High-power CW single-frequency Nd:YVO_4/LBO laser quasi-continuously tuneable over a wide frequency range

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ABSTRACT

In this work, we present for the first time a method for quasi-smooth tuning of the second harmonic radiation of an Nd:YVO_4/LBO laser within a 60-GHz range. Practicality of this method is demonstrated at the radiation output power of 1.5 W at 532 nm. The proposed method features automatic stitching of 12-GHz continuously tuneable ranges to the precision of the laser output line width (5 MHz). The stitching does not require a precision wavelength meter and is based on a high-finesse scanning confocal interferometer.

Keywords: DPSS laser, second harmonic generation, tunable laser, frequency doubling, quasi-continuous tuning.

1. INTRODUCTION

The gain bandwidth of Nd-doped active crystals in the vicinity of 1064 nm amounts to about 1 nm or 265 GHz [1–2]. Correspondingly, lasers based on such crystals can provide tuning of their second harmonic radiation (~ 532 nm) over more than 500 GHz [3]. High output power of these lasers makes them practical for pumping resonant frequency doublers [4] and parametric generators, enabling continuous radiation frequency tuning within both long- and short-wavelength spectrum ranges. Therefore, a CW source of continuously tuneable radiation in the green range may be a powerful precision optical instrument in many spectroscopic, analytical, and technological applications, including frequency standards, laser cooling, laser isotope separation, and others. The benefit of such equipment crucially depends on the possibility of continuous scanning within the largest possible spectral range, ideally over the entire gain contour of the laser.

Uninterrupted continuous frequency tuning of Nd:YVO_4 laser output over the entire 265-GHz range would scarcely be an optimal solution, since that would require smooth and precise adjustment of, let's say, a 0.5-m ring resonator by ~ 470 μm. This relatively large adjustment is complicated at least on two accounts: 1) an actuator is required, which would provide this large displacement range (for reference, standard piezo transducers can only generate displacements of several to several tens of micrometres); 2) adjustment of the resonator length must be accompanied by synchronous tuning of a spectral selector ensuring single-frequency operation. In case a Fabry-Perot etalon is used as the spectral selector, its free spectral range (FSR) must exceed 265 GHz, which means that its length cannot not exceed ~ 0.4 mm (for quartz).

The etalon must be sufficiently selective to guarantee single-frequency operation, and the problem of thin etalons is that in order to have the required spectral selectivity, their surfaces must have coatings with reflectivity of 0.1–0.3. Although the necessary selectivity can be achieved, such coatings introduce substantial optical losses, which further increase as the etalon is tilted for frequency tuning. If an uncoated etalon is used (with Fresnel reflectivity of 0.04 from a quartz surface), the required selectivity can be achieved at the expense of free spectral range (FSR) by increased separation of its reflective surfaces. But such an etalon will not cover the entire gain range because of limited FSR.

Among possible actuator types, which may provide relatively high continuously controllable excursion of the resonator length, one could mention electro-optical elements [5] and those relying on thermal expansion [3, 6]. However, these methods are normally used to tune the laser output frequency within the FSR of the laser cavity [7], and usually they

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don't cover tuning ranges over 1 GHz. Synchronous tuning of the spectral selector ensuring single-frequency operation of the laser makes it possible to overcome this limitation and to enable continuous scanning of the laser's output frequency in the range of several GHz [7] to 10 or 20 GHz [8–10].

Given a limited excursion of laser cavity length and a limited FSR of the spectral selector isolating single generation frequency, it is still possible to extend the range of continuous laser frequency scanning by quasi-smooth tuning, in which a broad overall frequency tuning range is composed of multiple continuous sub-ranges. The spectral position of the end of one such continuous sub-range must be seamlessly connected with the beginning of the next one, and so on. Continuous scanning of the generation frequency within one sub-range is done by synchronous adjustment of the laser cavity length and the position of the spectral selector ensuring single-frequency output. At the end of a continuously scanned sub-range, the actuator controlling the cavity length may be returned to its initial position, upon which the laser generation frequency must equal that at the end of the previous sub-range and the next continuously scanned sub-range will start at the point where the previous one reached its limit. Spectral values of sub-range terminal points cannot be matched better than to the precision of the laser's output linewidth, therefore sub-range stitching to this precision is the best attainable.

This type of spectral stitching was done in many systems [11–12] with the help of a high-precision radiation wavelength meter, whereas in the present report, it is performed by means of a high-finesse scanning confocal interferometer. We have also for the first time applied the method of quasi-continuous laser output frequency tuning to a powerful diode-pumped solid-state laser.

It must be noted that synchronised tuning of the spectral selector ensuring single-frequency operation and adjustment of the laser cavity length may be done both in active and passive modes. In the passive mode, the spectral position of the selector is calibrated prior to operation, and it then follows the laser’s frequency according to a pre-defined rule. The passive mode may be complicated because high calibration precision is required. The active mode relies upon some technique allowing the selector's transmission peak to automatically follow the laser’s generation frequency. This mode does not require precise calibration of the spectral selector position, though it does require, instead, a closed-loop system for tracking the laser’s output frequency and making the spectral selector follow it.

In the present report we chose active synchronisation of the laser cavity length adjustment and tuning of the spectral selector's transmission peak, which relied on modulation of the spectral position of the selector's transmission peak and phase-sensitive detection of the amplitude of the laser output power deviation at the modulation frequency with a lock-in amplifier.

The position of the selector’s transmission peak was tuned by tilting the Fabry-Perot etalon. Both tuning and modulation of the spectral position of its transmission peak were performed with a galvanometer drive. Maximal magnitude of etalon modulation is set by the requirement that it not lead to mode hopping. In many laser systems, the maximal etalon modulation amplitude cannot exceed the FSR of the laser cavity. Nevertheless, in lasers with highly efficient intra-cavity frequency doubling, the effect of self-suppression of neighbouring modes [14] relaxes this requirement, and the etalon modulation amplitude may be wider than the laser cavity FSR [6, 15].

This work presents for the first time a laser system based on a diode-pumped solid-state $Nd:YVO_4$ ring laser with intra-cavity frequency doubling in a non-linear LBO crystal with active etalon synchronisation. In this system, quasi-continuous frequency tuning over a 60-GHz range was achieved by stitching five 12-GHz continuously scanned sub-ranges to the precision of the laser radiation line width, without a precision wavelength meter.

2. EXPERIMENTAL SET-UP

A diagram of the experimental installation is shown in Fig. 1. The ring cavity of our $Nd:YVO_4$ laser is formed by four mirrors. Spherical mirror M1 has anti-reflection coating for 808 nm and highly reflective one for 1064 nm. Flat mirrors M2 and M3 are totally reflective at 1064 nm. Spherical output mirror M4 has highly reflective coating for 1064 nm and anti-reflection coating for 532 nm. The laser’s active medium is a $4\times4\times12\text{-mm}^3$ $Nd:YVO_4$ crystal. Its both working facets are anti-reflection-coated for 808 and 1064 nm. The pumping radiation is provided by a laser diode with the output power of 35 W at 808 nm. For compensation of astigmatism caused by non-normal reflection from spherical mirrors M1 and M4, a 4-mm Brewster plate is inserted. This Brewster plate, being a polarisation selector, is also a part of an optical diode ensuring unidirectional generation. Aside from the Brewster plate, it includes a 15-mm long TGG crystal and a half-wave phase plate $\lambda/2$.

A 25-mm long LBO crystal [16] was used for intra-cavity second harmonic generation. To fulfil the phase matching condition, this crystal was heated to the temperature of non-critical phase matching [17]. Etalon E1 mounted on a Camtech 6210H galvo-drive is 3 mm thick and has FSR of 34.5 GHz.

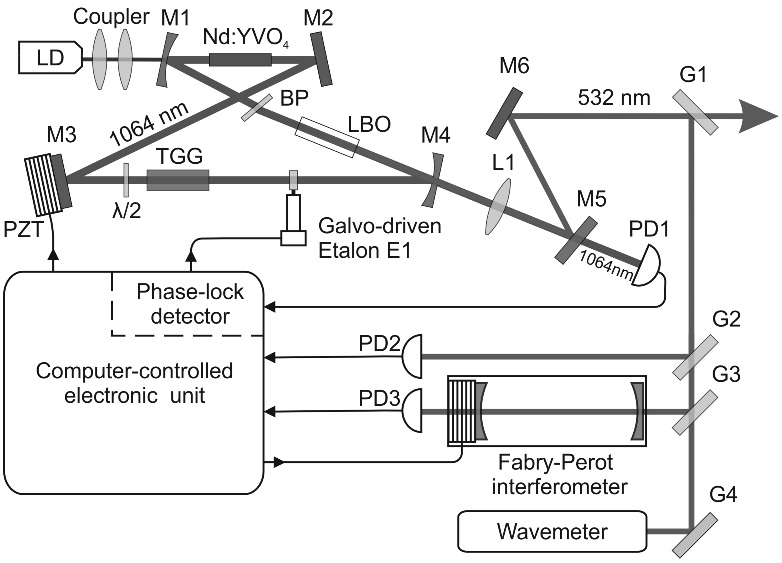

Fig. 1. Diagram of the experimental set-up.

The $Nd:YVO_4$ laser cavity is 50 cm long, corresponding to inter-mode spacing of 600 MHz. Continuous frequency tuning of the laser radiation was carried out through adjustment of the resonator length by displacing mirror M3 with a piezo transducer (PZT). The maximal resonator length excursion corresponds to a 9-GHz frequency detuning at 1064 nm and to a 18-GHz one at 532 nm.

The laser output radiation is analysed with a high-finesse scanning confocal interferometer as a part of the control ring, and with a high-precision radiation wavelength meter, which was only used for additional passive monitoring of the laser's output wavelength.

The laser's output power was 1.5 W at 532 nm. The second harmonic radiation line width measured with a Fabry-Pérot interferometer having FSR of 750 MHz and finesse of 250 amounted to 5 MHz.

3. ETALON SYNCHRONISATION

Etalon E1 mounted on a galvanometer drive oscillates around its set position at frequency f = 2 kHz with an amplitude corresponding to the spectral displacement of the etalon transmission peak by 1.2 GHz. This oscillation leads to a small modulation of the laser's output power, which is registered with photo-detector PD1. The signal from PD1 is fed into the phase-locked detector, which, in turn, generates an error signal according to the expression:

$$U_{error}(t) = U_{PD1}(t) \cdot \mathrm{sign}(U_{galvo}(t)), \tag{1}$$

where U_{PD1} — photo-detector signal and $U_{galvo} = \sin(2\pi \cdot f \cdot t)$ — oscillatory part of the signal applied to the galvanometer drive.

Detuning of the laser generation frequency from the etalon transmission peak may reach as high as $\Delta\nu_{detune} > 6$ GHz at 532 nm and correspondingly > 3 GHz at 1064 nm, thus largely exceeding the laser cavity FSR (600 MHz). As it was mentioned earlier, the possibility of such a significant continuous frequency detuning arises from self-suppression of neighbouring modes in intra-cavity frequency doubling of powerful lasers. The value of the maximal frequency detuning $\Delta\nu_{detune}$ may vary, since it depends on gain, second harmonic transformation efficiency, and cavity losses, while all these parameters depend, in their turn on the wavelength and temperature.

To ensure continuous tuning of the laser radiation frequency, it is important that in the process, the detuning of the etalon's transmission peak from the generated frequency not exceed $\Delta\nu_{detune}$. On the other hand, reduced amplitude of the étalon oscillation (and, therefore, also detuning of the etalon's transmission peak from the generated frequency) reduces modulation of the laser's output power. This, however, also reduces the magnitude of the error signal at the output of the phase-locked detector. The etalon oscillation amplitude corresponding to detuning of the transmission peak by 1.2 GHz led to the laser output power modulation of no more than 0.03%. The adopted technique of synchronous detection of the laser output power allowed automatic locking of the etalon's transmission peak onto the generated frequency. This lock-on enabled continuous tuning of the laser output frequency within the range $\Delta\nu_{PZT} \approx 18$ GHz at 532 nm (Fig. 2).

4. QUASI-CONTINUOUS TUNING OF LASER GENERATION FREQUENCY

It is possible to extend the continuous scanning range by using the technology of quasi-smooth frequency tuning, which functions in the following way: the laser's generation frequency is scanned along the forward movement of the PZT and, as the transducer displacement limit is reached, the automatic etalon synchronisation is switched off, then the PZT is returned into its initial position, and the etalon synchronisation is switched on again. Since the spectral position of the laser generation line is determined by the position of the etalon's transmission peak, the following continuous scanning sub-range will start close to the end of the preceding one. Using this approach, it is possible to expand the continuous scanning range of the laser frequency up to the entire FSR of the etalon.

The result of application of quasi-continuous frequency scanning technology is presented in Fig. 3. The diagrams indicate that this method allows stitching of individual continuously tuneable sub-ranges, but they overlap along the reverse PZT movement. It can be seen that although the etalon transmission peak remains stationary, the laser generation frequency is continuously tuned until the detuning exceeds the value of $\Delta\nu_{detune}$ (B–C interval). After that, multiple hops of laser generation frequency occur until the PZT is back in its initial position (C–D interval).

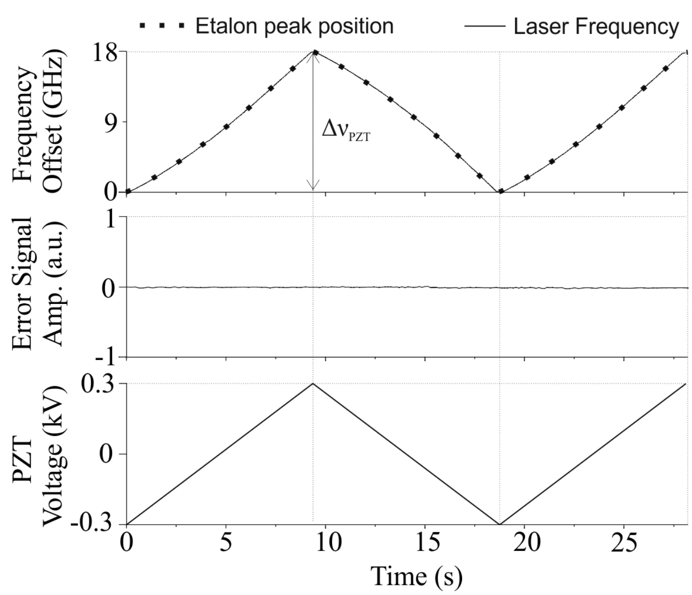

Fig. 2. Temporal evolution of the laser generation frequency as the laser cavity length is continuously adjusted with a PZT, on which one of the cavity mirrors is mounted. The etalon's transmission peak closely follows the generation frequency, as confirmed by the error signal, which is close to zero.

Therefore, the effective range of continuous frequency scanning is determined by the formula:

$$\Delta\nu_{effective} = \Delta\nu_{PZT} - \Delta\nu_{detune}, \qquad (2)$$

and in our case equals $\Delta\nu$effective ≈ 12 GHz. Then the number of stitches necessary to cover a frequency range $\Delta\nu$ is:

$$N_{stitch} = \Delta\nu / \Delta\nu_{effective} - 1. \qquad (3)$$

At $\Delta\nu$ equal to the etalon's FSR, the number of stitches is $N_{stitch} = 4$.

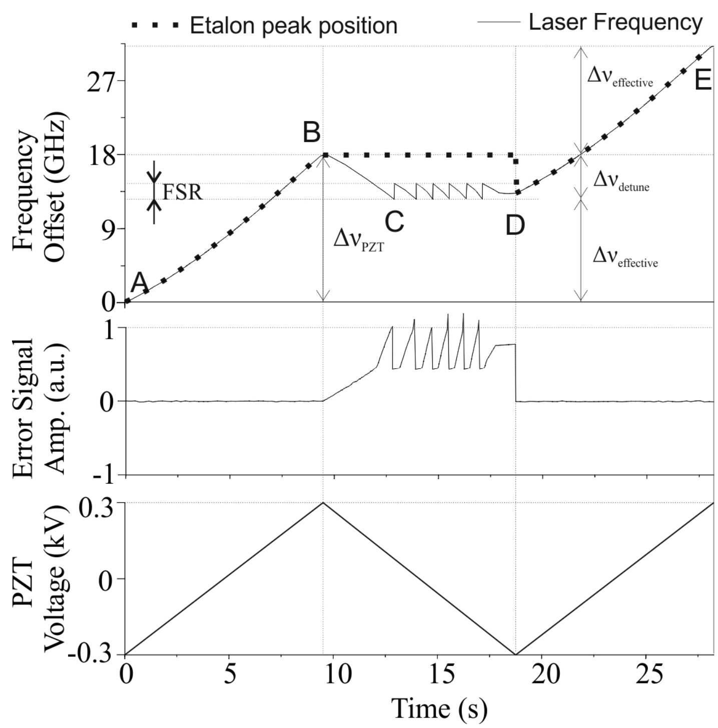

Fig. 3. Diagrams corresponding to quasi-continuous tuning of the laser generation frequency with a PZT, on which one of the cavity mirrors is mounted, and scanning of the etalon position within a range exceeding 18 GHz. A–B — continuous frequency uning along the forward PZT movement when the etalon's transmission peak is synchronised with the generation frequency and the error signal is close to zero; B–D — reverse PZT movement, during which the error signal grows proportionally to the frequency detuning until it reaches a threshold value and the laser frequency jumps; D — etalon locking system is switched on, and the error signal again drops to zero; D–E — the next sub-range of continuous frequency scanning.

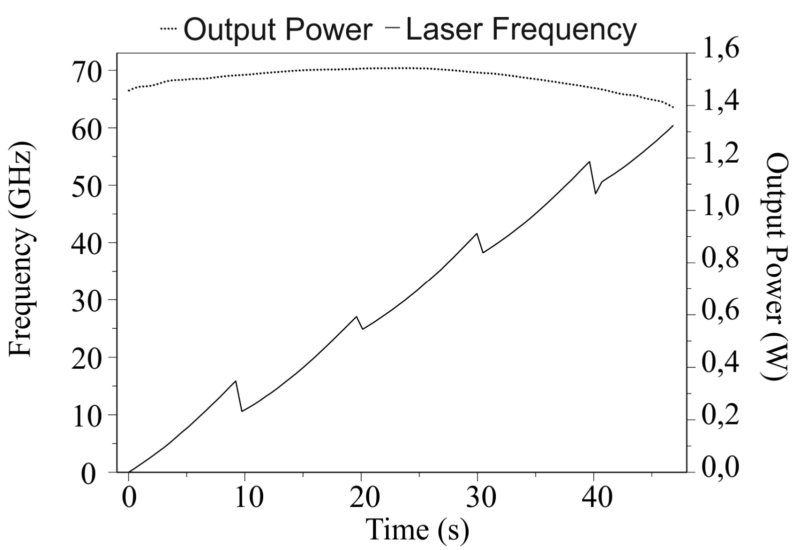

Fig. 4. Temporal evolution of the laser output power and its generation frequency as it is scanned within a 60-GHz range around 532 nm. The upper (dotted) curve corresponds to the output power.

5. STITCHING OF CONTINUOUS FREQUENCY SCANNING SUB-RANGES

Stitching of adjacent continuous frequency scanning sub-ranges can be done with a high-precision radiation wavelength meter. In order to do it to the accuracy of the laser output line width (the best achievable result), such a wavelength meter must have accuracy of at least 5 MHz. However, the cost of such a wavelength meter would be comparable with that of the entire laser system. Therefore, we have developed and practically tested a new stitching method without a high-precision wavelength meter (the latter was only used in our experiments for external passive monitoring).

The proposed method is illustrated in Fig. 5. Upon the completion of frequency scanning in a continuous tuning sub-range (the last frequency value corresponds to point A), the PZT returns to its initial position and the frequency jumps to point B. Further on, the PZT moves forward again until the minimum of the error signal is reached (the mean position of the etalon is fixed and the automatic frequency locking system is disengaged). On the basis of the error signal minimisation, point C can be brought within 200 MHz of point A (Fig. 5, stage I). More precise registration is done with a high-finesse Fabry-Perot interferometer, which is used to control the laser frequency at points A and C and to bring it to point D coinciding with point A to the accuracy of the laser radiation line width.

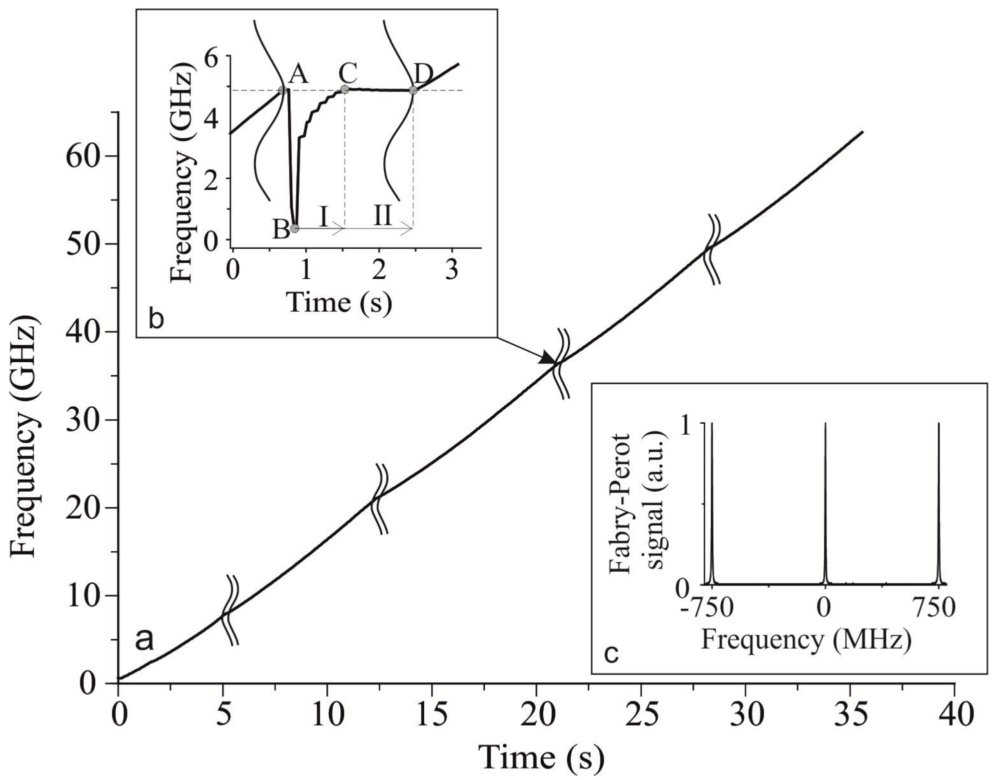

Fig. 5. Quasi-continuous frequency tuning with automatic stitching: a) 60-GHz scanning, b) magnified stitching detail, c) typical transmission curve of the used interferometer. A — the last frequency value of a continuous frequency tuning sub-range; A–B — reverse PZT movement; B–C — stage I of stitching based on minimisation of the error signal from the disengaged etalon locking system; C–D — stage II of stitching based on Fabry-Perot interferometer.

6. FEATURES OF QUASI-CONTINUOUS GENERAGION FREQUENCY TUNING

One of the specific features of the presented method of quasi-continuous scanning of laser radiation frequency within a broad spectral range is that the laser frequency does not automatically jump into the maximum of the etalon transmission peak as the PZT returns to its initial position (and the etalon is fixed). However, such a jump is necessary for quasi-continuous tuning and can be specially arranged.

For lasers without intra-cavity frequency doubling, this will happen if $\Delta\nu_{PZT} > FSR/2$. For lasers with intra-cavity doubling, however, the condition $\Delta\nu_{PZT} > \Delta\nu_{detune}$ must be met. When using an etalon with a broad transmission peak

$\Delta\nu_{detune}$ may reach tens or even hundreds of GHz, and it may be difficult to fulfil this condition. Nevertheless, our investigation has demonstrated that there exist at least two ways to trigger the required frequency jump and to perform quasi-continuous frequency tuning even in case $\Delta\nu_{PZT} < \Delta\nu_{detune}$.

The first of these ways consists in changing of the non-linear crystal temperature after or during the PZT's return to its initial position. This destroys the phase matching condition and minimises the mode self-suppression effect. In this case, when the PZT returns to its initial position, the laser generation jumps to the frequency with minimal losses, i.e. the frequency at the maximum of the etalon's transmission peak. Unfortunately, adjustment of the non-linear crystal temperature requires at least several tens of seconds, during which time the second harmonic (green) radiation will be absent.

The second method uses an intra-cavity shutter momentarily interrupting the laser beam and laser generation. In this case, generation resumes after the PZT has returned into its initial position and the shutter is opened. The new generation frequency will be determined by the spectral position of the etalon's transmission peak. We should note, in passing, that interruption of laser beam can also be achieved otherwise, for instance by briefly switching off the pumping laser diode.

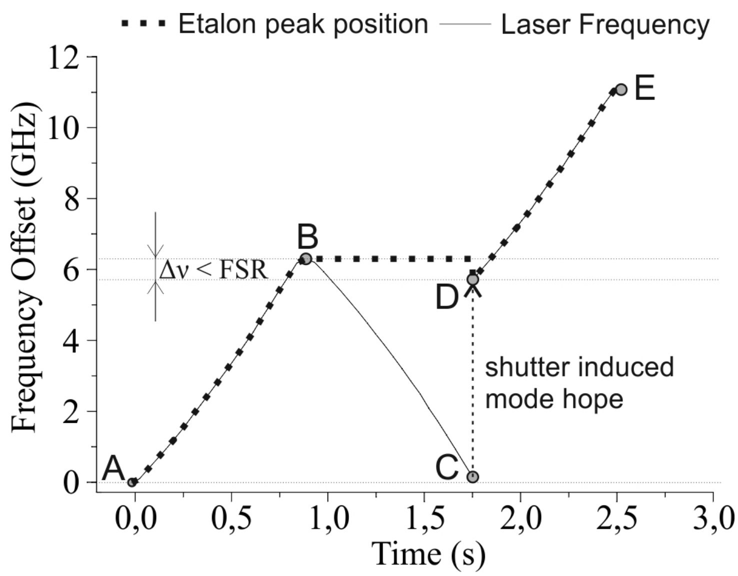

Fig. 6. A detail of quasi-continuous laser frequency tuning with the PZT tuning range smaller than the hop-free etalon range $\Delta\nu_{PZT} < \Delta\nu_{detune}$ assisted by an intra-cavity shutter: A–B — continuous laser frequency sub-range, B — disengagement of the etalon locking system, B–C — PZT return to its initial position, C–D — frequency jump after a brief interruption of generation by the intra-cavity shutter, D — engagement of the etalon locking system, D–E — next continuous frequency tuning sub-range.

Fig. 6 details quasi-smooth frequency scanning with an intra-cavity shutter and a PZT providing $\Delta\nu_{PZT}$ = 6 GHz at 532 nm, which is in our case below $\Delta\nu_{detune}$. It can be seen from Fig. 6, that quasi-continuous frequency tuning is, indeed possible even in this condition.

7. CONCLUSION

This report presents a powerful single-frequency laser system on the basis of a diode-pumped solid-state Nd:YVO_4 ring laser with intra-cavity frequency doubling in a non-linear LBO crystal, in which for the first time was achieved quasi-smooth laser frequency scanning over a 60-GHz range. The output power at 532 nm was 1.5 W and the radiation line width, 5 MHz. We also demonstrated our newly developed method of stitching of adjacent continuous frequency tuning sub-ranges with the help of a high-finesse Fabry-Perot interferometer to the precision of the laser radiation linewidth. The proposed laser may be used as a highly precise spectroscopic instrument in many research and technology applications.

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