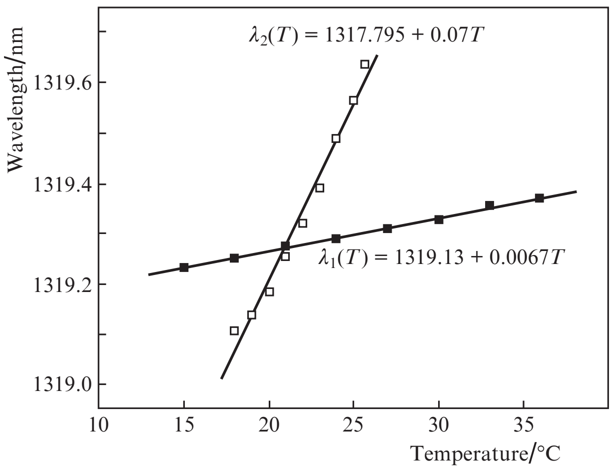

Figure 4. Dependences of the wavelength in a vacuum on the laser temperature in the case without [$\lambda_1(T)$] and with [$\lambda_2(T)$] a KTP filter.

The tuning range in the case with the KTP filter $\Delta\nu_2$ was considerably larger than without the filter, namely, about 90 GHz for the temperature range from 18 to 26 °C. The tuning curve slope was –11 GHz °C^{-1}.

Since the tuning range for the laser with the KTP crystal is considerably larger and is comparable with the gain line width, the output power changes substantially. The maximum laser power in this case is 240 mW at a temperature of 21 °C, which corresponds to the wavelength of 1319.25 nm, and decreases as the wavelength is detuned from the gain line centre, being 160 mW at a temperature of 18 °C and 70 mW at 26 °C (Fig. 3). With a further detuning from the optimal temperature, the laser ceased to operate in the single-frequency regime because the KTP filter cannot introduce necessary losses at stronger gain lines. The obtained wavelength tuning range was larger than required.

For precision spectroscopy and wavelength control of lasers used in systems with frequency auto-tuning, it is possible to tune the laser frequency within the range of the normal cavity dispersion by moving the mirrors using piezo actuators (see Fig. 1). The first piezo actuator (PZT-1) is used for a faster cavity length control with frequencies up to 50 kHz. The frequency tuning sensitivity in this case is ~ 0.9 MHz V^{-1} (Fig. 5). The second piezo actuator (PZT-2) serves for cavity length tuning with frequencies up to 1 kHz, the frequency tuning sensitivity being about 8 MHz V^{-1}. In this scheme, the frequency tuning range at scanning voltages of ±300 V is 2.7 GHz and overlaps the range of the normal cavity dispersion.

The working frequencies of piezo actuators are limited by intrinsic mechanical resonances, whose frequency and Q-factor impose limitations on the speed of auto-tuning of the laser frequency (Fig. 5). The resonance characteristics of the piezo actuators used in the laser allow one to realise a scheme of frequency auto-tuning with a band exceeding

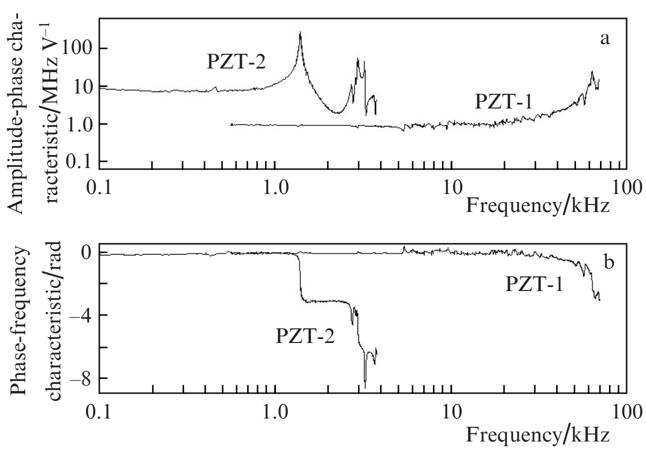

Figure 5. Amplitude-phase (a) and phase-frequency (b) characteristics of PZT-1 and PZT-2 piezo actuators.

10 kHz and to suppress the influence of acoustic noise on the laser.

4. Conclusions

The studied laser with a wavelength of 1319 nm is a promising spectroscopic instrument because it has an enlarged frequency tuning range (~90 GHz) due to the use of an intracavity selector based on a temperature-tunable birefringent KTP crystal. The laser power in the tuning range centre is ~250 mW. The laser frequency can be precisely tuned using two piezo actuators attached to the cavity mirrors. The piezo actuators with different frequency characteristics make it possible to tune or modulate the laser frequency with different rates, which is widely used in precision spectroscopy for frequency stabilisation.

An analogue of the laser with the closest characteristics is a Mephisto (Innolight) laser, which, however, has a shorter frequency tuning range (~30 GHz). The smaller dynamic range of tuning by the piezo actuator of this laser is caused by the monolithic laser cavity, which does not allow fast tuning within the entire normal dispersion range.

Due to the enlarged frequency tuning range and the possibility of precision stabilisation using piezo actuators, the laser developed by us can be used as a master oscillator for experiments on the spectroscopy of the D2 sodium line.

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