Third harmonic generation of a cw laser in external enhancement cavities

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Abstract

An all-solid-state tunable cw laser operating near 272 nm with a bandwidth $\Gamma \approx 3$ MHz has been developed. The third harmonic of light from a single cw Ti:Sapphire laser has been generated using two external enhancement cavities. An output power of 175 mW has been produced, corresponding to an overall conversion efficiency of 8%.

The goal of this work was to construct an all-solid-state cw laser system operating at deep-UV wavelengths. In the past, deep-UV has been generated by sum frequency generation with two diode lasers by Sayama and Ohtsu [1]. Doubly-resonant sum frequency light using two Nd:YAG lasers was generated by Kaneda and Kubota [2]. Also, by combining a Ti:S and a diode laser a narrow-band, cw UV source with several tens of milliwatts output power was designed by Fujii et al. [3]. Third harmonic generation using only a single Ti:S laser was demonstrated by Sayama and Ohtsu [4], producing 8 nW of deep UV radiation.

The power $P_{3\omega}$ generated in a sum frequency process is given by:

$$P_{3\omega} = \gamma P_{\omega} P_{2\omega} \tag{1}$$

Here P_{ω} and $P_{2\omega}$ are the incident fundamental and second harmonic power respectively and γ is the nonlinear coefficient of the process. Resonantly enhancing both wavelengths inside a cavity leads to a high conversion efficiency for the sum frequency process, expressed by:

$$P_{3\omega} = \gamma A_{\omega} P_{\omega} A_{2\omega} P_{2\omega} \tag{2}$$

A_{ω} and $A_{2\omega}$ are the cavity enhancement factors for the fundamental and second harmonic waves and now P_{ω} and $P_{2\omega}$ are the respectively powers of the light coupled into the cavity.

In our set-up the third harmonic of light from a tunable continuous wave (cw) Ti:Sapphire (Ti:S) laser is generated in two steps. Firstly second harmonic light is produced using an LBO crystal inside an external enhancement cavity (EEC). Subsequently this second harmonic light is coupled into a second EEC, together with the fundamental light. Here the sum frequency is generated in a BBO crystal. A schematic of the set-up is shown in figure 1. Narrow-band 817 nm light from a tunable cw Ti:S laser, which is pumped by a 10 W Nd:YAG laser at 532 nm, is separated into two beams using a $50/50\%$ beam-splitter. The light of one of the beams is frequency doubled inside a bowtie-shaped EEC using a LBO nonlinear crystal cut at angles of $\theta = 90°$, $\phi = 29.8°$ with respect to the optical axis. The crystal is cut at Brewster's angle for the fundamental wavelength. Mode matching of the Ti:S light into the EEC is performed by lens L1. The cavity losses per roundtrip are 1%, therefore the reflectivity of the input coupling mirror (M1) is chosen to be 99% to ensure impedance matching. This leads to a maximum coupling of 88% of the fundamental light into the EEC. The high reflecting mirrors M3 and M4 have a radius of curvature of

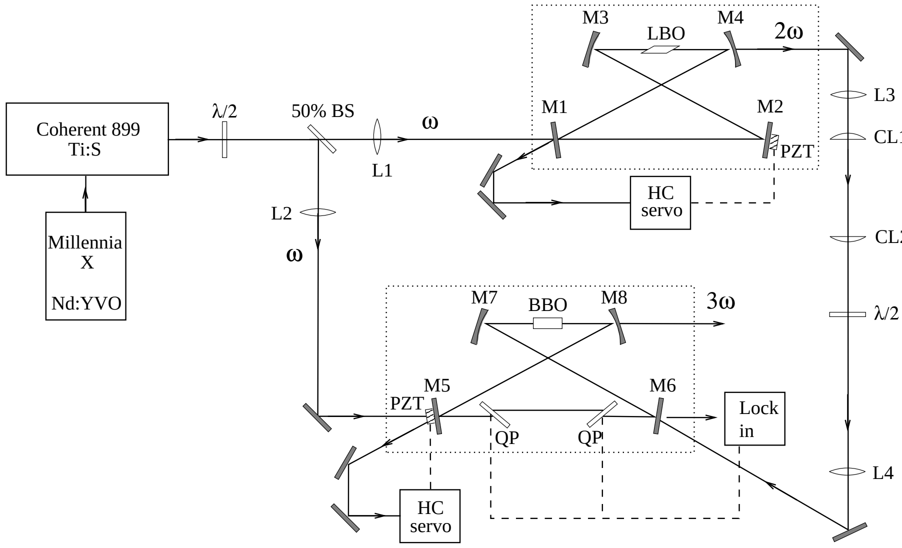

Figure 1: Schematic of the setup for generation of the third harmonic of a Ti:S laser. BS: beamsplitter, QP: quartz plate, PZT: piezo, L: mode-matching lens, CL: cylindrical lens, M: mirror, HC: Hänsch Couillaud locking set up.

-75 mm to focus the beam inside the LBO crystal. The distance between M3 and M4 is optimized for maximum conversion efficiency. To keep the EEC in resonance, the cavity is locked to the fundamental wavelength using the Hänsch-Couillaud locking technique [6]. From the FWHM of the cavity modes and the FSR of the cavity, a finesse of about 530 is deduced. This leads to a cavity enhancement factor of 150. From 1.00 W of input power at the fundamental wavelength 500 mW of usable second harmonic power is produced, a conversion efficiency of 50%. To our knowledge this is the highest conversion efficiency up to now reported for cw frequency doubling of a Ti:S laser.

The second EEC is built up using doubly-reflecting mirrors in order to enhance both the fundamental and the second harmonic. The small mirror M5 mounted on a piezo is the input coupler for the fundamental, whereas M6 is the input coupler for the second harmonic. The roundtrip losses for the fundamental are close to 1%. For impedance matching the reflectivity of M5 is chosen to be 99% for the fundamental and HR for the second harmonic. The roundtrip losses for the second harmonic are about 3%, hence M6 is chosen to be 97% reflective for the second harmonic and HR for the fundamental. The HR mirrors M7 and M8 have a radius of curvature of -75 mm, focusing both wavelengths inside a BBO crystal. Due to the spatial distribution of the resonator eigenmodes the waists of both wavelengths will automatically overlap inside this crystal. The waist sizes of both waves will differ by a factor of the square root of their wavelengths. The 42.2° BBO crystal is anti-reflection-coated for all three relevant wavelengths. For the fundamental light the EEC has a finesse of approximately 310 leading to an enhancement of 98. The finesse for the second harmonic light is measured to be 63, so the enhancement is 29. The light sent into this EEC is mode matched in order to maximize the coupling. For the fundamental and second harmonic 88% and 75% incoupling is achieved, respectively.

One would expect that when the cavity is resonant with the fundamental, it would also resonant with the second harmonic. However, this is not the case. Because of dispersion in BBO the optical path lengths of the respective waves differ, giving rise to a shift from resonance of the second harmonic when the cavity is locked to the fundamental. This dispersion can be compensated by two flat quartz plates in the cavity mounted on counter rotating galvos. These plates are mounted under Brewster's angle -which is almost the same for both waves- so cavity losses are minimal. Tuning the angle of these plates leads to an optical path length difference between both waves.

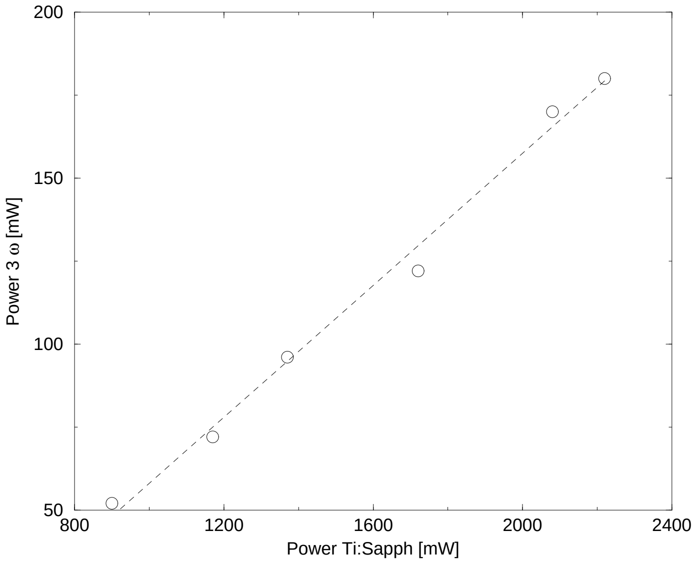

Figure 2: Output power of the 3rd harmonic as function of Ti:S power.

Thus the cavity can be made resonant for both wavelengths: firstly the cavity is locked to the fundamental using the Hänsch-Couillaud technique, subsequently the second harmonic is also made resonant by slightly rotating the plates. These plates can be locked to optimal incoupling of the second harmonic, a feedback signal is obtained by monitoring the rejected 408 nm light from M6. Fast disturbances (which are experienced by both wavelengths) are compensated by the fast Hänsch-Couillaud lock regulating the piezo, while the slowly varying dispersion is compensated by the galvo plates. The resulting third harmonic output as a function of Ti:S power is shown in figure 2.

The generated UV light can be continuously scanned over 10 GHz at 272 nm. With the present optics set the system can generate wavelengths in the range 280 nm to 265 nm. Using other sets of optics and crystals the entire Ti:S range can in principle be frequency tripled, generating wavelengths ranging from 235 nm up to 330 nm.

In summary, we have developed an efficient method to generate third harmonic light of any cw single mode laser. Starting with 2.1 W light at 817 nm up to 175 mW of output power at 272 nm has been attained. The overall conversion efficiency of the process is 8%. To our knowledge such high output power has never before been achieved using a single tunable laser system.

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