Resonant doubler with a 2-THz automatic quasi-smooth scan range for widely tunable CW single-frequency lasers

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ABSTRACT

In the present work, demonstrated for the first time is automatic quasi-smooth scanning of an resonant doubler cavity synchronously with the frequency of a CW auto-scanned Ti:Sapphire laser within a 1-THz frequency range (2 THz for second harmonic), which is limited only by the spectral acceptance bandwidth of non-linear crystal. Significant (more than by an order of magnitude) widening of the synchronous scanning range was achieved owing to the suggested method of automatic re-locking of the external cavity. The number of automatic cycles when the input frequency is re-locked to different transmission peaks of the doubler cavity can be arbitrarily large, and the domain of automatic quasi-smooth frequency scanning that is composed of multiple smooth scanning ranges (~ few GHz wide). The doubler was tested with bow-tie-shaped ring cavity configuration and LBO/BIBO crystals. Doubling efficiency was in the range of 25-42% at input power of 0.7-2.1 W.

Keywords: resonant frequency doubler, single-frequency laser, smooth scanning, second harmonic generation.

1. INTRODUCTION

Resonant high-Q frequency doublers of CW laser radiation are widely used for generation of radiation in UV and visible spectrum ranges [1–5]. In comparison with relatively simpler doubling technology which uses PPLN crystals [6, 7] and fibres [8, 9] frequency doubling in an external cavity is capable of delivering substantially higher output powers of the second-harmonic radiation. In combination with a single-frequency tuneable laser such a resonant frequency doubler efficiently widens the working spectral range into the short-wavelength domain.

As the fundamental frequency is detuned in combination with a frequency doubler, the second-harmonic radiation is also detuned accordingly, the continuous scan range, obviously, being twice as broad as the corresponding scan range of the fundamental radiation. Smooth detuning of the doubled radiation frequency is performed by continuous adjustment of the doubler cavity length driven by a PZT-mounted mirror. Typically, such PZT provides continuous detuning range of the second-harmonic radiation on the level of several to tens of GHz. This limitation is related only to the maximum possible mirror travel in the doubler cavity that can be provided by the actuators. The continuous tuneability range of the second-harmonic radiation which can be equal to, say, 5 or even 50 GHz is considerably narrower than the spectral width of phase matching in the crystal, which may be as broad as 1 THz. This means that because of relatively broad spectral width of phase matching in the non-linear crystal continuous (or quasi-continuous) detuning of the doubled radiation frequency is possible within a range of about 2 THz with unchanged position of the non-linear crystal.

Let's note that a 2-THz scanning range has already been mentioned in relation to resonant frequency doubling in Ref. [10], however in that paper this value was understood as the maximum change in the doubled radiation frequency with the used diode laser. This range mentioned in Ref. [10] is not related to continuous (or quasi-continuous) scanning of the doubled radiation frequency. In effect, the specified value simply corresponds to the width of possible spectral range of the second-harmonic generation with the diode source used in [10].

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In the present contribution, an efficient resonant frequency doubler is described that is capable of automatically following the frequency of the input laser radiation when the latter changes within a 1-THz range. In the developed doubler this detuning range is only limited by the spectral width of phase matching in the non-linear crystal.

2. EXPERIMENT

The layout of the developed resonant frequency doubler is presented in Fig. 1. The ring cavity of the doubler is formed by two spherical mirrors (R = 100 mm) and two flat ones. The fundamental radiation is guided into the doubler cavity through one of the flat mirrors that has transmission of 1.7%. This transmission strikes an optimum because at this value the power enhancement factor of the fundamental radiation inside the cavity reaches its maximum. With the non-linear crystal taken out of the resonator the enhancement factor for the fundamental radiation is as high as 130. Coupling of the second-harmonic radiation from the doubler cavity is done through a spherical mirror which has 90% transmission for the second-harmonic wavelength.

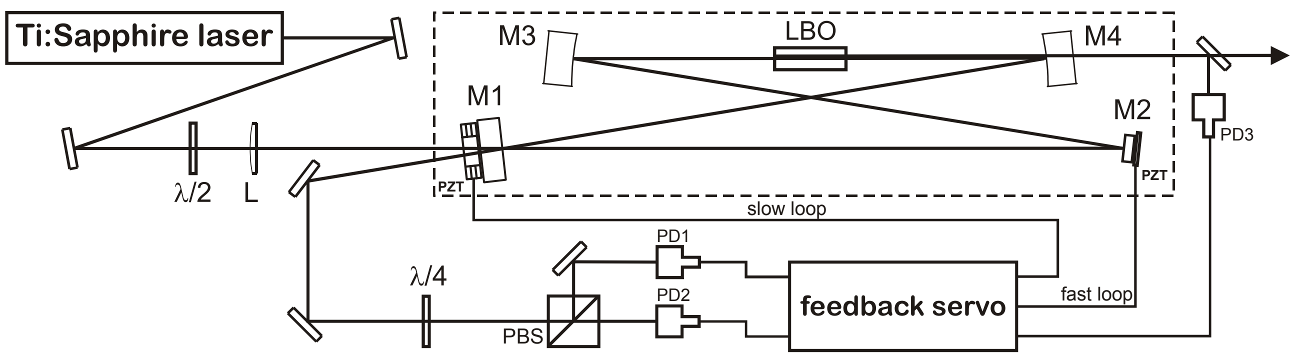

Fig. 1. Schematic design of the Resonant Frequency Doubler: M3, M4, concave mirrors (R=100 mm); M1, input coupler, slow-PZT-driven mirror; M2, fast-PZT-driven mirror; PBS – polarization beamsplitter cubes; PD1, PD2, photoreceivers of stabilization system; PD3, control photoreceiver; L – mode-matching lens

In our experiments we used a 15-mm LBO crystal manufactured by company "Siberian Crystals". The crystal had working faces cut for normal beam incidence, these faces having also AR coatings. The doubler cavity was optimised for this particular crystal in which the radius of the beam waist is ~ 30–40 µm. Given in Fig. 2 is a dependence of the beam waist W_0 in the employed LBO crystal upon the distance between the two spherical mirrors. The largest waist radius is 41 µm, it can be reduced to ~ 30 µm by adjustment of the distance between the spherical mirrors. Fig. 3 shows the calculated Boyd-Kleinman parameter for this non-linear crystal as dependent of the beam waist radius W_0 of the fundamental harmonic radiation inside the crystal. From the calculated curve it can be seen that the Boyd-Kleinman parameter for the used LBO crystal (proportional to the second-harmonic power) reaches its maximum at beam waist radius inside the crystal equal to about 28 µm; that is, for this crystal the resonator is quite close to the optimal configuration.

In Fig. 4, a photograph of the developed frequency doubler is presented. The resonant cavity has rigid compact construction that minimises passive instability in positions of its optical elements. The temperature of the non-linear crystal is automatically maintained at 55 °C for minimisation of thermal effects in the non-linear crystal.

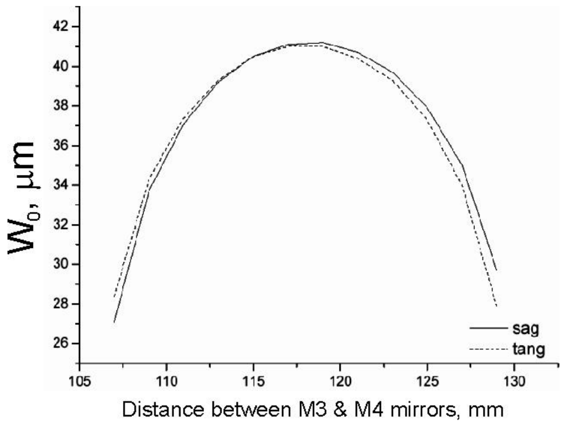

Fig. 2. Dependences of beam waist radius W_0 in used LBO crystal on the distance between spherical mirrors.

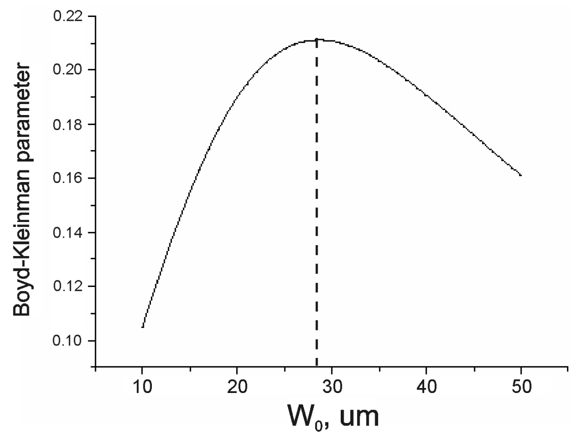

Fig. 3. Calculated Boyd-Kleinman parameter for used nonlinear crystal is given as a function of beam waist radius W_0 for fundamental harmonic of radiation inside the crystal.

Fig. 4. Resonant cavity together with optical elements of the frequency locking system .

In order to lock the maximum of the transmission peak of the doubler cavity onto the input radiation frequency a very well-known polarisation method of Hansch-Couillaud [11] is used. The tracking system has two control loops, a fast and a slow ones. The slow loop has frequency band-width of ~ 500 Hz, the maximum travel of the cavity mirror performed with a slow PZT element amounting to 4.7 μm. The frequency band-width of the fast control loop is as broad as 80 kHz, however the travel range of the fast mirror PZT is substantially smaller and is equal to 0.5 μm. Implementation of two control loops (fast and slow) is a guarantee for reliable operation of the frequency doubler under conditions of external perturbations (acoustic, mechanical, and others) as well as when unstabilised input lasers are used.

The range of continuous detuning of the doubled radiation frequency is determined by the longest possible travel of the cavity mirror driven by the slow PZT. For the specific PZT used in the experiment the smooth detuning range of the doubled radiation frequency is around 6 GHz for the Ti:Sapphire wavelength range.

In order to broaden substantially the scanning range of the resonant doubler in lock with the laser, for the first time a method was used of automatic re-locking of different transmission maxima of the doubler cavity to the input frequency that can be changed within 1 THz. The system operates in the following way: if the input laser frequency changes within the smooth scanning range of the doubler cavity the system keeps the transmission peak of the doubler resonator in lock with the input frequency. As the input laser frequency passes beyond this range the cavity of the frequency doubler is automatically re-tuned to the beginning (or to an otherwise set position) of the scanning range and then is locked in to the input laser frequency and follows it continuously. The number of automatic cycles when the input frequency is relocked to successive transmission peaks of the doubler cavity can be arbitrarily large, and the domain of automatic quasi-smooth frequency scanning that is composed of multiple smooth scanning ranges (~ 1–6 GHz wide) is only limited by the spectral width of the non-linear crystal phase matching, the latter being as wide as few THz.

In the diagrams shown in Fig. 5 we illustrate the process of automatic quasi-continuous detuning of the resonant frequency doubler. At moments when the resonator retracts to the initial position before beginning each cycle of continuous scanning, a brief drop in the output power of the second-harmonic radiation is observed. For this short duration the system of experimental data acquisition may be suspended by a signal from the electronic control unit of the frequency doubler. This is why for the data acquisition system frequency detuning will be smooth over a very wide spectral range, the second-harmonic output power in different cycles of continuous detuning remaining constant (the lower chart).

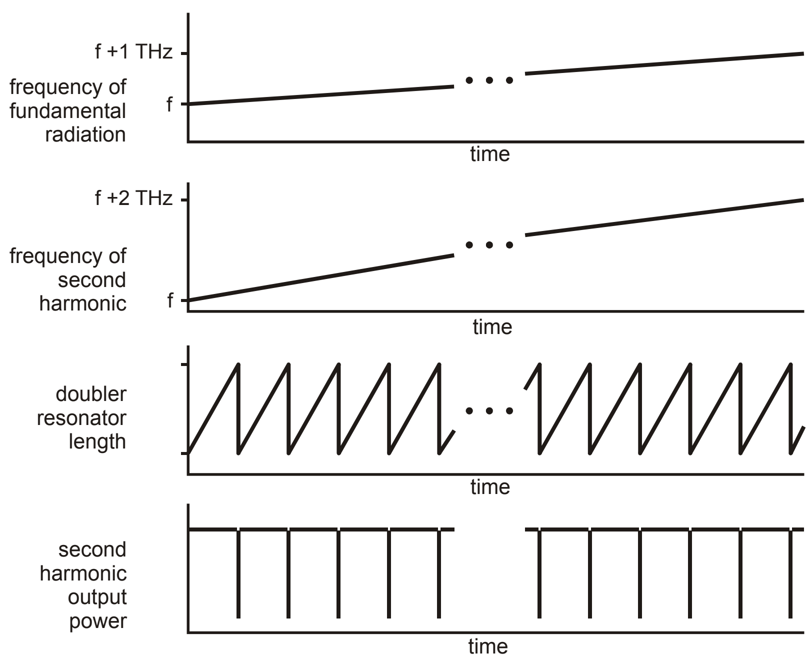

Fig. 5. Diagrams demonstrating the process of automatic quasi-continuous tuning of the resonant frequency doubler synchronously with the frequency of the fundamental radiation within a wide spectral range. Each cycle of resonator length adjustment on the second diagram below corresponds to continuous frequency scan of the second harmonic radiation.

An experimental dependence of the second-harmonic output power in a cycle of continuous scanning of the laser upon frequency is shown in Fig. 6 within the range from 387.1493 to 387.1588 THz. Studies were carried out with the use of single frequency Ti:Sapphire laser 899-29 Ring Autoscan II with the ability to automatically and quasi-smoothly scan the output frequency within a range in excess of dozens of THz, the continuous scanning range of this laser being ~10 GHz. Vertical lines in Fig. 6 correspond to momentary dips in the output power of the second-harmonic radiation each time when the doubler cavity is re-locked to frequency of fundamental input radiation. Typical duration of frequency re-lock is 1 ms. The doubler cavity was re-locked to the frequency of the input radiation automatically when that frequency changed by 1.3–1.9 GHz. Measurements of the absolute value of the fundamental radiation frequency and its detuning were carried out with a wavelength meter supplied within the kit of 899-29 Ring Autoscan II laser. Also given in Fig. 6 is simultaneously registered transmission function of the wavelength meter étalon (FSR = 6.8 GHz). As the fundamental frequency was continuously detuned by 9.5 GHz the second-harmonic frequency was quasi-continuously (with frequency re-locked 6 times) detuned by 19 GHz.

It was further interesting to examine how far the resonant frequency doubler can follow the frequency of the input radiation without changing the position of the non-linear crystal. In our experiment the widest range of automatic quasi-continuous scanning for the resonant frequency doubler was about 1 THz, the second-harmonic frequency changing by ~ 2 THz. In Fig. 7 experimental dependences can be seen of the second-harmonic output power in the beginning of this 1-THz range (the fundamental input radiation frequency within 386.0622 to 386.0723 THz), in the central part of it (fundamental radiation frequency between 386.2867 and 386.2968 THz), and in the end (fundamental frequency from 386.9366 to 386.9463 THz). In this experiment the automatic frequency re-lock system was set up in such a way that at the start of each continuous detuning range of the laser output frequency the doubler followed it continuously within a range of 2–3 GHz, thereafter frequency re-lock occurred after about every 0.5 GHz of change in the input radiation frequency. This amount of change (~ 0.5 GHz) corresponds to the free dispersion range of the doubler cavity, *i.e.* frequency was re-locked with each following peak of the resonant doubler. When broader continuous scanning ranges were used, the input frequency was re-locked with every fourth, fifth, or the sixth peak of resonant doubler transmission. The selection of operation mode of the frequency auto-relock system could be done through adjustments of the doubler control unit.

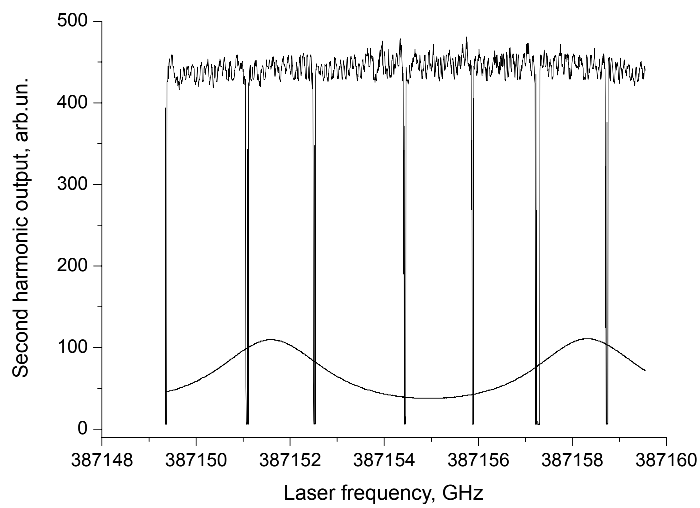

Fig. 6. Experimental dependence of second harmonic power on scanning frequency

A noticeable drop in the output power of the second-harmonic is visible in Fig. 7c, which is caused by the frequency drawing nearer to the end of the spectral range. When the doubler cavity is tuned differently, moving the frequency close to the boundary of the phase matching range of the non-linear crystal may cause instabilities in generation of the second harmonics. (Fig. 7d).

It should be also noted that broader scanning range of the doubler cavity between frequency re-lock (Fig. 6 and 7d) causes larger drops in the second-harmonic output at the moment of re-lock, up to 100%, whereas smaller scanning ranges between the frequency re-locks (Fig. 7 a–c) lead to less dramatic dips in the second-harmonic output power at the moment when frequency is re-locked, as a rule not exceeding 50%.

In our experiment the frequency of the input radiation was continuously scanned in each 10-GHz domain, although in principle it may be stopped until the frequency is locked again by monitoring a special signal from the electronic control unit. This capability is available in the system. This means that after the frequency scan of the input radiation is suspended the doubler cavity can return to the start of the next continuous detuning range while the user data collection system that depends on the frequency and output power of the second harmonic radiation may also be suspended. The next continuous detuning range will start from the same frequency at which the previous continuous range ended. Output power of the second-harmonic radiation at the end of previous scan range and at the start of the next one will be same allowing for the present fluctuations of the second-harmonic output (typically their magnitude does not exceed 10%).

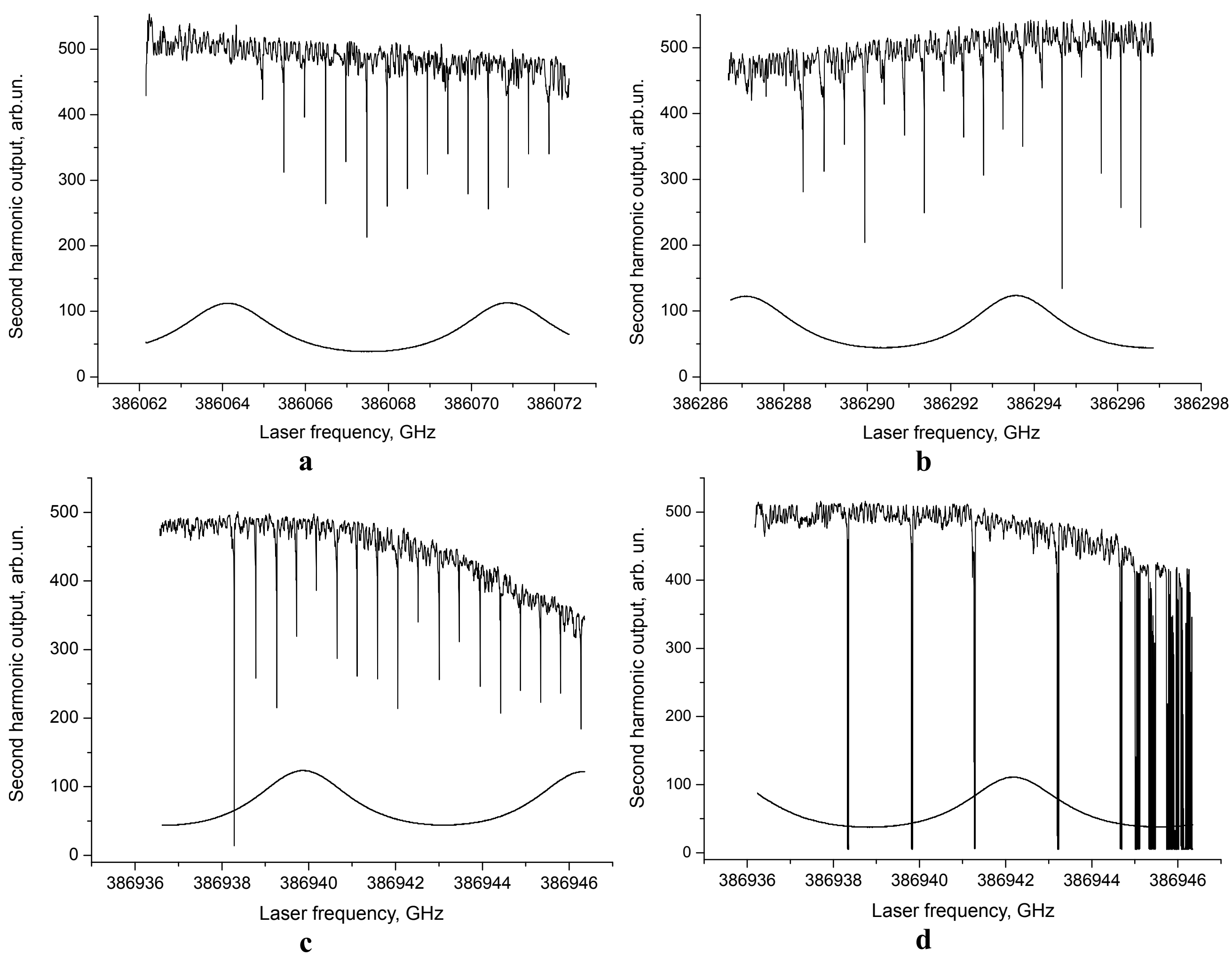

Fig. 7. Experimental dependencies of the second harmonic output power upon the wavelength of the fundamental radiation: Figs. *a* and *b* correspond to automatic quasi-continuous scanning of the frequency doubler approximately in the beginning of the 1-THz domain (Fig. *a*) and within a spectral range about ~ 0.3 THz from the beginning (Fig. *b*); Figs. *c* and *d* illustrate the behaviour of the

second harmonic output power when the fundamental wavelength approaches the edge of the phase matching domain of the non-linear crystal in different modes of automatic frequency re-locking.

Thus, the developed system of automatic re-locking of the input radiation frequency allows an efficient resonant frequency doubler to automatically and quasi-smoothly follow the frequency of the input radiation from a Ti:Sapphire laser within a 1-THz domain, quasi-continuous scanning of the second harmonic frequency extending to 2 THz and consisting of multiple continuous scanning sub-ranges of ~ 1 to 5–6 GHz wide each.

Output power of the second-harmonic radiation in Fig. 6–7 are given in arbitrary units, however the efficiency of the second harmonic generation in the developed doubler is sufficiently high and exceeds 40% at the input power of 2 W. In Fig. 8 a typical dependence of the second-harmonic output power of this doubler is given versus the input power of a Ti:Sapphire laser at 800 nm. Maximum of the output power of the second harmonic radiation at 400 nm is 850 mW with input beam power 2.1 W.

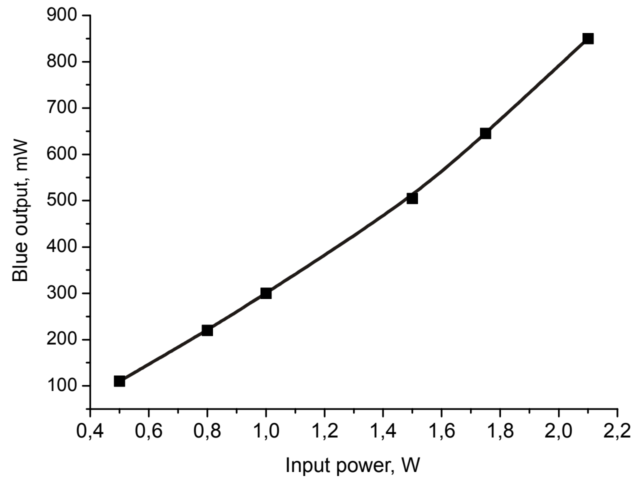

Fig. 8. A typical dependence of generated by developed doubler second harmonic power on power of input radiation at 800 nm produced by Ti:Sapphire laser. Maximum second harmonic power at 400 nm is 850 mW when input power is 2.1 W.

In the experiments we used also novel non-linear optical crystal BIBO (6-mm-long, produced by Foctek). For the first time by using this crystal in an external resonator a stable single-frequency generation of the second-harmonic radiation was achieved with the output power of 270 mW at the wavelength of 425 nm. Conversion efficiency is as high as 36%. At the output power of the second-harmonic radiation exceeding 270 mW with the BIBO crystal, which corresponds to 300 mW of power within the doubler cavity, high-magnitude power fluctuations of the second-harmonic radiation set in similar to those observed in [12].

3. SUMMARY

In this work, for the first time an efficient method of automatic quasi-smooth detuning of second-harmonic radiation was demonstrated in a 2-THz range. The range of this automatic detuning is only limited by the spectral width of phase matching in the non-linear crystal. In case of critical phase matching it is possible to extend this range by automatic adjustment of the position of the non-linear crystal. However, changing the position of the non-linear crystal also requires re-alignment of the resonator itself. In case of non-critical phase matching automatic adjustment of the non-linear crystal following the wavelength of the fundamental input radiation may be done by adjusting its temperature. In this case the total range of automatic quasi-continuous detuning of the doubled radiation frequency may be only limited by the possibilities of changing the frequency of the fundamental radiation.

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