240-GHz continuously frequency-tuneable $Nd:YVO_4$/LBO laser with two intra-cavity locked etalons

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Abstract: This work reports for the first time on study of a single-frequency $Nd:YVO_4$ laser with intra-cavity frequency doubling, in which quasi-continuous frequency tuning over an ultra-broad range is implemented with two intra-cavity locked etalons and automatic stitching between ranges of smooth scanning of the laser's output frequency. The proposed and demonstrated method allowed to continuously tune the output frequency of the studied 1.5-W $Nd:YVO_4$/LBO laser over a record-breaking broad range of 240 GHz at 532 nm.

OCIS codes: (140.3580) Lasers, solid-state; (140.3570) Lasers, single-mode; (140.3515) Lasers, frequency doubled; (140.3530) Lasers, neodymium; (140.3600) Lasers, tunable; (140.0140) Lasers and laser optics.

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1. Introduction

Single-frequency ring Nd:YVO_4 lasers with intra-cavity frequency doubling by nonlinear crystals (NC) are widely used in a variety of applications requiring powerful and stable green radiation with long coherence length. Because of a relatively narrow spectral gain profile of their active medium, these lasers are often considered "single-wave", even though the gain bandwidth in Nd:YVO_4 (257 GHz [1,2]) is as much as 4–5 orders of magnitude wider than the typical fundamental radiation line width of a single-frequency Nd:YVO_4 laser without frequency stabilisation (~1.2–25 MHz [3–5]). In this relation, it is quite natural to consider a single-frequency Nd:YVO_4 laser as a tuneable one, capable of relatively wide frequency tuning within tens and hundreds of GHz.

There is a well-known frequency tuning method [6], in which a phase-lock loop keeps an intra-cavity etalon aligned to the laser cavity. This method allows continuous tuning of the laser's generation frequency within a range exceeding the free spectral range (FSR) of the laser cavity by continuously adjusting the cavity length (*e.g.* with one of the mirrors mounted on a piezo-transducer (PZT)), while the transmission peak of the intra-cavity etalon is following the output frequency. In order to sweep the output frequency of an Nd:YVO_4 laser over the entire gain band (257 GHz) using a single solid quartz etalon, the thickness of this etalon cannot exceed 0.4 mm. The finesse of such an etalon corresponding to spectral selectivity sufficient for reliable isolation of a single axial mode should be relatively high (in [6], reflectivity of the etalon sides was 60%). In practice, this leads to considerable non-selective radiation losses and, consequently, to the corresponding reduction in laser efficiency.

In our opinion, the optimal solution for controlling the output frequency of Nd:YVO_4 lasers should rely on two low-finesse solid etalons, both featuring low non-selective radiation losses. The thicker etalon ensures reliable selection of a single axial mode, while the thinner one provides an FSR exceeding the required frequency tuning range of the laser output. It is this method that the authors implemented in the present work.

It is necessary to point out that single-frequency lasers with intra-cavity second-harmonic generation (SHG) exhibit the phenomenon of mode-hopping suppression [7]. On the one hand, this phenomenon may simplify laser frequency tuning by allowing continuous adjustment of the output frequency over a range exceeding the laser cavity FSR at one invariable position of the etalon selecting this frequency. On the other hand, mode-hopping suppression may also complicate frequency tuning, for instance when switching from one smooth frequency scanning range to another because a frequency hop is necessary at this moment in order to take the laser generation frequency from the end of one smooth scan range to the beginning of the next one. In this relation, it appears interesting to study the specific features of the effect of mode-hopping suppression in wide-range continuous tuning of the output frequency of single-frequency Nd:YVO_4/LBO lasers.

Continuous generation frequency tuning in Nd:YVO_4/NC lasers over ranges exceeding the FSR of the laser cavity was earlier reported in various publications where the following continuous frequency tuning ranges of the second-harmonic radiation (532 nm) at the specified output power were demonstrated: 6.4 GHz @ 18 W [8], 8.2 GHz @ 12 W [8], 17 GHz @ 200 mW [9], 17.2 GHz @ 480 mW [10], 24 GHz @ 10.5 W [11], 60 GHz @ 1.5W [12]. Continuous (without mode hopping) tuning of the fundamental harmonic frequency in Nd:YVO_4 lasers was previously achieved in the ranges 2.9 GHz [13], and 107 GHz @ 103 mW [2]. All the work quoted in this paragraph (except [12]) featured continuous frequency tuning of Nd:YVO_4/NC lasers in a single smooth frequency scanning range, not relying on methods for stitching several such ranges into one.

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This work explores for the first time a technique of continuous frequency tuning across an ultra-broad range using two locked intra-cavity etalons and automatic stitching of continuous output frequency scanning ranges in a single-frequency ring $Nd:YVO_4$ laser with intra-cavity frequency doubling. Also demonstrated for the first time is the possibility of continuous frequency tuning of the second harmonic of an $Nd:YVO_4$/LBO laser at 532 nm delivering 1.5 W of output power across a record-breaking wide spectral range of 240 GHz.

2. Experiment

Our experimental installation is schematically presented in Fig. 1. A 50-cm long bow-tie ring cavity is formed by four mirrors M1–M4. Dichroic spherical mirror M1 has an anti-reflection coating for the pumping wavelength of 808 nm and a highly reflective one at 1064 nm. Flat mirrors M2 and M3 are reflective at 1064 nm. Dichroic output spherical mirror M4 is highly reflective for the fundamental radiation and highly transparent for the second harmonic radiation. The following are the respective lengths of crystals used in the cavity: $Nd:YVO_4$ – 12 mm, TGG – 15 mm, LBO – 25 mm. A terbium gallium garnet (TGG) crystal as a Faraday rotator, a Brewster plate, and a $\lambda/2$ wave plate were used to ensure unidirectional lasing in the ring cavity. The LBO crystal was placed in a thermo-stabilised oven (working temperature ~150 °C) in order to keep non-critical phase matching condition. The calculated phase matching width for the used LBO crystal is 400 GHz at the fundamental wavelength. Two uncoated quartz Fabry-Perot etalons with FSR = 345 GHz (E1, 0.3-mm thick) and FSR = 34.5 GHz (E2, 3-mm thick) acted as spectrally selective elements of the laser. In order to enforce single-frequency generation, a single etalon (E2) would be sufficient. The second, thinner, etalon E2 was necessary to achieve a broad frequency tuning range. Continuous frequency tuning of the laser output radiation was carried out through adjustment of the position of mirror M3 by a PZT within the range of 4 µm. This corresponded to continuous adjustment of the fundamental laser frequency within 9 GHz (18 GHz for the second harmonic, respectively). The output power of this $Nd:YVO_4$/LBO laser amounted to 1.5 W at 532 nm at the pumping radiation power of 15 W.

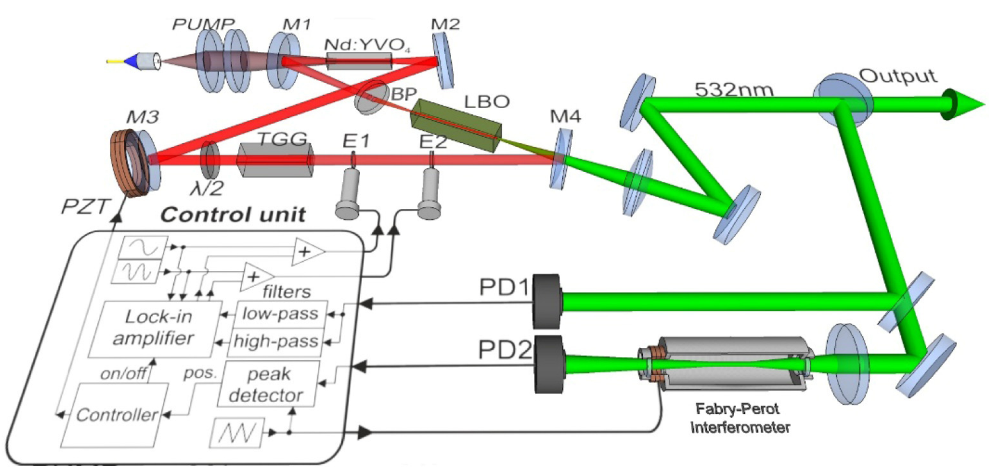

Fig. 1. Schematic diagram of the experimental set-up: M1 - M4 - cavity mirrors of the $Nd:YVO_4$ laser; E1, E2 - Fabry-Perot etalons; PD1, PD2 - photo-detectors; TGG - Terbium Gallium Garnet, BP - Brewster plate and astigmatic compensator.

To lock the transmission peaks of etalons E1 and E2 onto the generation frequency, two phase-lock loops were used with a relatively high and a relatively low modulation frequencies of 2 kHz and 100 Hz correspondingly (Figs. 2(a) and 2(b)). The angular positions of electro-mechanically driven etalons E1 and E2 were modulated at these frequencies, thus also leading to the corresponding modulation of the laser's output (Fig. 2(b) and 2(c)). This output

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modulation was comparatively shallow (not exceeding 1%), yet sufficient for its detection and use in the two phase-lock loops for automatic locking of the transmission peaks of the etalons to the generation frequency.

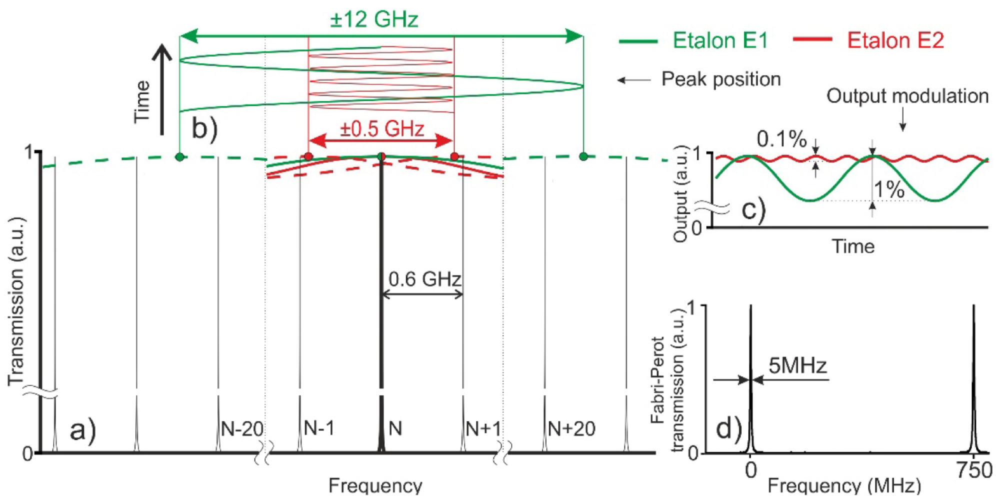

Fig. 2. Diagrams of etalon transmission peak movement and the parameters of the studied system. (a) longitudinal modes of the laser cavity and the tops of the transmission peaks of etalons E1 and E2 at different moments during their modulation. (b) position of the transmission peaks of etalons E1 and E2 as a function of time. (c) modulation of the laser's output power caused by modulation of positions of etalons E1 and E2. (d) transmitted intensity of the Fabry-Perot interferometer.

Since we used low-finesse etalons E1 and E2, registration of the output intensity modulation with an adequate signal-to-noise ratio could require a fairly large swing of the etalon transmission peaks, exceeding, for example, the laser cavity FSR. According to our research, reliable operation of phase-lock loops was achieved at the amplitude of transmission peak oscillations equal to the laser cavity FSR (600 MHz) for etalon E2 (FSR = 34.5 GHz), and equal to 20 times the laser cavity FSR (12 GHz) for etalon E1 (FSR = 345 GHz). There was no laser output frequency hopping under these conditions due to the effect of self-suppression of axial mode hopping [7].

Continuous frequency tuning of the experimental laser was carried out as follows. The laser cavity length was adjusted with the PZT-driven mirror M3, leading to the corresponding change in the laser generation frequency by 9 GHz (1064 nm) / 18 GHz (532 nm), while the transmission peaks of etalons E1 and E2 followed the output frequency. Once mirror M3 reached its extreme displacement, it was returned to the starting position and the end of the previous smooth frequency scanning range was stitched to the beginning of the next one. After this, the entire procedure was repeated.

Return of mirror M3 into the starting position does produce mode hopping of the laser output. However, due to the effect of mode-hopping suppression, this mode hopping only occurs when the laser frequency (as a result of returning mirror M3) is changed by as much as 1.5–2 GHz, instead of the nominal amount of 1/2 of the laser cavity FSR (300 MHz). Our studies have demonstrated that this amount is not constant and depends on the evolution of the generation parameters (gain, frequency doubling efficiency) during wide-range scanning of the laser generation frequency. This behaviour leads to effective reduction of the laser's continuous tuning range by 1.5–2 GHz, resulting in a value around 7–7.5 GHz. After covering each 5 continuous tuning ranges, etalon E2 was also returned into its starting position as part of the procedure of stitching adjacent continuous tuning ranges.

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In order to stitch together adjacent ranges of continuous laser frequency tuning, a spectral instrument is necessary, which can determine the spectral position of the end of the previous continuous tuning range and the beginning of the next one. In this work, we demonstrate a new technique for doing this that relies on a scanning Fabry-Perot interferometer. We used an interferometer with FSR = 750 MHz and finesse ≈300 at 532 nm. Computer processing of the signal from the scanning interferometer was used to store the relative spectral position of the laser generation frequency at the end of one continuous scanning range and to compare it with the corresponding spectral position in the beginning of the next continuous tuning range. High spectral resolution of the chosen interferometer was sufficient to stitch adjacent continuous laser frequency scanning ranges to the precision of one laser output line width, measured with this same interferometer to be 5 MHz (Fig. 2(d)).

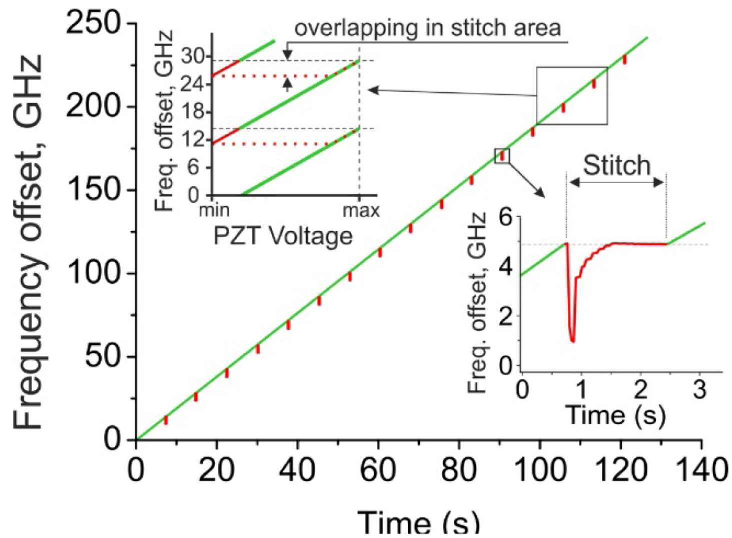

Fig. 3. Laser output frequency tuning profile. Upper-left insert: generation frequency evolution corresponding to scanning of the drive voltage on the PZT of mirror M3 within a continuous frequency scanning range and within a stitching area (solid lines - frequency sweep caused by rising PZT voltage, red lines - stitching areas, dotted red lines - frequency change caused by dropping PZT voltage). Lower-right inset: temporal evolution of the laser output frequency within a stitching area (green lines - continuous tuning ranges, red line - stitching sequence).

Figure 3 presents a profile of the laser generation frequency scanning. It demonstrates the full range of smooth laser frequency tuning across 240 GHz composed of 17 individual continuous scan ranges. Further frequency tuning was not smooth and suffered from uncontrollable output frequency hopping. In the authors' opinion, this may result from some parasitic spectral selection within the laser cavity caused by polarisation effects in the crystals contained therein. Within each continuous frequency scanning range, the laser output power variation did not exceed 1% (due to modulation of losses introduced by the cavity etalons), whereas over the entire 240-GHz tuning range, the output power did not vary by more than 5%.

The upper-left inset of Fig. 3 shows how the laser generation frequency changes as the PZT drive voltage of mirror M3 is scanned within a continuous scanning range and around the stitching area. An overlap between neighbouring ranges of continuous frequency scanning can be clearly seen (marked as "overlapping in stitch area"), which effectively shortens, as we noted before, each continuous scanning range by 1.5–2 GHz.

Table 1 summarises the laser parameters in frequency units, making it clear that because of a considerable overlap between adjacent continuous frequency scanning ranges resulting from self-suppression of axial mode hopping, the effective continuous frequency scanning in

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a single cycle of wide-range smooth scanning amounts to 7–7.5 GHz for the fundamental wave and 14–15 GHz for the second harmonic radiation (the parameters for the fundamental wave were calculated from those measured for the second harmonic radiation). Therefore, the entire smooth scanning range achieved for the second harmonic radiation is 240-GHz wide and consists of 17 spectrally stitched individual continuous tuning ranges with the average width of ~14.5 GHz.

Table 1. Overview of the laser parameters expressed in frequency units

Parameter	Value, GHz
FSR of the laser cavity	0.6
Frequency offset produced by PZT of M3 mirror, 1064 / 532 nm	9 / 18
Overlapping ranges of smooth frequency tuning, 1064 / 532 nm	1.5–2 / 3–4
Effective width of smooth frequency tuning range, 1064 / 532 nm	7–7.5 / 14–15
Total smooth frequency scanning range, 1064 / 532 nm	120 / 240

It is pertinent to note that the term “generation frequency tuning” used in numerous publications on single-frequency Nd:YVO_4 lasers [9–16] does not always imply smooth adjustment of the laser’s output frequency. This term may refer, for instance, to the possibility of setting any (or a specific) wavelength within the specified spectral range. Generally, this does not preclude mode hopping in the process of frequency tuning [12, 14–16] and furthermore does not guarantee automatic continuous or quasi-continuous scanning of the generation frequency over the entire specified spectral range.

3. Conclusion

The authors of the present work proposed and practically implemented a method of smooth automatic output frequency tuning in a single-frequency Nd:YVO_4 laser with intra-cavity second-harmonic generation, achieving quasi-continuous tuning of the laser’s fundamental (1064 nm) output frequency within the range of 120 GHz and of the laser’s second-harmonic (532 nm) output correspondingly over the range of 240 GHz. The proposed method relies on two electro-mechanically driven intra-cavity low-finesse Fabry-Perot etalons and an external high-finesse scanning Fabry-Perot interferometer for spectral stitching of individual ranges of continuous laser frequency tuning. The experimental results achieved during the conducted studies demonstrate a practical possibility of using this method to achieve quasi-continuous scanning of the generation frequency in a laser with intra-cavity SHG across spectral ranges of around 0.5-nm width and wider. The demonstrated algorithm of automatic laser frequency adjustment may be advantageously applied in many CW diode-pumped solid-state lasers with intra-cavity SHG (Nd:YAG/YLF/YAP, Yb:YAG/LuAG, and others) that use analogous configurations of a ring cavity to ensure single-frequency operation. Furthermore, this algorithm will also be useful in tuneable single-frequency lasers with intra-cavity SHG, in which the two-etalon smooth frequency tuning range is limited to around 0.5–1 nm by a coarser wavelength selector, such as a birefringent filter [17].

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