2 GHz repetition-rate femtosecond blue sources by second harmonic generation in a resonantly enhanced cavity

Tzu-Ming Liu, Cheng-Ta Yu, and Chi-Kuang Sun[a)]
Department of Electrical Engineering and Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei 10617, Taiwan Republic of China

(Received 8 July 2004; accepted 12 December 2004; published online 3 February 2005)

We report a 2 GHz repetition-rate, all-solid-state femtosecond blue source. Pumped by a 740 mW femtosecond Ti:sapphire laser with the same repetition rate, 150 mW femtosecond pulses at 409 nm can be efficiently generated from the external resonant cavity with a lithium triborate crystal. [DOI: 10.1063/1.1862785]

GHz-repetition-rate (GRR) femtosecond lasers open a wide range of applications.[1–5] In an optical communication system, these lasers provide necessary bandwidth and repetition rate for the hybrid wavelength-division multiplexed and optical time-division multiplexed systems.[1] For spectroscopy and sensing applications, GRR lasers reduce the peak intensities while maintaining a high average power, which is important for achieving high signal-to-noise ratios (SNRs). With a high free spectral range, GRR lasers are also widely applied for frequency metrology.[2] With much enhanced nonlinear signal while maintaining the viability in a live objects, GRR femtosecond lasers allow the realization of *in vivo* real-time second harmonic generation (SHG) microscopy.[6] Although GRR femtosecond lasers have diversified applications, no high-power blue or ultraviolet (UV) sources exist at such high repetition rate, which has particular importance for the study of physical science. In the tests of quantum electrodynamics theory, an intense GRR UV source is required to perform two-photon resonance of hydrogen 1*S*-2*S* transition with better accuracy and SNR.[7] In the study of femtosecond-laser-excited coherent acoustic phonons, intense GRR blue source can reach the acoustic phonon decay rate ($<1/500$ ps), thus allowing the generation of sustained acoustic phonon oscillations.[8–10] To generate GRR blue or UV pulses, a straightforward method is frequency doubling a GRR Ti:sapphire laser. But due to its low pulse energy, the yield of the nonlinear SHG process is too low for efficient energy transfer. For example, with the same average power and other parameters, an increase in the femtosecond laser repetition rate from 80 MHz to 2 GHz will decrease the SHG conversion efficiency by 25 times. Many methods have been developed to achieve higher conversion efficiency without degrading the phase-matching bandwidth.[11–15] A cavity-dump method gives a one-shot release of all energy stored in the laser cavity,[12] thus providing much higher peak power for more efficient energy conversion. With similar consideration of higher peak powers, intra-cavity frequency doubling method moves the SHG crystals into the cavity.[13,14] But these two methods lower the laser repetition rate and introduce nonlinear loss in the cavity. To meet the requirements, building an external resonant cavity for the enhancement of SHG is one possible method.[15–17] In this letter, we demonstrate a high power femtosecond blue source at 2 GHz repetition rate. This was achieved by a resonant cavity matched to a 2 GHz repetition-rate Ti:sapphire laser.

In Fig. 1 we show a schematic diagram of our experimental setup. The fundamental beam came from a 2 GHz repetition-rate femtosecond Ti:sapphire laser[4] (GigaOptics, GigaJet 30), whose center wavelength was 816 nm. The typical output power was 840 mW with 34 nm bandwidth and 80 fs pulse width. After two mirrors, the beam path and the polarization were both horizontal to the optical table. Then a pair of lenses, L1 and L2, was used to manipulate the *q*-parameter of the fundamental beam before the resonant cavity. The fundamental power reaching the nonlinear crystal was enhanced with a four-mirror ring cavity consisting of two flat mirrors, M1 and M2, and two curve mirrors, C1 and C2. M1 was a coupling mirror with partial reflectivity ($R=80\%$), whereas M2, C1, and C2 were coated for high reflectivity at the fundamental wavelength. The radius of curvature of C1 and C2 was 2.5 cm, and the circulating beam inside the ring cavity was focused between them. At the focus between C1 and C2, a Brewster cut lithium triborate (LBO) crystal was chosen as the SHG material because of its small walk-off angle and large nonlinear coefficient.[18] The thickness of the LBO crystal was 0.5 mm and the astigmatism compensation angle of curve mirrors was approximately 11° based on a calculation.[19] The generated SHG was output

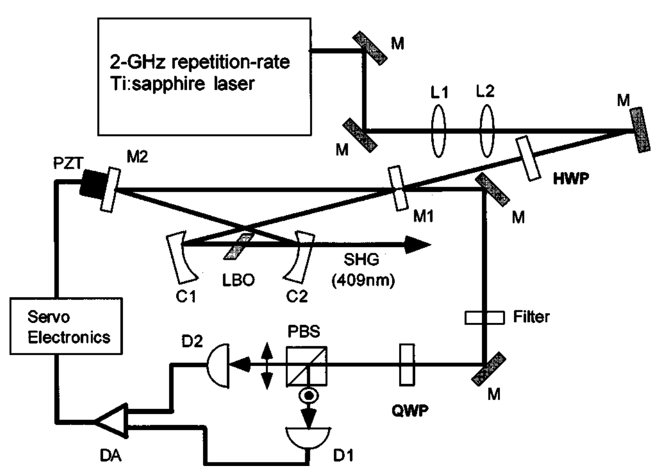

FIG. 1. Schematic diagram of the experimental setup. M: folding mirror; L1, L2, mode-matching lenses; HWP, half-wave plate; M1, input coupler; M2, PZT driven mirror; C1, C2, concave mirrors; F, neutral density filter (ND=4); QWP, quarter-wave plate; PBS, polarization beam splitter; D1, D2, photodiodes; DA, differential amplifier.

[a)]Author to whom correspondence should be addressed; electronic mail: sun@cc.ee.ntu.edu.tw

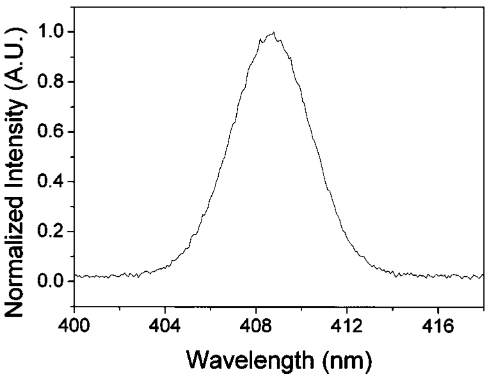

FIG. 2. Spectrum of the generated SHG from the resonant cavity.

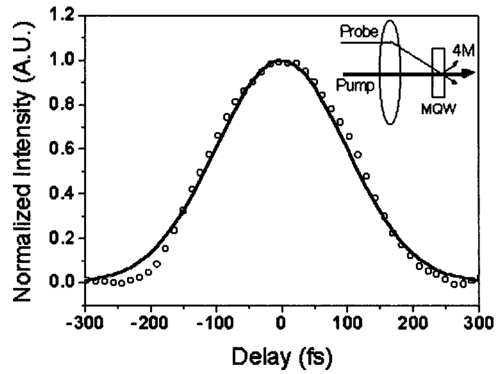

FIG. 3. Third-order correlation trace measured by nondegenerate four-wave mixing (open circles). Solid line is a Gaussian fit. Inset shows a schematic plot of the four-wave mixing setup. 4M: four-wave mixing signal.

from C2, whose transmission was 66% at 409 nm. To achieve better transverse mode matching, the length of the resonant cavity (45 cm) is chosen to be three times that of the pumping Ti:sapphire laser (15 cm). This ratio is kept with the aid of the Hänsch–Couillaud method,[15] which employs depolarization signals as feedback error signals. Following this technique, the LBO also served as a polarization-limiting element. In order to make the feedback system sensitive to the change of cavity length,[15] we turned the polarization by a half-wave plate HWP and reduced the effective input power to 740 mW. Then the combined multiple-reflection output was directed into a depolarization system, which was constructed by a quarter-wave plate QWP, a polarization beam splitter PBS, and a pair of detectors D1 and D2. The error signals were generated with a differential amplifier and feedback to a piezoelectric transducer (PZT) driver through servo electronics. Then the driver applied voltage on the PZT (300 kHz resonant frequency) to move M2 and formed a closed loop with 500 Hz unit-gain bandwidth. We changed the open loop gain and the low-pass frequency of the servo electronics in order to perform proportional-integral control. When the control system operates in the stable region, the mirror M2 can dynamically compensate the thermal and mechanical disturbance on the resonant cavity system and follow the disturbance in the laser system. With the experimental setup described above, we can estimate the conversion efficiency ε by the equation[20]

$$\sqrt{\varepsilon} = \frac{4T1(E_{\mathrm{NL}}P_1)^{1/2}}{\{2-(1-T1)^{1/2}[2-L-(\varepsilon E_{\mathrm{NL}}P_1)^{1/2}]\}^2}, \tag{1}$$

where $T1$ is the transmission of input coupler, P_1 is the input fundamental power, L is the linear loss exclusive of $T1$, and E_{NL} is the effective single-pass nonlinear conversion efficiency based on average power. In our case, $T1=0.2$, $P_1=0.74$, $L=0.05$. When we removed the coupler and the half-wave plate, the resulted average blue power was 1.9 mW, indicating $E_{\mathrm{NL}}=2.74\times10^{-3}\ \mathrm{W}^{-1}$. With these parameters, we can solve Eq. (1) and expect our scheme to greatly increase the SHG conversion efficiency up to 22.7%.

With the servo loop turned on, 150 mW averaged SHG power was obtained right after the LBO crystal. The available output power after the low transmission output coupler was 100 mW. The power fluctuation is less than 10% for a period of 5 h. The achieved high conversion efficiency (20%) agrees well with the estimated value. The spectrum of the resonant SHG output is centered at ~409 nm with a 4 nm bandwidth (Fig. 2). The SHG bandwidth is determined by the phase matching bandwidth and the dispersion of the LBO crystal. At the operation wavelength of 409 nm, there exists no phase matching condition for available SHG crystals to perform an SHG-type autocorrelation measurement.[21] In order to measure the pulse width of the generated blue pulses, we employed an alternate method by using a four-wave mixing based third-order correlator[22] with an InGaN/GaN quantum well sample.[10] This setup is similar to a pump-probe measurement system,[10] where pump provides two photons and probe gives one photon with a controlled-time delay (inset of Fig. 3). Taking advantage of the strong $\chi^{(3)}$ in the InGaN/GaN quantum well sample with an ultrashort dephasing time at room temperature,[23] we can measure the nondegenerate four-wave mixing signal also at 409 nm on its unique direction. Based on a Gaussian fit, the resulted third-order correlation trace shows a 248 fs full width at half maximum (FWHM) (Fig. 3), corresponding to a 200 fs pulse width. The excellent fitting supports the fact that the dephasing time is much shorter than 200 fs. Because C2 and the collimation optics introduced dispersion on the pulses, the original pulse width should be shorter than this value. To obtain much shorter SHG pulse width, much thinner LBO crystal should be employed to provide enough phase matching bandwidth and accurate dispersion compensation, before pulse entering the resonant cavity and inside the resonant cavity might be required.

In conclusion, based on an external resonant cavity, we have realized a high-power femtosecond blue source with 2 GHz repetition rate. Pumped by 740 mW fundamental power, we can obtain 150 mW averaged SHG power. The 20% conversion efficiency is closed to the estimation by the theory. The operation wavelength is centered ~409 nm with 4 nm FWHM. With the help of nondegenerated four-wave mixing on the InGaN/GaN quantum well sample, the measured third-order correlation showed 200 fs pulse width.

This project is sponsored by the National Science Council of Taiwan, Republic of China, under NSC 92-2112-M-002-044.

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