# RF Dynamics of Mode-locked Intracavity Frequency Doubled Laser

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**Abstract**— We report on the radiofrequency (RF) dynamics of intracavity frequency doubled $Nd : YVO_4/KTP$ laser operating in mode-locked regime. For a certain parameter range, the second harmonic is weakly modulated while the fundamental output remains not modulated. The effect manifests itself as weak sidebands of the beat note signal and a low-frequency signal (order of 50–100 MHz) in the RF spectrum. Applying additional cavity length modulation via a piezoelectric transducer leads to occurrence of a squared Lorentzian shaped spectrum for the weak sidebands and low-frequency signal but the beat note is not affected. We propose that this regime is an evidence of the phase bounding effect in the mode locked state.

## 1. INTRODUCTION

Mode-locked lasers are of a great interest in fundamental and applied sciences. Their capability to generate ultrashort pulse trains and equidistant optical spectra has already revolutionized such fields as spectroscopy, data networks, optical clocking and biomedicine.

Solid-state lasers based on $Nd:YVO_4$ gain medium with intracavity frequency doubling are promising sources for mode-locked radiation and capable of self-starting mode-locking which has been explained by the Kerr nonlinearity in the active medium [1, 2], cascaded $\chi^{(2)}$ lens process and nonlinear mirror formed by the doubling crystal and an output coupler [3, 4].

In this paper we report on the radiofrequency (RF) dynamics of intracavity frequency doubled $Nd : YVO_4/KTP$ laser operating in mode-locked regime. Self-starting passively mode-locked operation in such a laser has already been demonstrated in [5]. We report on an effect of self-modulation in the second harmonics output which supposedly occurs due to phase bound state of the laser [6], and does not affect the fundamental output.

## 2. EXPERIMENTAL SETUP

The schematic layout of the experimental setup is shown in Figure 1.

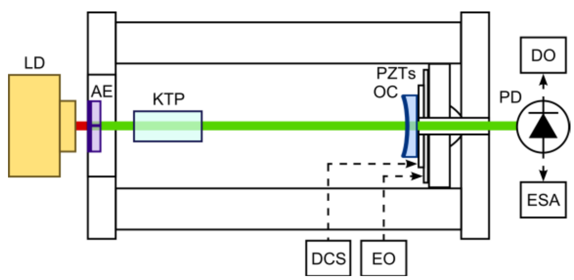


Figure 1: Schematic layout of the experimental setup.

The linear cavity length was ∼109 mm (corresponding to ∼1.38 GHz free spectral range) and its stability amounted $3 * 10^{-6}$ for 100 s averaging time in terms of Allan deviation. Low thermal expansion material (invar) was used for the cavity frame. The active element (AE) was a right-angle a-cut $1*3*3\,mm^3$ 1% at. doped $Nd : YVO_4$ crystal. The high reflection coating for 1064 and 532 nm was applied to the rear facet of the AE forming the end mirror. The type II KTP crystal had dimensions $5 * 3 * 3\,mm^3$ and the angle between and the KTP crystal z-axis and the active element $c$-axis was 45° to implement type II SHG. The KTP was antireflection coated for both fundamental and second harmonic radiation. The temperature of the KTP crystal was stabilized by thermoelectric cooler with 0.1°C precision.

An output coupler (OC) was mounted on fast and slow piezoelectric transducers (PZTs) for the cavity length modulation and the output coupler precise position attenuation. The OC had a curvature radius 150 mm, and was high reflection coated for the fundamental radiation and had 50% transmission for the second harmonic. The voltage from a controllable direct current source

(DCS) and an electronic oscillator (EO) were applied to the outlets of the slow and fast PZT correspondingly.

A commercial 808 nm laser diode (LD) with stabilized temperature was used as a pump source. The LD radiation was condensed through a lens system to the AE rear facet overlapping the cavity eigenmode. The resulting laser $TEM_{00}$ output beam was linearly polarized due to the AE properties.

The output was detected by a 1.5 GHz bandwidth avalanche photodiode (PD) and analyzed by means of digital oscilloscope (DO) and electronic spectrum analyzer (ESA).

## 3. EXPERIMENTAL RESULTS AND DICUSSION

A stable mode-locking regime was obtained while pumping the active element with 380 mW of 808 nm pump source. It resulted in 29 mW average output power at 532 nm and 6 mW output power at 1064 nm. A narrow RF beat signal (less than 300 Hz FWHM) was observed for both fundamental and second harmonic radiation as an evidence of mode-locking regime. For a certain power and temperature range (the KTP temperature 28 ± 0.2°C, 420 mW pump power) and a proper placing of the output coupler against the KTP crystal, the second harmonic has shown weak (about 7%) power modulation. The fundamental radiation remained not modulated. The RF spectra (Figure 2(a)) have two sidebands of the central beat note frequency and a low-frequency (50–100 MHz) difference signal. It can be seen from the time trace of the output radiation (Figure 2(b)) that modulation is nearly sinusoidal and exposed only to the second harmonic.

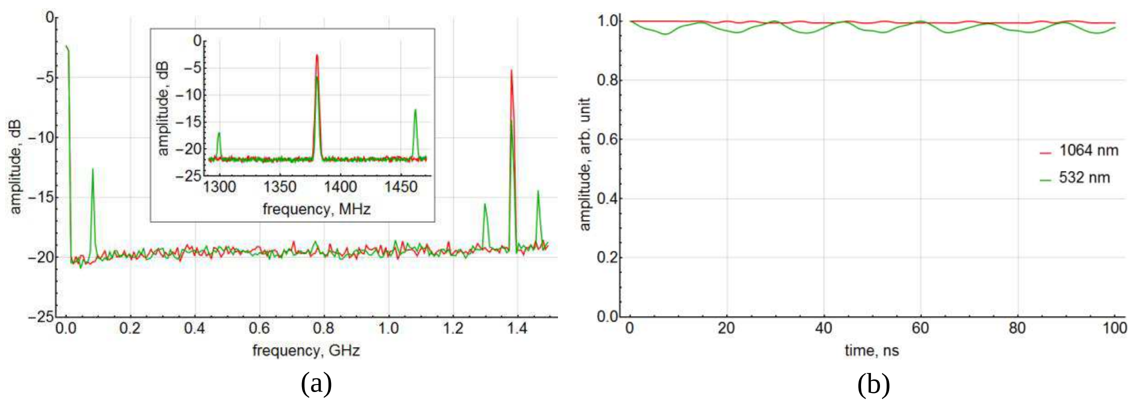


Figure 2: (a) Spectra of the laser beat note signal for fundamental and second harmonic outputs (resolution bandwidth 3 MHz, sweep time 5 ms). Inset: the zoomed part of the central beat note frequency and its sidebands for the second harmonics output (resolution bandwidth 1 MHz, sweep time 4 ms). (b) Experimental time traces: fundamental (red) and second harmonics (green).

The side bands in the RF spectrum have the same width as the central beat note signal (see Figure 3).

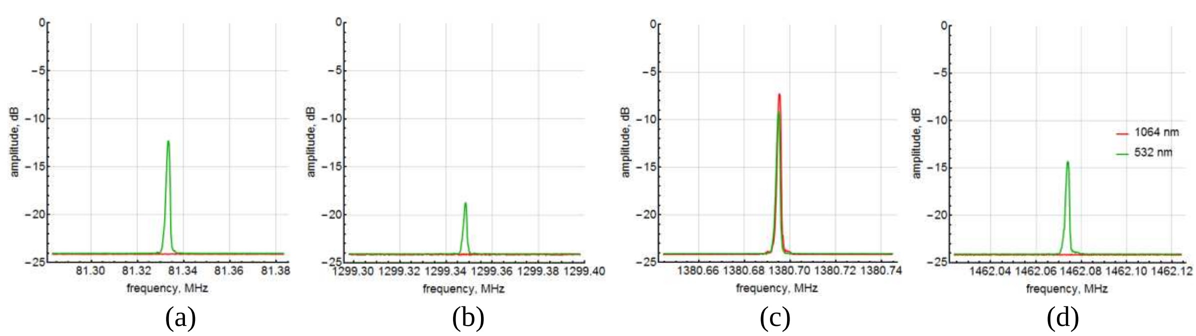


Figure 3: The RF spectra of the laser beat note signal (resolution bandwidth 1 kHz, sweep time 128 ms) for the fundamental and second harmonics radiation: (a) the low-frequency spectral component, (b) the left side-band of the central beat note, (c) the central beat note, (d) the right side-band of the central beat note.

The transition from and to the regime with the second harmonic power modulation occurs continuously via changing the KTP temperature and OC position with the slow PZT. The appearance and vanishing of the regime does not lead to extinguish of the mode-locking. The laser is capable of stable operation in this regime for over 300 s. The stability was only limited by the cavity elements alignment stability. The weak modulation frequency shows a dependence on the central beat note frequency which is well fitted by a parabola (Figure 4).

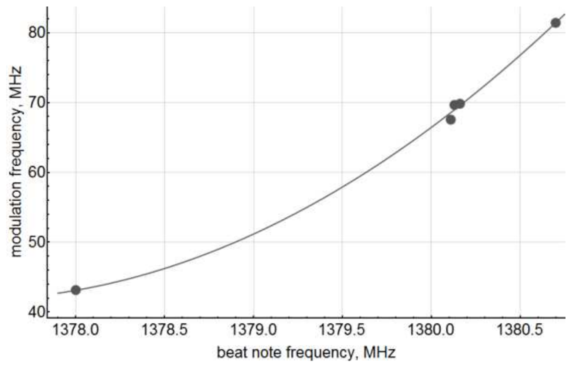


Figure 4: The dependence of second harmonics modulation frequency on the beat note frequency and its approximation by parabolic function.

In order to investigate the effect in more detail, we implemented the small amplitude cavity length modulation via the fast PZT with the frequency of several kilohertz. It led to the occurrence of two weak sidebands of the central beat note for both the second and fundamental harmonics (see Figure 5(c)) and several sidebands of the low-frequency signal and the sidebands for the second harmonics only (see Figures 5(a), (c)–(d)). The distance between the spectral components was equal to the modulation frequency. The spectra shapes can be approximated by a squared Lorentz profile which is determined by the following equation:

$$L(f) = \frac{k^2}{\left(1 + \left(\frac{f-l}{m}\right)^2\right)^2} + n, \tag{1}$$

where coefficients $k$, $l$, $m$, $n$ were calculated to fit the spectral data.

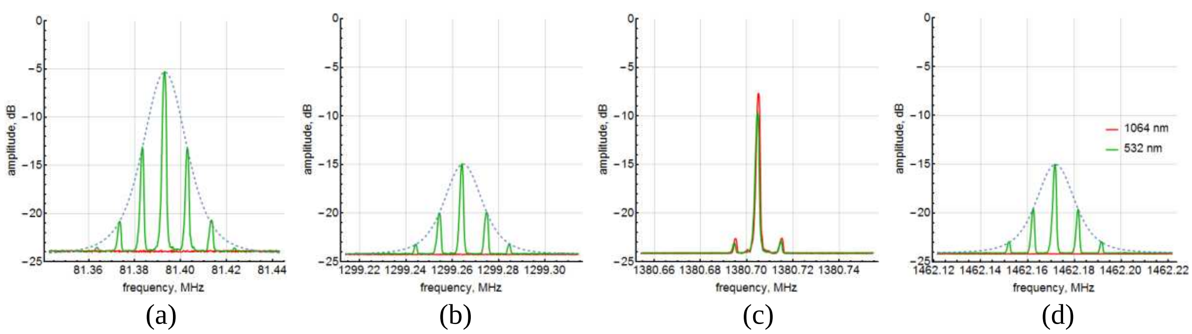


Figure 5: Detailed RF spectra of the laser beat note signal obtained in case of the cavity length modulation with 10 kHz frequency (resolution bandwidth 1 kHz, sweep time 128 ms). Letters (a)–(d) correspond to the Figure 3. The dotted line corresponds to the approximation by a squared Lorentz profile.

We propose that the appearance of the second harmonic modulation regime results from bound phase variations of the laser field which are neither related to the polarization interplay (because of properties of the active medium) nor to the antiphased states (in this case the fundamental frequency would be modulated). The detailed properties, boundaries and underlying mechanism of the effect are the subject of further research.

## 4. CONCLUSION

This newly obtained regime of the phase bound mode-locked operation can be utilized for synthesis of low-noise microwave frequencies, and can be used for iodine-stabilized schemes of laser frequency standards without additional modulators.

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