Narrow linewidth 578 nm light generation using frequency-doubling with a waveguide PPLN pumped by an optical injection-locked diode laser

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Abstract: This study demonstrates 578 nm yellow light generation with a narrow linewidth using a waveguide periodically poled lithium niboate (PPLN) and an optical injection-locked diode laser. The frequency of an external cavity diode laser used as a master laser operating at 1156 nm in optical injection-locking mode was locked into a high-finesse cavity with the Pound-Drever-Hall technique, which results in a linewidth reduction of the master laser. The linewidth of the master laser was estimated to be approximately 1.6 kHz. In an effort to amplify the optical power, a distributed feed-back laser was phase-locked to the master laser by an optical injection-locking technique. A waveguide PPLN was used for second harmonic generation. Frequency-doubled yellow light of approximately 2.4 mW was obtained with a conversion efficiency of 6.5%.

OCIS codes: (140.2020) Diode lasers; (140.3425) Laser stabilization; (140.3515) Lasers, frequency doubled; (140.3520) Lasers, injection-locked.

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1. Introduction

Recently there has been a specific need for yellow light in the field of optical frequency metrology [1–3]. This type of light can be used to prove the clock transition of ytterbium (Yb) atoms near 578 nm with a narrow natural linewidth [1–3]. In an optical clock, the motional state of ultra-cold Yb atoms are squeezed into a motional state in a specially designed optical lattice to provide surroundings optimized for measuring the center frequency of the transition with a fractional uncertainty of less than 10^{-16} [4]. In this type of high-resolution spectroscopy, a yellow light laser near 578 nm with an ultra-narrow linewidth and high stability is essential.

Conventional dye lasers or copper vapor lasers have been used for this wavelength because it is very difficult to generate yellow light directly from solid-state gain media [1–3]. The recent development of nonlinear optics technology for second harmonic generation (SHG) [5–15], sum frequency generation (SFG) [16–18], or difference frequency generation (DFG), optical parametric oscillator (OPO) technique [19,20] has made it easier to obtain coherent yellow light with a solid-state laser system in which the linewidth of the laser

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frequency can be more easily narrowed. Hence, various approaches have been tested and a number of successful methods have been reported [5–22]. Recently, the optical clock transition line of lattice-based Yb atoms was probed with a 578 nm-yellow light laser via SFG [23–25]. This method has value in that there are many sets of available combinations of frequencies of well-developed high-power solid-state lasers, including Nd:YAG lasers, diode lasers and fiber lasers. As this system uses the well-developed Nd:YAG laser system with a 1 kHz linewidth and a high level of power, the narrowing of the linewidth and the generation of sufficient power for precision spectroscopy are easily achieved.

In principle, a simpler means involves the frequency-doubling of a diode laser system [26]. This is feasible due to the compact size and relatively low cost of this system. However, this method is associated with difficulty in terms of finding an adequate high-power laser system operating at 1156 nm. Recently, diode lasers were developed for this IR region. Additionally, Nevsky et al. used a Littrow-type external cavity quantum dot diode laser with a wavelength of 1156 nm and an output of 200 mW [27]. They obtained light at nearly 3.5 mw-578 nm with the help of a buildup cavity and a PPLN. Although high-power quantum dot lasers remain unavailable commercially in the near-infrared range, this method is the most compact and cost-effective for a laser system compared to the aforementioned system.

This paper demonstrates another type of SHG method that direct generates 578 nm light with a waveguide periodically poled lithium niobate (WG-PPLN) nonlinear crystal pumped by an optical injection-locked 1156 nm diode laser. Littrow-ECDL at a low power (10 mW) was used as master laser, and the laser was locked to a high-finesse cavity to reduce the linewidth. Low power laser diode has merits that build-up intensity inside cavity of ECDL is not so high to damage the gain medium so that needs less caution to handle and insure long lifetime. But it needs one more step inconveniently, i.e. amplifying the output for SHG. In order to amplify the ECDL output for SGH, an injection-locking method with a distributed feed-back (DFB) laser was utilized, as it can be very tightly locked at a low seeding power. The advantage of this approach is its simplicity and relatively low cost. Moreover, the ECDL, DFB laser, and WG-PPLN used in this experiment are commercially available. This is the first known report of the use of an optical injection-locking technique for coherent yellow light emission near 578 nm.

2. Experimental setup

For coherent yellow light generation near 578 nm, the experimental setup shown in Fig. 1 was used. The upper part of Fig. 1 represents the experimental setup for the linewidth reduction of a master ECDL via stabilization of the master laser into a high-finesse cavity; the lower part shows the frequency-doubling of a DFB laser with a WG-PPLN. The maser ECDL uses a Littrow configuration (TOPICA model DL100), and the lasing frequency can be tuned by controlling the grating angle and current injected into the laser diode. The tuning range of the laser is approximately 1140~1160 nm with an output power of 10 mW. It also exhibits a free running linewidth of about 200 kHz. The high-finesse optical cavity was fabricated to reduce the linewidth of the ECDL further. A cavity spacer was created with a low-expansion material. One of the cavity mirrors was glued onto one end of the polished surface of the cavity spacer and a PZT (piezo electric transducer) tube was placed between the order cavity mirror and the cavity spacer to control the length of the optical cavity. The optical cavity was horizontally mounted inside an air-tightened enclosure with two AR-coated windows.

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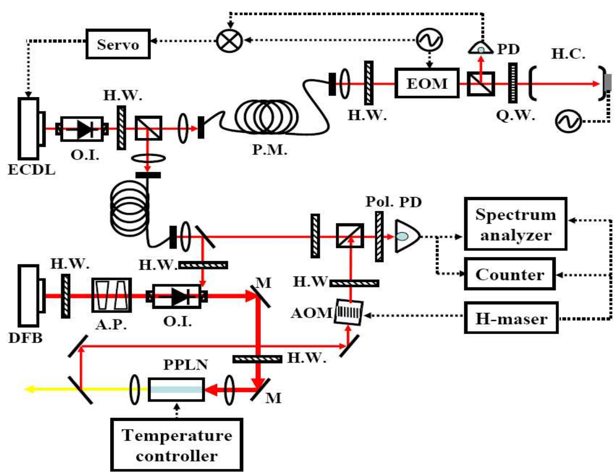

Fig. 1. (Color online) Experimental diagram of coherent 578 nm yellow light generation. DFB: distributed feed-back laser A.P.: anamorphic prism pairs, O.I.: optical isolator, ECDL: external cavity diode laser, H.C.: high-finesse cavity, P.M.: polarization maintaining fiber, M: mirror, IF: interference filter, H.W.: half-wave plate, Q.W.: quarter-wave plate, P.O.: polarizer, PD: photo diode, PPLN: waveguide periodically poled lithium niobate.

The finesse of the cavity was approximately 10,000 at 1156 nm. The ECDL was stabilized in the high-finesse cavity by the Pound-Drever-Hall (PDH) method [28]. After the optical isolator, the output of the ECDL was divided into two by a polarization beam splitter and coupled to two polarization-maintaining single-mode fibers for mode filtering. A part of the fiber output was phase-modulated at 13 MHz with an electro-optical modulator (EOM), and close to 10 μW of optical power entered the high-finesse cavity. The PDH error signal was extracted by mixing the signal reflected from the cavity with the modulation frequency in a passive phase detector. The amplified error signal was sent to a loop filter, where the signal was divided into two parts. The first controlled the diode laser current, and the second controlled the PZT.

A DFB laser (Nanoplus, 1157 nm DFB laser) was used as a slave laser to boost the master laser power. The DFB laser was phase-locked to the master laser by the optical injection-locking technique. Using an operating current above 250 mA, the maximum output power of the DFB laser was close to 47 mW near 1156 nm. Nearly 36.7 mW of the output power was available in front of the WG-PPLN due to the non-perfect laser beam profile and the insertion loss of the optical components. Generally, the locking range in the injection-locking technique is dependent on the incident optical density and polarization, and on the mode-matching condition. Therefore, the entering power and polarization was adjusted by means of two half-wave plates. To monitor the injection locked condition, a heterodyne beat signal between the injection-locked DFB laser and the ECDL, where the ECDL was shifted by an acousto-optic modulator (AOM), was measured with an RF spectrum analyzer. Frequency-doubling of the injection-locked DFB laser was performed by a wave-guide PPLN. The WG-PPLN crystal was 0.5-mm thick and 20-mm in length. The crystal end faces were anti-reflection-coated at 1156 nm and 578 nm. The crystal was placed in a copper oven and was temperature controlled for optimum phase matching.

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3. Experimental results

3.1 Linewidth and reference cavity

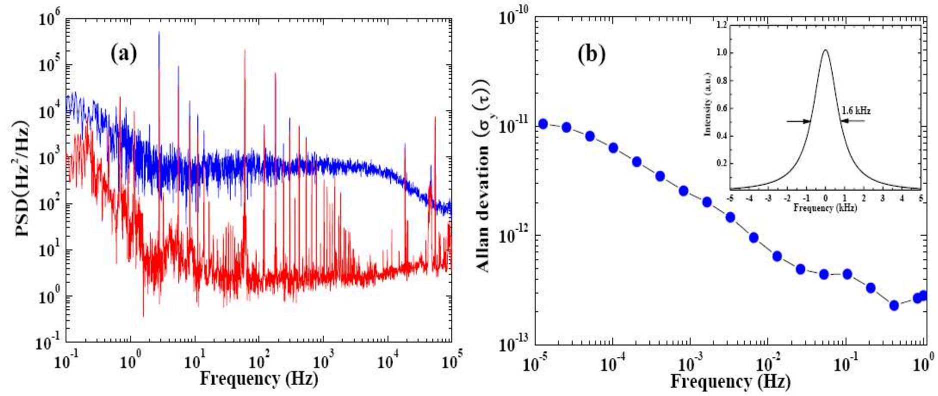

Fig. 2. (Color online) (a) Spectral density of frequency fluctuations using a stabilized PHD error signal (blue curve) and the noise limit of the measurement system (red curve) (b) The stability of the stabilized ECDL using the Allan deviation, which was calculated by the power spectrum density of (a).

The linewidth of a stabilized laser can be measured with various techniques, such as the power spectral density (PSD), the self-heterodyne (or self-homodyne) technique, and by the beat signal between two independent lasers in which both lasers have similar performances or one laser has a narrower linewidth than that of the other laser [27–31]. Here, the PSD method was used to estimate the linewidth of the stabilized ECDL. The slope of the PHD signal near the resonant frequency was measured at about 7.2 MHz/V. The FM noise power spectral density ($S_f(f)$) was measured by utilizing a fast-Fourier-transform (FFT) spectrum analyzer, as shown in Fig. 2 (a). The blue curve of Fig. 2(a) corresponds to the PSD of the laser that was frequency-locked, and the red curve indicates the FM noise limit in the measurement system. The blue curve at 10 Hz $< f <$ 10 kHz was composed of a white frequency noise (f^{0}), the noise level of which corresponds to the phase noise with a PSD proportional to f^{-2} and the linewidth of the Lorentzian field power spectrum. The white noise level was approximately 540 Hz^2/Hz, which corresponds to an inherent linewidth of $\pi\, S_f(f)$ = 1.7 kHz (full widths at half-maximum) [30]. The flicker noise (f^{-1} noise) can also be seen at $f <$ 10 Hz in the blue curve.

The frequency stability of the stabilized ECDL in the time domain was estimated with the Allan variance ($\sigma_y^2(t)$), as shown in Fig. 2(b). The blue circular curve in Fig. 2(b) corresponds to the blue curve in Fig. 2(a). The Allan variance was derived from the PSD of Fig. 2(a) and the equation $\sigma_y^2(\tau) = (2/v_0)\int df\, S_f(f) sin^4(\pi f\tau)/(\pi f\tau)^2$, in which f and τ are the Fourier frequency and the averaging time, respectively, and v_0 is the carrier frequency of the laser [31]. The Allan deviation at an averaging time of 1 s was found to be 2.8 parts in 10^{13} and was determined as inversely proportional to $\tau^{1/2}$, which implies that the stability depends on the white frequency noise. This result is feasible because the ECDL was stabilized in a high-finesse cavity with the PDH technique.

To estimate the laser linewidth, the field spectrum of the laser $I(v)$ was numerically calculated using the Allan deviation data of Fig. 2(b) and the equation $I(v) = 4\, Re[\int exp[2\pi\, i(v-v_0)\tau] \times exp[-2\, (\pi\tau)^2\sigma_y^2(\tau)]d\tau$, where Re represents the real part of the complex number, v_0 is the carrier frequency of the laser, and $\sigma_y^2(\tau)$ is the Allan variance [31]. The result is shown by the solid curve in the insert on the right in Fig. 2(b); the Lorentzian linewidth of the laser was estimated at about 1.6 kHz, which agrees well with the above PSD results. In a future work, the authors plan to use an optical cavity with a finesse value of 200,000 to obtain a stabilized laser with a sub-Hz linewidth to probe the clock transition lines in neutral ytterbium [32].

The mode-hop-free frequency tuning range of the stabilized ECDL through control of the high-finesse cavity length is important for many applications in high-resolution spectroscopy.

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One study applied a triangle voltage signal to PZT in a high-finesse cavity and then measured the frequency change of the ECDL at near 1157 nm. The result was approximately 8.8 MHz/V. When the voltage is controlled from 1 to 120 V, the measured tuning frequency range exceeds over 1 GHz.

3.2 Injection-locking and frequency-doubling

A DFB laser was used as a slave laser for optical injection locking because it has a large continuous tuning range and a mode-hop-free scan range.

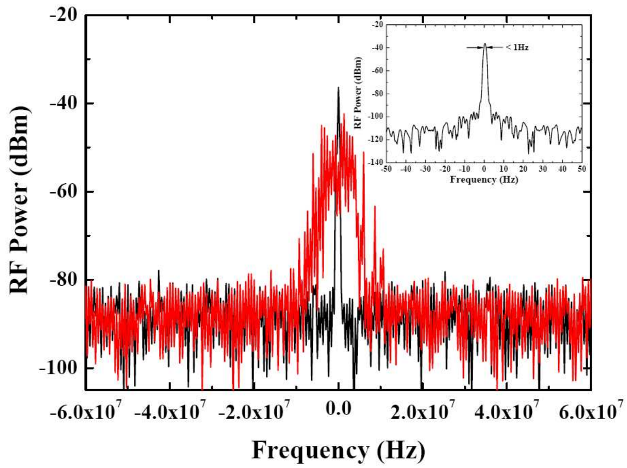

Fig. 3. (Color online) Heterodyne beat signal between the ECDL and before (red line) and after (black line) the injection-locked DFB laser with a resolution bandwidth of 300 kHz. The beat spectrum of the 1 Hz resolution bandwidth is shown in the inset on the right.

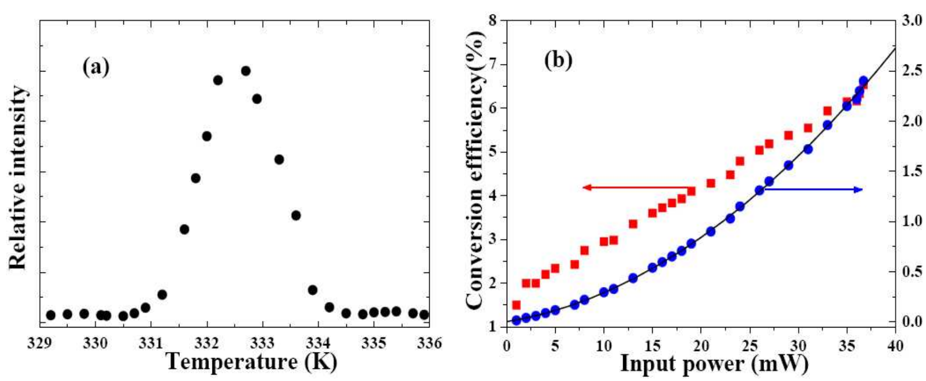

Fig. 4. (Color online) (a) Output power of second harmonic generation on the WG-PPLN as function of the temperature. (b) The output power of yellow light (blue circle) and the conversion efficiency (red square) as a function of the pump power at 1156 nm.

In order to investigate the characteristics of the optical injection locked slave laser, the heterodyne beat signal was measured between the maser laser and the slave laser with a 300 kHz resolution bandwidth, as shown in Fig. 3, in which the master frequency was shifted by 80 MHz with an AOM. An 80 MHz signal of a RF frequency synthesizer to drive the AOM was referenced to the hydrogen maser (H-maser) with frequency stability of 2×10^{-13} at 1 s. The center frequency of the beat signal was identical to the driving frequency of the AOM. The spectral width of the beat signal was measured at about 5 MHz before injection-locking (red line) and at less than 1 Hz (black line) with the limited resolution of the RF spectrum analyzer after injection-locking (right hand insert). The narrow spectral width indicates that the slave laser was optically injection-locked by the stabilized ECDL. In addition, the stability

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of the beat signal was measured and calculated using a high-resolution frequency counter referenced to the H-maser. The Allan deviation for a sampling time of 1 s was 5.5×10^{-16} and had a 1/t dependence, which indicates that the slave laser was phase-locked to the master laser. When the optical power of about 53 μW was entered into slave laser, the locking range was measured at approximately 200 MHz with the RF spectrum analyzer.

The efficiency of frequency-doubling in the WG-PPLN is sensitive to phase-matching conditions, which depends on temperature of the nonlinear crystal. Figure 4(a) shows the change in the yellow light power when the temperature of the crystal was changed from 328 to 337 K. The best phase-matching temperature was 332.7 K, as determined near 578 nm. Figure 4(b) shows the power conversion efficiency of the second harmonic generation (SHG) as a function of the pump power. The maximum output power was found to be nearly 2.4 mW near 578 nm; the pump power was about 36.7 mW at 1156 nm and the corresponding conversion efficiency was close to 6.5%. The black dashed curve in Fig. 4(b) was calculated under polynomial fitting, which indicates that the fundamental wave depletion effects were not yet present at these power levels. Thus, if a high-power diode laser is supplied, the yellow light power will be increased to over 10 mW with less than 85 mW of pumping power.

4. Conclusion

This study proposed and demonstrated yellow light generation at near 578 nm via the frequency doubling of a DFB diode laser phase-locked to an ECDL using an optical injection technique. The ECDL was frequency-stabilized and the linewidth was reduced by locking it into a high-finesse cavity with a finesse value of 10,000. The linewidth of the stabilized ECDL was estimated to be 1.6 kHz. With the optical injection-locking technique, the entire output power of the slave laser could be used for yellow light generation at 578 nm without any loss of power. This compact and user-friendly system was realized with a WG-PPLN. The maximum yellow light power and conversion efficiency were approximately 2.4 mW and 6.5%, respectively, which is sufficient power for high-resolution spectroscopy and biomedical investigations. The proposed configuration can be used with various application tools, such as probing optical lattice clocks, high-resolution spectroscopy, and in the biophysics field because due to its simple configuration. Moreover, it is compact and has a relatively low cost compared to previous yellow light generation schemes. In the near future, after further reduction of the laser linewidth with an ultra-high-finesse optical cavity, this laser system will be used as a probe laser of a Yb optical lattice clock.

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