External power-enhancement cavity versus intracavity frequency doubling of Ti:sapphire lasers using BIBO

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Abstract: We report on continuous-wave second harmonic generation of near infrared Ti:sapphire lasers using room temperature critically phase-matched, angle-tuned BIBO (bismuth triborate, BiB_3O_6) crystals, placed both in an external power enhancement cavity and inside the laser resonator. In the first case we generate 70 mW of single-frequency radiation at 423 nm for 330 mW of input power at 846 nm. For intracavity frequency doubling we achieve 690 mW at 423 nm for 7.3 Watts of the Ti:sapphire laser pump power at 532 nm, representing a conversion efficiency of 9.5% from 532 to 423 nm. These tunable blue-violet systems are particularly attractive for laser cooling and trapping of alkaline-Earth atoms.

OCIS codes: (140.3580) Lasers, solid state; (140.3515) Lasers, frequency doubled; (140.3590) Lasers, titanium; (160.4330) Nonlinear optical materials; (190.2620) Harmonic generation and mixing.

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1. Introduction

The large interest that exists today in blue and UV laser generation is driven both by industrial and scientific applications. Industrial applications include microscopy, medical instruments, micromachining and semiconductor processing. Scientific applications include spectroscopy, atom cooling and trapping, quantum optics and quantum information. Blue and UV laser generation is still difficult to achieve without nonlinear frequency conversion. Several nonlinear crystals are available to generate visible light, but the choices are reduced when going into the blue and UV, either because the crystals are not transparent or phase-match can not be achieved.

In this paper we investigate blue light generation by second harmonic conversion of Ti:sapphire lasers at 846 nm, using the relatively new BIBO (bismuth triborate, BiB_3O_6) crystal. BIBO belongs to the same family as BBO and LBO, and has advantages such as higher nonlinearity (9 times that of LBO [1]), reduced walk-off, very good optical quality with low scattering and absorption losses, and good transparency into the blue region. It can for example replace $KNbO_3$, which has higher efficiency but presents an infrared absorption induced by blue generation (BLIIRA [[2]). This severely limits the maximum power at which $KNbO_3$ can be used. Compared, on the other hand, to periodically poled crystals such as PPLN and PPKTP [3], which have very high nonlinearities, BIBO has advantages of optical quality, reduced cost and also in avoiding the difficulties associated with poling, especially when going into shorter wavelengths.

We generated blue light at 423 nm both in an external power enhancement cavity and in intracavity configuration, using Ti:sapphire lasers as sources of fundamental radiation at 846 nm. In external cavity we generated up to 70 mW of stable single-frequency blue light for 330 mW of incident power. For intracavity generation, we achieved 690 mW for 7.3 Watts of the Ti:sapphire pump power at 532 nm. This represents a conversion efficiency of 9.5 % from 532 to 423 nm, and to our knowledge is the highest efficiency achieved at these powers for a Ti:sapphire laser. This work is particularly motivated by our interest in powerful coherent radiation sources for atomic manipulation of alkaline-Earth atoms, and particularly neutral calcium atoms [4]. However the blue laser systems described here are suitable for a variety of other applications.

2. Theory

According to the Boyd-Kleinman theory [5], the second harmonic power $P_{2\omega}$ generated by a nonlinear crystal is given by:

$$P_{2\omega} = \eta P_\omega^2 = \frac{2\omega^2 d_{eff}^2 k_\omega}{\pi \varepsilon_0 n_1^2 n_2 c^3} L_c P_\omega^2 h(\sigma, B, \xi) \quad (1)$$

where P_ω is the fundamental incident power and η is the conversion efficiency. The conversion efficiency η depends on the crystal length L_c, fundamental frequency ω, indices of refraction n_1 and n_2 at the fundamental and second harmonic frequencies, and the effective nonlinear coefficient d_{eff} of the crystal (c is the speed of light in vacuum and ε_0 is the dielectric constant). The function $h(\sigma, B, \xi)$ depends on parameters that are adjustable in the experiment: the phase-mismatch $\sigma = (k_\omega \omega_0^2 \Delta k)/2$, the focusing parameter $\xi = L_c/(k_\omega \omega_0^2)$ (where ω_0 is the waist size at the crystal, k_ω is the wavenumber, and $\Delta k = 2k_\omega - k_{2\omega}$) and the walk-off parameter $B = 0.5\, \rho\, (L_c k_\omega)^{1/2}$ (where ρ is the double-refraction walk-off angle). In ref. [5], $h(\sigma, B, \xi)$ is plotted as function of ξ assuming perfect phase-matching (σ=0). For

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noncritical phase-matching, for example, B=0 and h is maximized for ξ=2.84, which then sets the optimum waist size ω_0 for a crystal of length L_c. For SHG of 846 nm radiation, BIBO has a nonlinear coefficient d_{eff} = 3.61 pm/V [6] that results in $\eta = 0.004\ L_c\ h(\sigma,B,\xi)$. We have used two crystals with L_c = 6 and 10 mm. Because these crystals were cut for critical phase matching SHG at 846 nm ($\theta = 155^0$, $\phi = 90^0$, ρ = 53 mrad), we estimate B = 9.8 for the 10-mm long crystal. For an optimum ξ of 1.4 [5], corresponding to an optimum waist size of 23 μm, this gives $\eta = 3.2\text{x}10^{-4}\ W^{-1}$.

The conversion efficiency η is usually a small number, between 10^{-5} and 10^{-2}, and therefore the second harmonic power for cw lasers in single-pass configuration is also small. For this reason the crystal is either placed inside an external power enhancement cavity or inside the laser cavity, where P_ω is much higher and the second harmonic power $P_{2\omega}$ is greatly increased.

The enhancement factor G of an external cavity, defined as the ratio of the intracavity power P_c to the incident power P_i, is given by:

$$G = \frac{P_C}{P_I} = \frac{T}{1-2\sqrt{(1-T)(1-L)}+(1-T)(1-L)} \tag{2}$$

where T is the transmissivity of the input coupler (IC) mirror at the fundamental frequency, and L represents all losses in the cavity, including absorption and scattering in the crystal and mirrors and second harmonic conversion, but excluding the transmission of the IC. For a fixed value of losses L in the cavity, the optimum transmission of the input coupler mirror which maximizes G, is simply T=L (impedance matching). A cavity loss of 1% (L=0.01), matched by an IC with 1% transmissivity (T=0.01), will result in an enhancement factor of 100 (G=1/L).

3. Experimental setup and results

3.1 Ti:sapphire lasers

We have built two cw and tunable Ti:sapphire lasers whose diagrams are shown in Fig. 1 and 2. Figure 1 shows a single-frequency Ti:sapphire laser built with a ring optical cavity. The Ti:sapphire crystal is Brewster-cut with a length of 20 mm and a 0.10% Ti^{3+} concentration. It is pumped with up to 5.5 W of single-frequency radiation at 532 nm (Coherent Verdi). The crystal is mounted in a copper support piece that assures good heat sinking, and does not need to be cooled. Angles of incidence on the curved mirrors are such that compensate the astigmatism introduced by the Brewster faces of the Ti:sapphire crystal [7]. To enforce unidirectional oscillation we use a standard homemade optical diode based on the Faraday effect. It comprises a Brewster-cut, 2-mm long, TGG Faraday crystal placed inside a stack of permanent Sm-Co ring magnets, which produce fields of 2.5 kGauss. A thin quartz plate is used to compensate, via optical activity, the polarization rotation induced by the TGG crystal. Alternately, we have also used a $\lambda/2$ waveplate instead of a quartz plate.

For frequency tuning and selectivity we use a three plate birefringent filter (BRF, we have BRFs both from Coherent and CVI). A thin coated etalon is added for single-frequency operation. This etalon is mounted on a galvanometer, but its support piece also has a small piezo-stack that allows fast angle modulation. This stack is driven at one of the mechanical resonance frequencies of the etalon structure (typically at 18 kHz), causing a small laser frequency modulation that is used for locking the etalon modes to the laser cavity modes, assuring operation without mode hops. The laser cavity converts the frequency modulation into amplitude modulation, which is detected by a photodetector outside the cavity. A lock-in amplifier phase sensitively detects this modulation and derives an error signal for locking, which is then fed back into the galvanometer. Stable single-frequency oscillation is achieved

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in this way. One of the cavity mirrors is mounted on another piezo-stack driven at voltages up to 100 Volts. This is used for fine tuning and also for locking the laser to an external reference cavity for linewidth reduction.

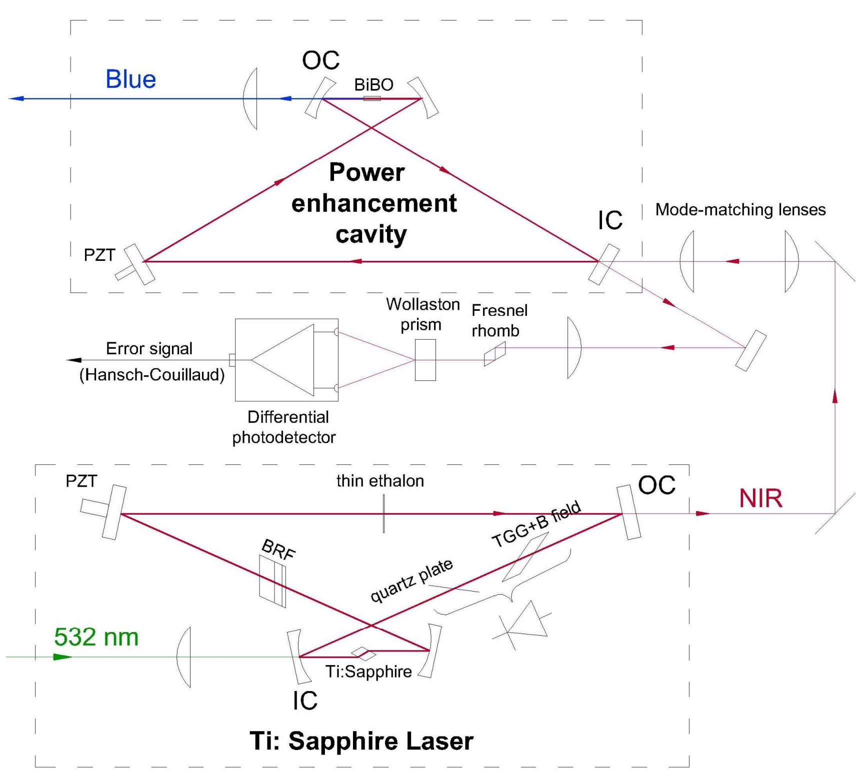

Fig. 1. Schematic diagram showing our single-frequency Ti:sapphire ring laser and its frequency doubling into an external cavity, locked by the Hänsch-Couillaud technique [8]. The Ti:sapphire laser and doubling cavity lengths are 104 and 62 cm.

Figure 2 shows a diagram for another Ti:sapphire laser with similar design, also pumped with up to 10 W at 532 nm, but with a Ti:sapphire crystal that has a lower Ti^{3+} concentration, more suitable for pumping with argon ion lasers. We replaced the output coupler mirror by a high reflecting one, and have added two concave mirrors (ROC = 5 cm) to the longer arm of the cavity in order to produce a small waist (22 μm) size required for efficient SHG. Although bow-tie cavities produce a secondary waist at this position, usually they have hundreds of microns, and thus are not optimum for SHG. With this laser we initially did not include the optical diode, and therefore the laser oscillated in both directions. In this case, two power meters have been used simultaneously to detect the blue light, and were calibrated against a third power meter. We then added an optical diode and a thin etalon to achieve single-frequency operation.

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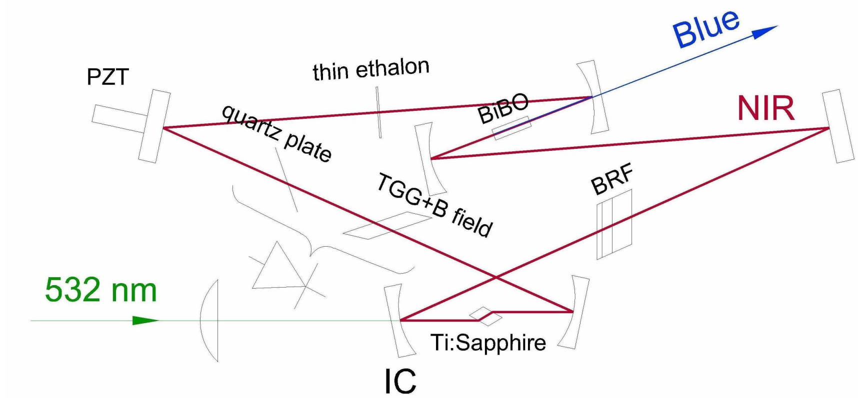

Fig. 2. Schematic diagram for intracavity second harmonic generation in another Ti:sapphire laser (total cavity length is 114 cm). Two fold mirrors (ROC=5 cm) were used to produce a tight waist at the BIBO position. An optical diode and a thin coated etalon were introduced for single-frequency operation.

3.2 Second harmonic generation in external power enhancement cavity

We performed our measurements of second harmonic generation near 846 nm, because of our interest in generating light at 423 nm for laser cooling and trapping of neutral calcium atoms. Spectroscopy, cooling and trapping of other alkaline-Earth atoms, such as Strontium (461 nm) and Ytterbium (400 nm) could also be performed with similar systems. We tested two BIBO crystals with dimensions of 4x4x6 mm and 4x4x10 mm, both AR-coated at 846 and 423 nm. The crystals were cut at $\theta = 155^0$, $\phi = 90^0$ for type I, critical, angle-tuned phase-matching SHG of 846 nm at room temperature. As a precaution for possible residual absorption, the crystals were mounted with good contact to their copper support pieces in order to assure effective heat sinking.

Figure 1 also shows the diagram for the external power enhancement cavity. It is a bow-tie type of cavity formed by two concave mirrors (ROC = 7.5 cm) and two flat mirrors. The output coupler is one of the concave mirrors and transmits 94% at 423 nm. The input coupler (IC) is one of the flat mirrors. We have tested ICs with transmissivities of 1 and 2% at 850 nm, achieving better results in the first case. The cavity produced a tight waist of 30 μm between the curved mirrors, where the 10-mm long BIBO crystal is placed, and a bigger waist of 430 μm between the flat mirrors, on which the input beam is mode-matched by using a pair of plano-convex lenses (Fig.1). Mode-matching efficiency into the TEM_{00} mode of the cavity was not optimized and was measured to be 80 %.

Locking of the doubling cavity resonance to the laser frequency was done by the Hänsch-Couillaud technique [8]. The polarization of the light reflected from the ring cavity, which continuously changes states across its resonance when a polarization sensitive element is placed inside [8], is detected by a polarization analyzer comprising a Fresnel rhomb (acting as a $\lambda/4$ waveplate) and a Wollaston prism (Fig.1). An error signal is produced by a differential photodetector which collects the two orthogonally polarized beams from the Wollaston prism. This signal is then amplified by a loop filter and a piezo driver and fed back into the piezo-stack that supports one of the doubling cavity mirrors.

In principle the efficiency for SHG in external power enhancement cavities can approach 100 %. In fact, efficiencies up to 85% have been demonstrated in the past [9]. This technique can basically be applied only for SHG of single-frequency lasers (or more recently to frequency combs, or phase stabilized femtosecond lasers), because in this case the cavity resonance can be locked to the laser frequency by a variety of well established techniques.

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When a cw laser is not single-frequency, efficient SHG is done inside the laser cavity. In this case the well-known effect of power instability due to multimode sum-frequency generation known as the "green problem" [10] can be a limitation.

To achieve optimum efficiency for SHG in external cavities, minimum losses and careful choice of mirrors are required. We have determined the intracavity losses L in eq. 2 by measuring the power enhancement factors G, which for computing the cavity losses, have been corrected by the 80% mode-matching efficiency into the TEM_{00} mode. The factor G has been measured by the ratio of the power transmitted through one of the HR cavity mirrors, with and without the IC. Without the crystal we obtained G = 125, which combined with T = 1% for the IC, gives L=0.79%, due to the other three cavity mirrors. When the 10-mm crystal is inserted but blue light is not generated (either by detuning the input laser or changing its polarization), we achieve G=73, which gives L= 1.35%. Subtracting 0.79 % due to mirrors, this gives 0.28% for absorption or scattering mainly at the AR coatings, in good agreement with data provided by the manufacturer. Scattering at the crystal surfaces sometimes led to problems with optical feedback to the Ti:sapphire laser, which could be removed by alignment or the use of an optical isolator.

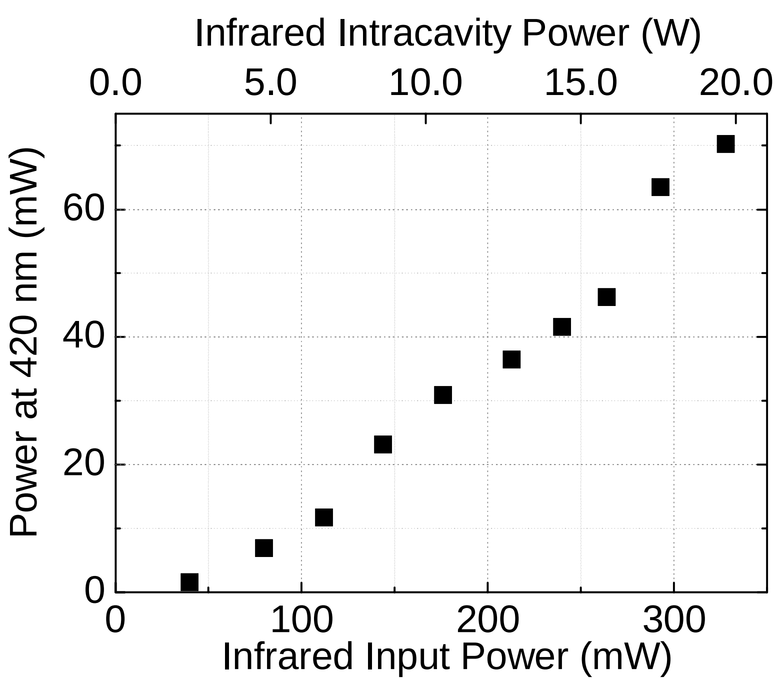

Fig. 3. Second harmonic power at 423 nm as function of incident fundamental power, for the setup in Fig.1. Blue power has been corrected by 94% transmission of the OC at 423 nm and 80% mode-matching efficiency.

Figure 3 shows the results for SHG in the external power enhancement cavity using the 10-mm crystal. The blue power has been corrected by the 94% transmissivity of the output coupler and the 80% mode-matching efficiency. The 6-mm crystal showed a problem also reported by others [1]: when the cavity is locked, within a few seconds the second harmonic power reduced to a quite smaller value. Power is recovered when the crystal is moved, but the effect repeats for this new position. We have verified, as others [1], that this happens even when there is no blue light generation. We also observed that the higher power could be recovered by a small polarization rotation of the fundamental light, rather than moving the

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crystal. This was done by a $\lambda/2$ waveplate not show in Fig.1. Similar dependence on polarization has been observed in [1]. Although it is not clear if there was damage to the coating, as seen in [11], the above behaviors suggest the presence of a photorefractive effect.

The 10-mm long crystal showed much less of these problems, and the results that we report in Fig. 3 are for this crystal. For an input power of 320 mW and a power enhancement factor of 48, we obtained 70 mW at 423 nm. From these numbers, a crystal efficiency $\eta = P_{2\omega}/(P_{\omega})^2 = 3 \times 10^{-4}$ W^{-1} is obtained for the 10-mm long crystal, which is in good agreement with our measurements of single-pass efficiency and the theoretical estimation of 3.2 x10^{-4}W^{-1}. Second harmonic generation with BIBO in an external cavity has been performed in references [1] and [12]. The authors of ref. [1] obtained a maximum power of 130 mW at 384 nm when the cavity is scanned, but saw severe instabilities when the cavity is locked. The authors used a Brewster-cut crystal, with no coatings. Ref. [12] seems to report the best numbers for SHG with BIBO in an external cavity. They obtained 400 mW of blue light at 390 nm for 900 mW of fundamental incident power in the cavity. Their cavity power enhancement factor is 47. Although our numbers were obtained for lower incident powers, we see in Fig. 3 that they agree well with the results from ref. [12]. Based on this and our results for intracavity doubling, we expect that single-frequency blue powers above 500 mW can be obtained for 1 Watt of incident fundamental power.

The results for SHG with BIBO should also be compared with other crystals. Promising options are periodically poled crystals, such as PPLN and PPKTP. They can have much higher conversion efficiencies and quasi-phase matching can be used when phase matching can not be obtained for bulk crystals. Ref. [13] reports the generation of 330 mW at 426 nm with PPKTP in an external cavity, for 600 mW of incident power at 852 nm. They report an efficiency $\eta = 0.0176$ W^{-1} for a 20-mm crystal, but a small cavity power enhancement G = 7.5.

3.3 Intracavity second harmonic generation

Intracavity SHG has been performed with the setup of Fig. 2. Similarly to the generation in the external cavity, the 6-mm crystal showed a much poorer performance. The power was not stable and limited to 30 mW, and the unstable spatial profile showed contributions from higher order modes. This behavior changed dramatically when this crystal was replaced by the 10-mm long crystal. It has been placed between the two 5 cm long mirrors, and mounted on a rotation stage attached to a XYZ micrometer translation stage for fine positioning. Initially the optical diode was not inserted and blue light was generated in both directions of the ring cavity. The results are summarized in Fig. 4, which shows the blue power as a function of the pump power of the Ti:sapphire crystal at 532 nm, measured before the pump lens. Two power meters were used simultaneously for curve a, when the laser was bidirectional, and before each one a “cold” dichroic mirror (Thorlabs FM04) was used to separate the residual infrared from the blue light. The total power in Fig. 4 (curve a), corresponding to the reading of both powermeters has been corrected by the 95% reflectivity at 423 nm of the two cold mirrors and the 95% transmissivity of the 5 cm concave mirrors.

We see in Fig. 4 that 690 mW is generated for 7.3 W of pumping power at 532 nm, representing a conversion efficiency of 9.5% from 532 to 420 nm. We note however that, because the Ti:sapphire crystal used in this laser was doped for pumping with argon ion lasers (515 nm) and not at 532 nm, a ~10% increase in the fundamental power would be expected for optimum doping, which in turn could lead to a ~20% increase in the blue power. Intracavity SHG of Ti:sapphire lasers with BIBO has also been performed in ref. [11], where a maximum output power of 100 mW at 405 nm has been achieved, representing a conversion efficiency of 1.82% from 532 nm. For pump powers above 5 Watts, the blue dropped similarly to what was observed in the external cavity. In addition to this effect, there was some instability in the blue light caused by sum-frequency generation between different modes of the Ti:sapphire laser. We then added an optical diode, similar to the one used in the laser of Fig.1, and obtained curve b in Fig.4. This optical diode introduced significant loss in

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the cavity, and possibly another diode with a better quality could give better results. The introduction of a coated thin etalon assured single-frequency operation and led to curve c in Fig.4. We achieve 266 mW (166 mW) of single-frequency light at 423 nm generated for 6.9 W (5.1 W) of pumping power at 532 nm. Surprisingly now the blue light was stable up to 7.3 Watts of pumping, which indeed indicate that we were seeing instabilities without the etalon due to the "green problem" in multimode operation. Although we do not present a more direct comparison with Fig. 3 in terms of incident infrared power, due to the difficulty of precise measurements of its intracavity values, we clearly found easier to generate the same amount of blue power for lower green pump powers in the case of intracavity SHG.

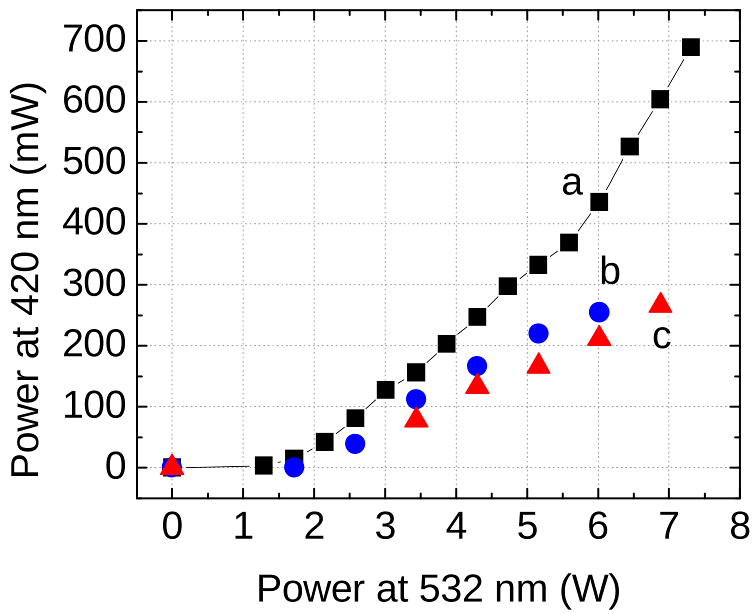

Fig. 4. Second harmonic power at 423 nm as function of the Ti:sapphire pump power at 532 nm, for intracavity doubling with the setup of fig.2. Curve a (squares): multi-mode, bidirectional operation, no optical diode (OD) or thin etalon; curve b (circles): OD inserted; curve c (triangles): OD and thin etalon inserted, single-frequency operation.

4. Conclusion

Second harmonic generation of near infrared cw Ti:sapphire lasers with BIBO can be very efficient both in external cavity and intracavity configurations. We obtained higher blue power with intracavity doubling (690 mW at 423 nm for 7.3 W at 532 nm, 9.5% 532-to-423 nm conversion efficiency) because of power limitations of our Ti:sapphire laser used for external cavity doubling. External cavity doubling requires careful selection of mirrors, powerful fundamental input lasers, and is very sensitive to intracavity losses. We achieved 70 mW of single-frequency light at 423 nm for 330 mW at 846 nm. Intracavity doubling, however, has the advantage of requiring less pump power for the Ti:sapphire laser. Because there is no output coupler for the near infrared, the threshold is greatly reduced and the alignment and insertion of optical elements are much easier. Pump powers at 532 nm of 4 or 3 Watts already produce significant blue power, enough for example for laser cooling and trapping of alkaline-Earth atoms. Since most commercial Ti:sapphire lasers require pump powers higher than this for regular operation and subsequent doubling in external cavities,

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intracavity doubling can be a better option when high power (and more expensive) pump sources for Ti:sapphire lasers are not available.

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