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Single-frequency microchip solid state diode pumped lasers

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Abstract. The paper deals with the basic set-up of single-frequency microchip laser – so called Lyot filter configuration. Description of its operation and practical realization is given. Some results obtained for Nd:YAG/KTP microchip laser are presented. The evidences of single-frequency operation and its limits are emphasized. Described construction constitutes the base for building the frequency stabilization of green 532 nm microchip laser.

Key words: microchip laser, birefringent filter, single frequency operation.

1. Introduction

Optical communications, optical metrology (precise interferometry, holography), high resolution spectroscopy require compact, stable, single frequency and narrow linewidth laser sources with the output power at the level of tens of mW or even higher. Development of new technology such as optical coherent telecommunication requires laser sources with stable and tunable frequency. These requirements are fulfilled quite well by microchip solid state lasers pumped by semiconductor diode lasers. These lasers are characterized by narrow linewidth at the level of a few kHz, single frequency operation, precise frequency tuning in wide range (up to a few THz), very good beam quality, high efficiency (up to 50%). Availability of laser gain media for the eye safe region around 1.5 μm (erbium and ytterbium co-doped glasses – Er-Yb:Glass [1]) is the reason for increasing interest in solid state microchip lasers.

Classical approach of single frequency operation of microchip solid state lasers involve very short laser cavity, for which the free spectral range of a laser cavity must be comparable to the laser gain linewidth. Gain linewidth of solid state media ranges from hundred GHz to a few THz. Therefore in practice it is difficult to obtain single frequency operation. For example, the gain linewidth of Nd:YVO$_4$ at 1064 nm is about 250 GHz, and the laser cavity length assuring the single frequency operation should be in that case shorter then 0.3 mm. When a single frequency microchip laser with second harmonic generation or internal electro–optical frequency modulation is required, another element (nonlinear or electrooptical crystal) in laser cavity should be inserted, substantially increasing the total laser cavity length. As a consequence, the laser starts operating in undesirable multimode regime. In order to obtain single frequency operation other techniques must be used. Some of them are listed below:

1. Using additional etalon inside the laser cavity [1, 2].
2. Inserting the quarter wave plate inside the cavity – single mode selection by standing wave elimination. This method is useful only for isotropic gain media (Nd:YAG) [3],
3. Application of special ring configuration resonator NPRO (Non Planar Ring Oscillator) [4],
4. Increase an air gap between gain element and an anisotropic one, which ensures thermal isolation of both of them and single-frequency operation [5, 6].
5. Using Lyot filter in the laser cavity consisting of a polarizing element and an birefringence crystal [7].

Below we present our construction and single-frequency operation of Nd:YAG/KTP microchip lasers based on Lyot filtering.

2. Microchip laser with Lyot filter

The basic set-up stimulating single-frequency operation is based on so called Lyot filter configuration. The idea of microchip Nd:YAG laser with the Lyot filter is shown in Fig. 1a where the Lyot filter consists of two main parts: a polarization element (for example Brewster plate) and a birefringent element (for example KTP crystal). In that configuration the KTP crystal plays two roles: it introduces birefringency, and it operates as a nonlinear crystal for second harmonic generation. For settled conditions (temperature, the length l_2 of the KTP and the state of polarization) the round trip of the beam passing through birefringent crystal reproduces the same polarizations – the Lyot filter operates like multiplication of a half-wave-plate. Hence, the configuration with Lyot filter forces single frequency operation. For each other conditions the polarization does not match its input state and the Brewster plate introduces losses.

There is still additional role which the KTP crystal can play. Because of its birefringence it can operate as an internal electrooptical frequency modulator. In order to simplify KTP crystal mounting and its electrical driving, the special cutting was required. A typical cutting of KTP crystal and this applied by us are depicted in Fig. 1b and Fig. 1c, respectively.

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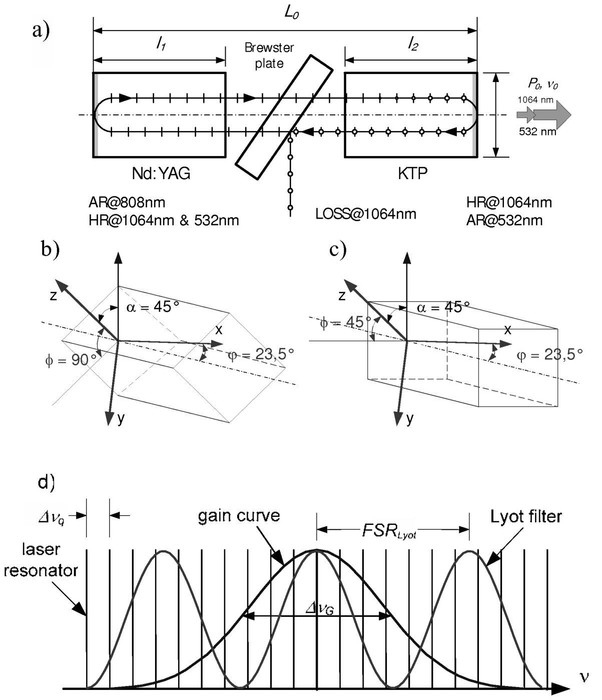

ccc Fig. 1. (a) – The idea of microchip laser with Lyot filter, (b) – typical configuration (KTP cutting for SHG), (c) – our configuration (KTP cutting for SHG and EO modulator), (d) – transmission characteristics explaining the operation of a laser with Lyot filter, (spectra of gain medium, Lyot filter and laser resonator)

The Lyot filter has periodical spectral characteristic with maxima spaced by FSR_{Lyot}

$$FSR_{Lyot} = \frac{c}{2\Delta n \cdot l_2}, \tag{1}$$

where $\Delta n = n_z - n_y = 0.0844$ – is the natural birefringence of KTP, l_2 – geometrical length of KTP.

To obtain the single frequency operation the FSR_{Lyot} should be larger then the spectral gain width of the medium which is about $\Delta\nu_G = 160$ GHz for 1% doped Nd:YAG. To fulfill these criteria the length of the KTP should be shorter then:

$$l_2 < \frac{c}{2\Delta n \cdot \Delta\nu_G}. \tag{2}$$

Spectral relations between: gain medium, Lyot filter and laser resonator transmission characteristics are illustrated in Fig. 1d. In our case l_2 is calculated to be shorter then 11 mm. We have chosen the length of KTP $l_2 = 5$ mm fulfilling two conditions: the above expressed by (2) and taking into account second harmonic generation efficiency [6]. The phase difference ϕ between ordinary and extraordinary waves passing twice the KTP is given by:

$$\phi = \frac{4\pi}{\lambda} \cdot l_{op}, \tag{3}$$

where l_{op} is KTP optical length.

Taking in account the relatively strong temperature dependence of KTP optical length expressed by formula:

$$l_{op}(\Delta T) = l_2\left(\frac{dn_z}{dT} - \frac{dn_y}{dT} + \Delta n\alpha\right)\Delta T, \tag{4}$$

where $dn_z/dt = 1.6 \cdot 10^{-5}{}^\circ\mathrm{C}^{-1}$, $dn_y/dt = 1.6 \cdot 10^{-5}{}^\circ\mathrm{C}^{-1}$ thermo-optic coefficients for z and y refractive indices of the KTP crystal, $\alpha = 11 \cdot 10^{-6}{}^\circ\mathrm{C}^{-1}$ – thermal expansion coefficient along the optical axis.

Calculated thermal tuning range ΔT for above data of Lyot filter with the length $l_2 = 5$ mm gives the value $\Delta T = 19.7^\circ\mathrm{C}$. The change of temperature allows to select one longitudinal required mode. From above, the temperature change ΔT_q of birefringent element causing mode-hoping between two neighboring longitudinal modes is given by:

$$\Delta T_q = \frac{\Delta n}{\left(\frac{dn_z}{dT} - \frac{dn_y}{dT} + \Delta n\alpha\right)} \cdot \frac{\Delta\nu_q}{\nu_0}, \tag{5}$$

in our case $\Delta T_q = 0.35^\circ\mathrm{C}$. To obtain single frequency operation on the same mode without mode-hoping, the temperature of the laser has to be kept with ΔT_q accuracy.

2.1. Description of device.

The optical resonator length minimizations is the crucial procedure in microchip lasers design [7]. Such approach gives advantages:

1. Laser free spectral range maximization,
2. Increasing a free mode-hoping range.

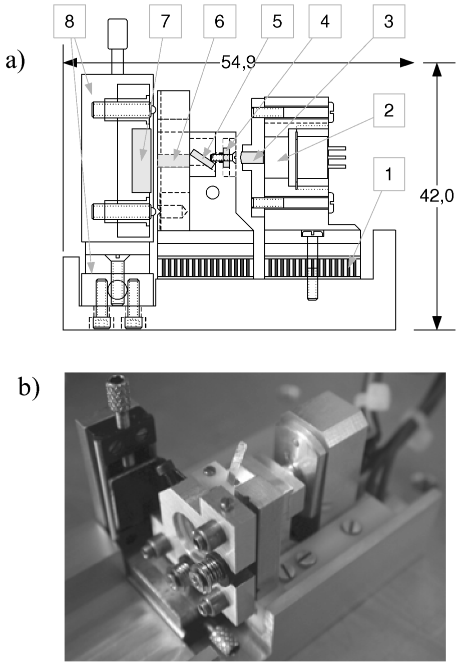

Fig. 2. The construction of our single frequency Nd:YAG/KTP: (a) – assembly drawing, where: 1 – Peltier thermoelectric cooler (TEC),2 – Laser pumping diode, 3 – GRIN, 4 – Nd:YAG crystal, 5 – Brewster plate (fused silica 1mm), 6 – KTP crystal 2x2x5mm according to specification – Fig. 1c, 7 – output mirror, 8 – micro positioning stages (XY) to moving the pin-hole diaphragm, (b) – the photo of the device

According to our primary estimation we designed and built the compact configuration of microchip laser based on

Nd:YAG with KTP crystal and the Brewster plate between them. Figure 2 illustrates the assembly drawing and the photo of the device.

The laser was pumped by 808 nm laser diode via GRIN collimator. For 1 W pumping power we obtained over 50 mW of output power at 532 nm and enough power (~4 mW) at 1064 nm enabling us to perform spectral analysis.

2.2. Investigation of the frequency structure of the microlaser with Lyot filter. We checked the spectral mode structure of the designed laser at $\lambda = 1064$ nm. The green beam, directly connected with the first harmonic, has identical, but scaled to 532 nm mode-frequency structure. Fig. 3a shows typical multimode operation of Nd:YAG/KTP for the case without Brewster plate (there is no Lyot filter). We found that the polarization state of different modes is difficult to control. However, inserting the Brewster plate into the laser cavity causes strong mode selection with remaining one strong single-frequency mode operating at well defined linear polarization (Fig. 3b).

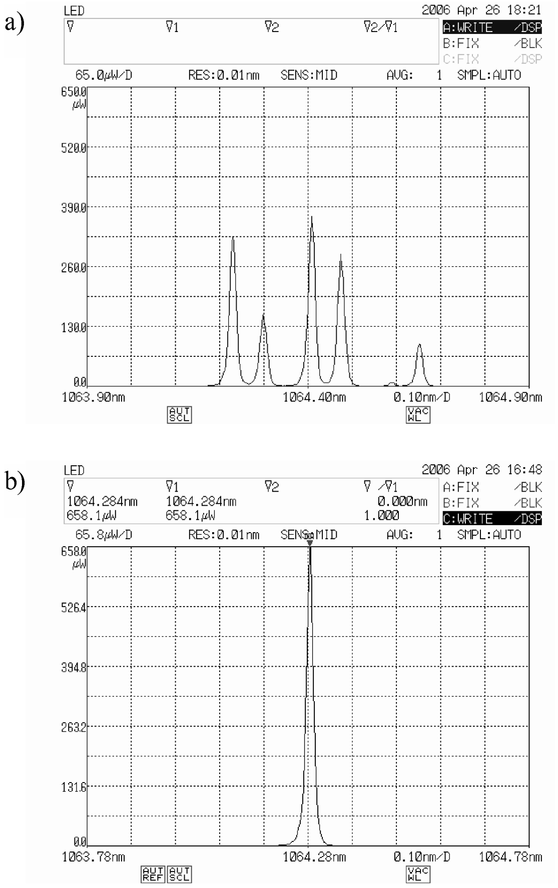

Fig. 3. The spectra of Nd:YAG output power illustrating: (a) – multimode operation of the laser without Brewster plate, (b) – single-mode operation with inserted Brewster platev

Changing the temperature of the laser via Peltier TEC (Fig. 2a) by the amount of $\Delta t = 0.35°$C causes the mode-hoping into the next single frequency mode (Fig. 4a). Our investigation of temperature laser tuning demonstrated its ability to tune the laser up to 110 GHz in the temperature range of $\Delta t = 5.3°$C (see Fig. 4b).

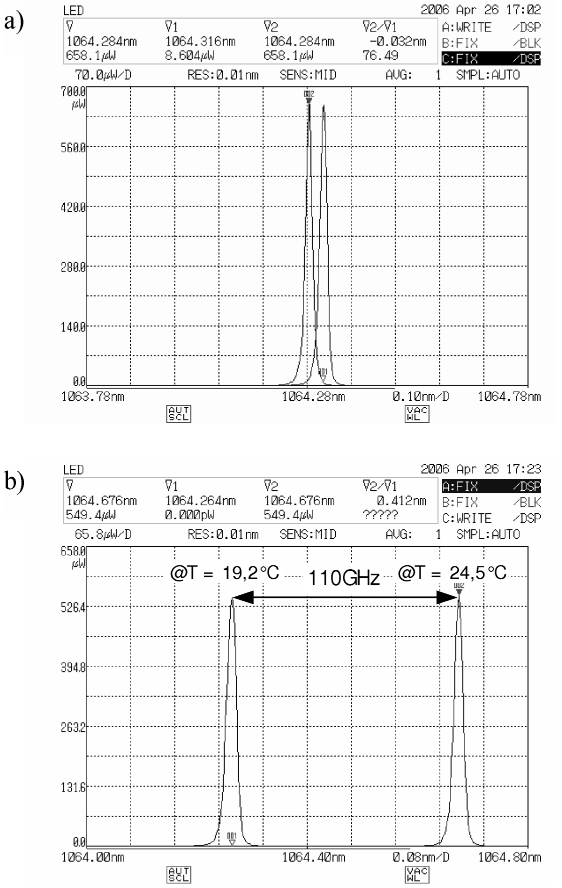

Fig. 4. Spectrum of: (a) – mode-hoping (8.48 GHz) due to characteristic temperature tuning at $\Delta T_q = 0.35°$C, (b) – two extreme states of the laser full tuning – 110 GHz (single frequency operation range)

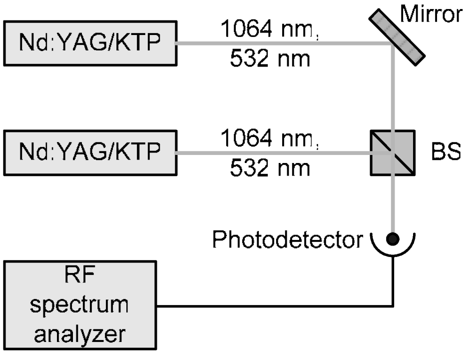

Fig. 5. The heterodyne set-up for measuring the spectral purity of the Nd:YAG/KTP lasers with the RF resolution

In order to confirm the single frequency operation with much higher resolution than this obtained by optical spectrum analyzer, we built the heterodyne set-up consisting of two identical microchip lasers as is shown in Fig. 5. Using fast pin diode we were able to observe the beats between both lasers. We found pure single-frequency operation of both lasers observing the heterodyne signal at the RF Spectrum analyzer. Of course each output beam consisted of main 1064 nm radiation and its second harmonic 532 nm. Hence, we observed pair of heterodyne signals strongly correlated. The beat frequency at 532 nm was twice higher than the beat frequency at 1064 nm, This situation is illustrated in the Fig. 6.

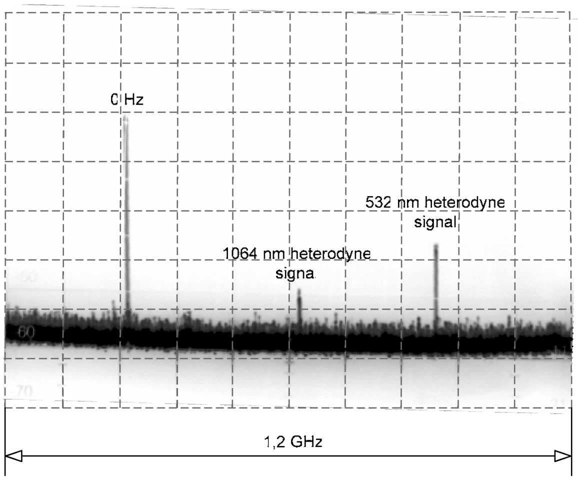

Fig. 6. The spectral analysis of the heterodyne signal from the output of two Nd:YAG/KTP laseers. There are two heterodyne signals – stronger corresponding to 532 nm and weaker to 1064 nm. The fact that there are only two heterodyne signals proves that both lasers are single-frequency ones

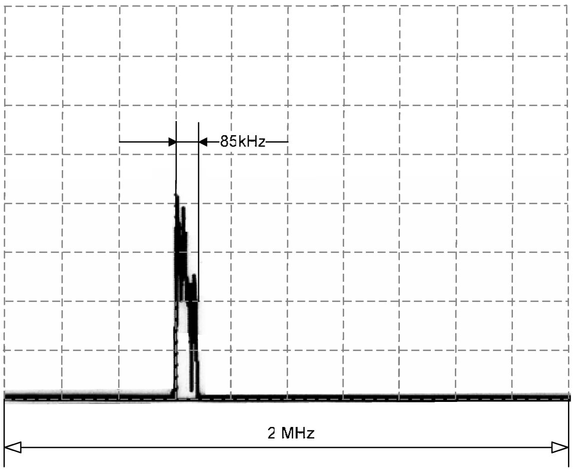

Fig. 7. The zoom of the heterodyne signal taken from RF spectrum analyzer with the 30 ms scan (HP8592L)

In order to estimate the linewidth of the laser radiation we observed the single heterodyne signal with the small frequency span (Fig. 7).

This technique allows only to estimate the linewidth of the laser radiation with accuracy of a few tens of kHz. The laser has one mirror separated from the microchip. Hence, it is less resistant to the environmental noise and the acousto-vibrations influence are observed (as the line broadening of the heterodyne signal). The line in fact is much narrower that it can be registered at the RF spectrum analyzer. It is clear from the spectrogram shown in Fig. 7 that the analysis was performed for too slow sweep time. Hence the acoustic broadening appears and it spoils the analysis. From this measurements we can say that the laser linewidth is less below 60 kHz.

3. Conclusions

We showed the procedure of single-frequency operation applied to Nd:YAG/KTP laser with so called Lyot filter. The basic parameters such as: thermal tuning range, free mode hoping range were introduced. Using these procedures we built Nd:YAG/KTP. The calculated values of these parameters, such as thermal tuning (200 GHz), well match the experimental results. The laser operates at single-frequency with the output power 50 mW at 532 nm (with the pumping power of 0.8 W@808 nm) and is very good candidate to frequency active stabilization. The laser linewidth of a few tens of kHz was estimated.

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