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Second Harmonic Generation and Frequency Stabilization of a Diode Laser Using an External Ring Resonator

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The second harmonic light of an 842 nm diode laser was generated from a $KNbO_3$ crystal in an external ring resonator. The power of the second harmonic light was about 0.8 mW at an input fundamental power of 87 mW. The laser frequency was stabilized to the resonance frequency of the ring resonator, and the frequency fluctuation was measured as about 3 MHz.

Diode lasers are used widely for light sources in many fields such as optical communication, high resolution spectroscopy, laser cooling of atoms, and optically pumped atomic clocks. Various techniques have been developed to reduce the linewidth of diode lasers [1–3]. Recently, using nonlinear optical processes such as second harmonic generation (SHG), laser applications have been expanded to the ultraviolet and blue spectral region [4–14].

Direct SHG of a diode laser is limited by the low power output because SHG shows quadratic behavior to a fundamental power. Using an external enhancement resonator, in which the fundamental power is built up, can enhance SHG conversion efficiency of a diode laser. Dixon et al. [8] generated 0.215 mW of 432 nm second harmonic (SH) light at a fundamental power of 12.4 mW in a Fabry-Perot resonator using a $KNbO_3$ crystal, and Hemmerrich et al. [9] generated 6.7 mW of 421 nm SH light at a fundamental power of 62 mW in a ring resonator.

In this study, we employed a bow-tie ring resonator to enhance fundamental power and produce narrow-linewidth blue light for high resolution spectroscopy. We used a $KNbO_3$ crystal for SHG and stabilized the diode laser frequency to the resonance frequency of the ring resonator by an optical feedback technique. We put the $KNbO_3$ crystal in a vacuum chamber to prevent it from being frosted as the operating temperature was below 0 °C. For easier handling, we put only the crystal in the chamber rather than the whole system.

Fig. 1 depicts the schematic for the SHG experiment using a bow-tie ring resonator. M3 and M4 are concave mirrors of radius 75 mm. M4 has a reflectivity of about 99.9 % at the fundamental light frequency and a transparency of about 85 % at the generated SH light frequency. The input mirror M1 has a reflectivity of about 97 % and the others have reflectivities of above 99.9 % at the fundamental light. The optical path between the two concave mirrors is d = 81.6 mm and the optical path of a round trip is x = 573 mm so that the beam waist at the center between the two concave mirrors is ω_0 = 29.7 mm.

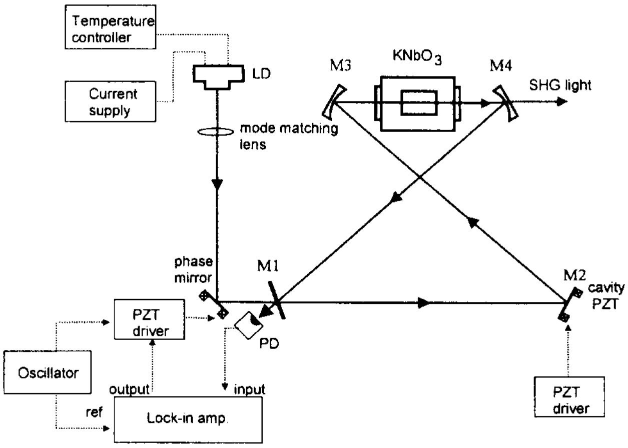

FIG. 1. Experimental setup. M1, M2: planar mirrors, M3, M4: concave mirrors (R=75 mm), PD: photodiode.

A $KNbO_3$ crystal (Virgo Optics, Port Richey, Florida) was prepared with dimensions of 5 × 5 × 10 mm, with the longer dimension parallel to the a-axis of the crystal. The $KNbO_3$ crystal was located in a vacuum chamber because it is hygroscopic. The windows and the crystal facets were coated with anti-reflection material for both the fundamental and SH light frequencies. The polarization of the fundamental light was parallel to the b-axis of the crystal and the beam propagated along the a-axis. For the noncritical phase matched (NCPM) SHG, the crystal was temperature-controlled by a 3-step thermoelectric cooler in the range from room temperature to - 35 °C within ± 0.1 °C.

The frequency of the diode laser was stabilized to the resonance frequency of the ring resonator by an opti-

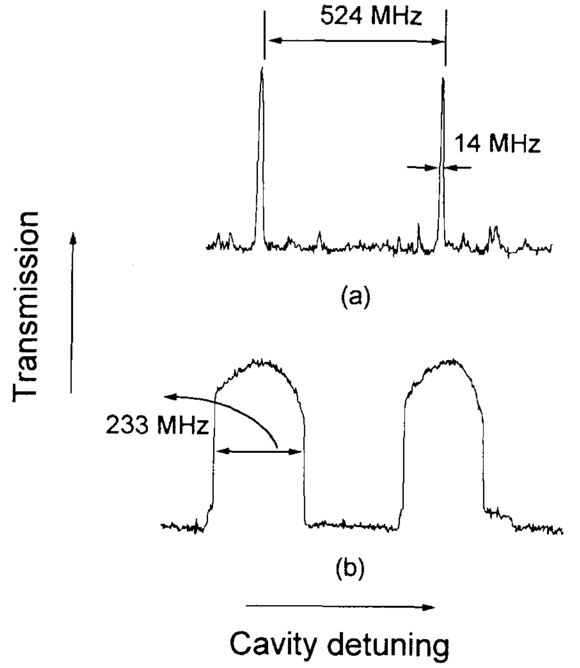

FIG. 2. The transmission curves of the ring resonator, when KNbO3 crystal is (a) absent and (b) present in the resonator.

cal feedback technique. The counterpropagating fundamental light, which was generated from scattering due to imperfections of the crystal surfaces, was fed to the diode laser. The phase of the feedback light was adjusted by a phase piezoelectric transducer (PZT) and the output frequency was tuned by a cavity PZT.

The transmission curves of the ring resonator are shown in Fig. 2. Fig. 2 (a) is the transmission curve when the KNbO3 crystal is absent from the ring resonator. In this case, there is no counterpropagating light. The free spectral range (FSR) of the resonator is 524 MHz and the finesse is about 35. Fig. 2 (b) is the transmission curve when the crystal is present in the resonator. It shows that the laser frequency is locked to the resonance frequency of the resonator. The locking range is about 233 MHz. We observed that the locking range was broadened as both the phase PZT and the current of the diode laser were synchronously scanned with the cavity PZT.

Fig. 3 shows the temperature-tuned NCPM curve of the type I SHG at the fundamental light frequency of 842 nm when the laser beam propagates along the crystal a-axis. The solid curve in Fig. 3 is a theoretical fit based on the sinc function of $(sin\xi/\xi)^2$, where $\xi = \Delta kL/2$ and L is the length of the crystal. $\xi = 0$ signifies the PM condition [15].

The phase mismatch is

$$\Delta k = \frac{2\omega}{c}[n_c^{2\omega}(T) - n_b^{\omega}(T)], \tag{1}$$

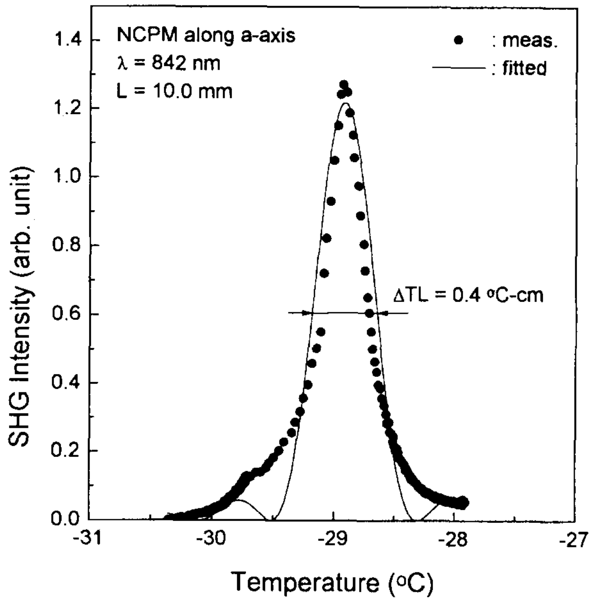

FIG. 3. The temperature-tuned phase-matching curve.

where $n_c^{2\omega}(T)$ and $n_b^{\omega}(T)$ [16,17] are the refractive index of the fundamental and SH light of the crystal at the crystal temperature T, respectively. The measured NCPM temperature and temperature bandwidth of the KNbO3 crystal at 842 nm was about - 29 °C and ΔTL = 0.4 °C − cm, respectively.

The generated SH power in a resonator can be expressed as

$$P_{SH} = \frac{2\omega^2 d_{eff}^2 kL}{\pi n^3 \epsilon_0 c^3} h_o(\zeta) P_c^2, \tag{2}$$

where P_{SH} and P_c are the generated SH power and circulating power in the resonator, respectively [11,18]. The circulating power is

$$P_c = M\frac{t_1}{(1-\sqrt{r_1 r_m})^2}P_1, \tag{3}$$

where P_1 is an input fundamental power, M is a mode-match parameter, t_1 and r_1 the transmissivity and reflectivity of the input mirror, respectively, and r_m is the resonator reflectance parameter [11]. This parameter is

$$r_m = r_2 r_3 r_4 t t_{SH}, \tag{4}$$

where r_2, r_3, and r_4 are the reflectivity of the M2, M3, and M4 mirrors in Fig. 1, respectively, and t is the transmissivity of the crystal. t_{SH} is the loss of fundamental light by SHG, and can be approximated by 1 when SHG conversion is low enough to neglect depletion of the fundamental power.

Since the crystal temperature is lowered to about - 29 °C for the NCPM SHG at 842 nm in our experiment, and moreover a KNbO3 crystal is hygroscopic, the crystal has to be separated from air to prevent frosting. Instead of putting the whole experimental

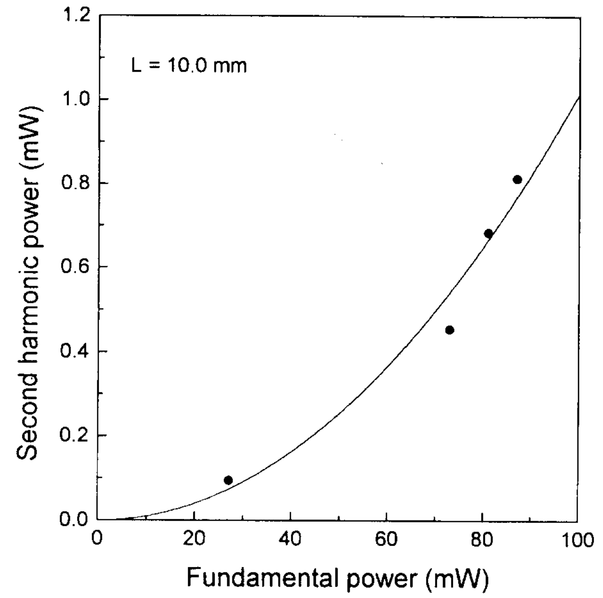

FIG. 4. Second harmonic power as a function of fundamental power.

system into a vacuum chamber, we put only the crystal into a vacuum chamber so as to handle it more easily. Therefore, the scattering loss by the windows of the vacuum chamber should be contained in the calculation of t. The decrease of t in the Eq.(4) results in lowering SHG conversion efficiency.

The output SH power versus the input fundamental power is shown in Fig. 4. About 0.8 mW of SH light was obtained at the input fundamental power of 87 mW. The conversion efficiency was thus about 1 %. SHG conversion efficiency was lower than those reported by others [8,9] due to the reduction of circulating power.

The frequency of a diode laser should be stabilized for the application of high resolution spectroscopy, since the output frequency is sensitive to the variations of the temperature and current of the diode laser. The frequency fluctuation of the diode laser, when the laser frequency was stabilized to the resonance frequency of the resonator, is shown in Fig. 5. The frequency fluctuation was monitored using a Fabry-Perot interferometer with a resolution of about 1 MHz. As shown in the figure, the fluctuation is about 3 MHz. Although there was some frequency drift due to the variation of the ambient temperature, we could lock the laser frequency to the resonator for over one day.

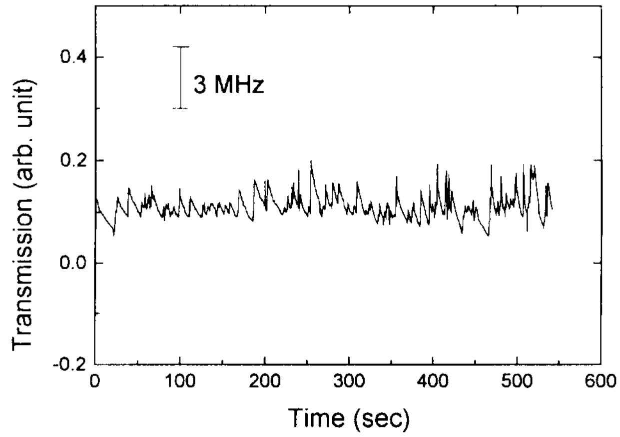

FIG. 5. The Frequency fluctuation of the diode laser locked to the resonance frequency of the ring resonator.

In summary, we have generated SH light of 421 nm from a diode laser using an external ring resonator. The measured NCPM temperature was about - 29 °C and SHG conversion efficiency was about 1 %. We also achieved frequency stabilization of the diode laser by optical feedback and confirmed that the frequency fluctuation was about 3 MHz. We expect that this tunable SH light (421 nm) can be used as a light source for high resolution spectroscopy. We are now progressing in the high resolution spectroscopy of the transitions between $5^2S_{1/2}$ and $6^2P_{3/2}$ levels of trapped rubidium atoms [19], whose resonance wavelength is 421 nm.

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