Low intensity noise and narrow line-width diode laser light at 540nm

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Abstract. We present a convenient method to generate high quality single-frequency green light at a wavelength of 540 nm. It consists of a noise suppressed external cavity diode laser (ECDL) at a wavelength of 1080 nm by optical filtering and resonant optical feedback, and a frequency doubling of the fundamental light with an a-cut KTP crystal. Highly efficient conversion is realized by type II non-critical phase matching. A stable single-frequency operation with a maximum power of about 20 mW is performed for more than three hours. Both the intensity noise and line-width reach the level of a monolithic nonplanar ring laser, which is well-known for its extraordinarily narrow linewidth and extremely low noise among available single-frequency operating lasers.

Keywords: Intensity noise, linewidth, optical filtering, and resonant optical feedback

(Some figures may appear in colour only in the online journal)

1. Introduction

Extra-cavity diode lasers (ECDLs) are very important light sources in modern physics experiments such as laser cooling and trapping, high-resolution spectroscopy, and frequency standard, owing to their compactness, convenient operation, effective cost and large spectrum coverage [1]. To satisfy requirements of high precision optical-experiments, linewidth and intensity noise of light sources are important specific performances [2, 3]. Applications in optical clocks, frequency metrology, quantum optics, and high precision measurement require light with passive laser linewidth at the level of kHz and noise at the shot noise level (SNL). The other specifics also include different wavelength regimes and wide tunability. ECDLs are the best candidates for such applications, since they satisfy most of the requirements except for specifics of linewidth and noise [4, 5, 6, 7, 8]. Hence, it is very important to further improve the quality of linewidth and noise for extending the application of ECDL [2, 3, 9]. Noise suppression and linewidth reduction of diode lasers have been investigated thoroughly in both theory and experiment during the past 30 years [10]. A common method is optical feedback by an additional grating. It significantly suppressed the intensity noise and even reduced below the SNL. However, the residual phase noises, which is related to linewidth of laser light, are generally more than 30 dB above the SNL. This huge phase noise hinders a broader utilization of this type of light source in experiments which are sensitive to phase, such as phase-sensitive optical amplifier. Furthermore, the excess phase noise always converts into intensity noise when light propagates in a dispersion medium. Hence, it also limits the accuracy of locking the laser frequency to an atomic or molecular resonance lines [11].

On the other hand, lasers with the stable output frequency are used as a frequency standard used in a number of high precision optical tests and measurements. Usually, atomic or molecular transition lines are desirable frequency standard references in such a system [12]. The realization of laser stabilization on atomic or molecular transition line requires a laser with a power of few tens of milliwatts, narrow-linewidth and low noise. To date, the monolithic nonplanar ring laser is the best candidate for such applications. For instance, relative frequency stability for a iodine-stabilized Nd:YAG laser, which is used as a second-order optical frequency standard, reaches better than 10^{-14} at 1 s [13, 14]. Although it is possible to stabilize a diode laser frequency to the above-mentioned frequency reference, the stability is usually two or three-order worse than that of monolithic nonplanar ring laser [17]. The unique way to improve the stability is to further reduce noise of diode laser. In recent years, it was reported that both intensity noise and phase noise can be reduced to SNL by a method of optical filtering and resonant optical feedback [9, 15, 16]. From the viewpoint of matching atomic or molecular resonant lines, frequency conversion is also a most important technique in many cases.

In this letter, we report on the realization of 20 mW green light by frequency doubling a noise-suppressed ECDL at 1080 nm. It can be extremely useful for iodine molecular spectroscopy around 540 nm. In this range, the spectroscopy of iodine is not investigated in detail since it is a challenge to operate a laser at this wavelength. Both the intensity noise and line-width have reached the level of a monolithic nonplanar ring laser, which is well-known for its extraordinarily narrow linewidth and extremely low noise among available single-frequency operating lasers. Our method gives a new way to prepare ECDLs for extending their applications.

2. Experimental setup

The experimental setup is illustrated in Fig. 1. The light source is a commercial ECDL in Littrow configuration. Its maximum output power is 150 mW at the wavelength of 1080 nm. Usually, the spatial mode of ECDL is not perfectly TEM_{00} (elliptical with ratio of 3:2). It is known that the ellipticity will degrade the mode coupling factor to a filter cavity; the beam is re-circularized with a prism pair. The circularized beam is

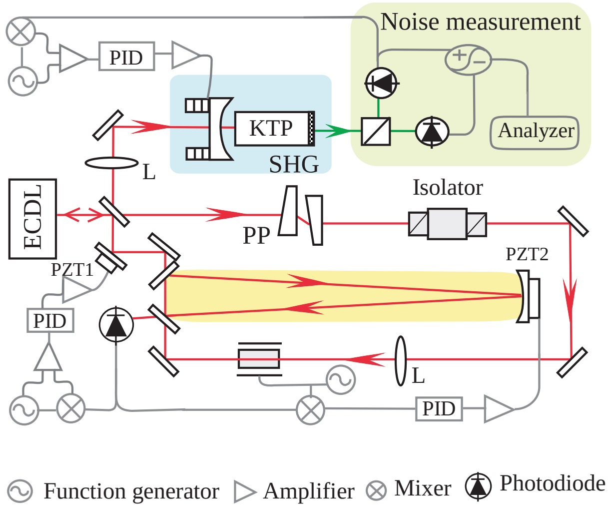

Figure 1. (color online) Schematic diagram of 540 nm laser system. PP: prism pairs; PID: Proportional-Integral-Derivative controller; KTP: a-cut KTP (Type II).

phase modulated and then coupled into the filter cavity. A 60-dB isolator is inserted to prevent optical reflection back into the diode laser. The filter cavity consists of three mirrors in a ring configuration with a round trip length of about 460 mm. The input and output mirrors are identical plane mirrors with a reflectivity coefficient of 99% for s-polarization at 1080 nm. The end mirror is a concave mirror with a radius of curvature of 1000 mm and a reflectivity coefficient close to 99.99%. A small fraction of the transmitted light is sent into the diode laser as a resonant optical feedback. Most of the noise suppressed output power is introduced into the frequency doubler to generate second harmonic (SH) at 540 nm. The frequency doubler has a semimonolithic configuration consisting of an a-cut KTP crystal (Type II) and a concave mirror of 20-mm radius of curvature. This mirror, which was coated with a transmission of 1% for 1080 nm and high reflection for 540 nm, serves as an input coupler. A facet of the KTP inside the cavity was coated for antireflection at both 540 nm and 1080 nm. The other facet was coated for antireflection at 540 nm and high reflection at 1080 nm. It acts as the output coupler for the generated SH light. The noise power of the SH output is analyzed with a balanced detector. All the optics components were arranged on half place of a 60cm×60cm board and the other half place were leaved for arranging the components of frequency stabilization with iodine molecular.

The cavity must be kept on resonance with the laser when the cavity is used as a filter cavity. The cavity frequency is locked on the diode laser frequency using the Pound-Drever-Hall technique [18]. The laser light is phase modulated with an electro-optic modulator and coupled to the filter cavity. Its reflection light is detected by a fast detector. The photocurrent signal was demodulated to provide an error signal and control the length of the filter cavity. When the filter cavity is locked, the transmitted power is 75 mW and the transmission efficiency is almost 60%. The resonant optical feedback locking occurs only when the optical feedback phase and the laser frequency

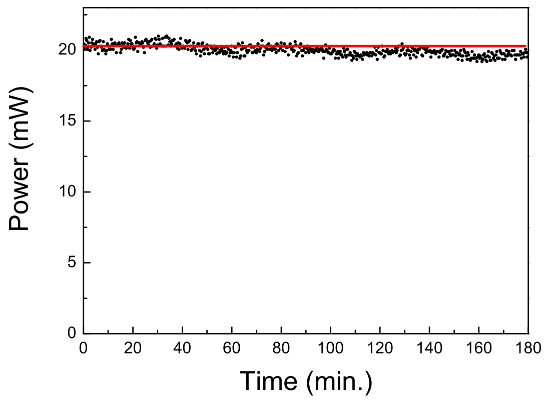

Figure 2. (color online) Long-term measurment of the generated 540 nm power.

are simultaneously in the vicinity of the optimum values. It was realized by dithering piezoelectric transducer (PZT1) with a 30 kHz sinusoidal signal and detecting by the photodiode. The error signal is derived by a mixer and then feed back to the PZT1 via a piezo driver. It was enough to keep the optical lock for several hours.

To realize type II 90 degree noncritical phase matching for second harmonic generation of 540 nm light, we adopted a 3mm×3mm×10mm a-cut KTP crystal. The type II phase matching demands that both ordinary and extraordinary beams are simultaneously resonance on the enhancement cavity. Our method is to control the crystal temperature at which both the beams are brought to resonance. The doubly resonant temperature nearest to the center was found at 67.25 °C with a tolerance of 0.01 K. Furthermore, the fundamental-wave frequency was servo-controlled to track the doubly resonant frequency. For this purpose, the cavity is locked by using the dithering scheme that was used to lock the phase of optical feedback phase. This kept the cavity length to the doubly-resonant frequency.

3. Experimental results and analysis

Figure 2 gives the long-term power stability near the maximum output power. Each point was recorded every one minute by averaging the power meter readout. For 45 mW input, a maximum power of 20 mW (This corresponds to a conversion efficiency of 44%) was emitted out from the SHG cavity. The power variation is kept within ±1 mW for more than three hours. Other issues are the reproducibility of the system and day-to-day operation. As a matter of fact, this system has been operated for several months. It is very easy to keep the output power of more than 15 mW. By slightly adjusting the enhancement cavity, the output power can be resorted. This demonstrates the robust nature of the optical feedback, and shows an advantage over other electronic locking methods. We also measured the beam quality factor for the generated SH beam, and found M^2 ∼1.05 with a waist size asymmetry between perpendicular radii less than 2%

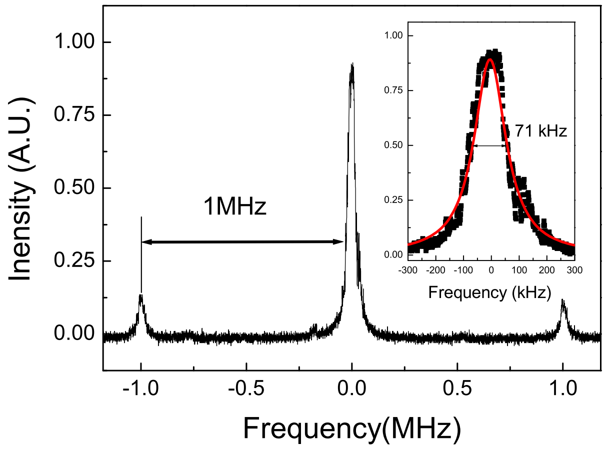

Figure 3. (color online) Transmission of the scanned F-P cavity. In the inset, spectrum of the 540 nm light observed with a non-confocal F-P spectrum analyzer. The red curve is the fit with a Lorenzian.

for the diode laser light was passed through filter cavity and enhanced SH optical cavity.

Reduction of the linewidth is another promising feature of the optical feedback. The spectrum of the fundamental light was observed with a high finesse Fabry-Perot (F-P) cavity, since no cavity for 540 nm was available at this time. Figure 3 shows the transmission signal of F-P cavity. To calibrate the frequency scale, the input light is phase modulated by a RF signal with a frequency of 1 MHz. The inset of Fig. 3 gives the spectrum of 540 nm, which is obtained by multiplying a factor of 2 for the fundamental frequency scale. The observed spectrum fits well to the Lorentzian line shape with a full-width at half maximum of 71 kHz. This linewidth is much smaller than the free running width of about 1 MHz. However, this measurement was strongly limited by the resolution of the F-P cavity, and the resolution gives the limit of the measurement. The calculated resolution of our home-made F-P cavity is about 60 kHz, and we estimated that of the second harmonic linewidth to be better than 71 kHz when the measurment precision is considered.

To investigate the intensity noise, we compared it with that of a commercial monolithic nonplanar ring oscillator (NPRO) Nd:YAG laser. Figure 4 gives a typical measured intensity noise power which is normalized to the SNL. Without optical feedback, the noise is above the shot noise level in the analysis frequency range of below 30 MHz, and it is also above the noise level of the NPRO laser. Clearly, it is not sufficiently suppressed the laser noise only by optical filtering. To characterize the optical feedback in quantity, we define an optical feedback ratio between the power being fed back to the diode laser and its total output power. With increasing the optical feedback ratio from -40 dB to -20 dB, the noise was suppressed by 10 dB and its level reached the noise level of the NPRO laser at the analysis frequency range of 10 to 50 MHz. Note tht it was even better than the level of the NPRO laser at the range of

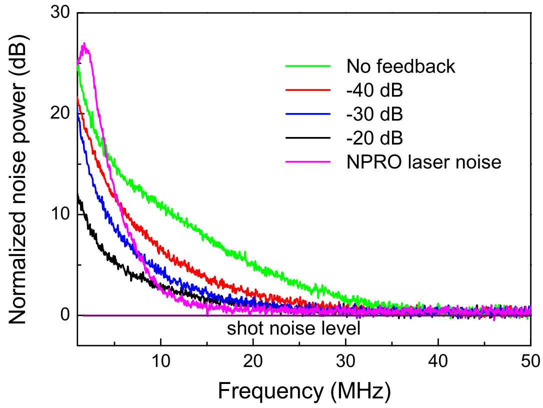

Figure 4. (color online) Normalized noise power of 540 nm light based on various optical feedback rations. A noise power of NPRO Nd:YAG laser light with same power was also shown for comparison.

below 10 MHz at the feedback ratio of -20 dB. Unfortunately, further improvement of feedback level was not performed, because the laser got into multimode operation when the optical feedback ratio was more than -20 dB. A mode-hope free tuning range of 20 GHz, which is almost as the same as the fundamental wave laser light, was preserved. A total tuning range of near 100 GHz around 540 nm was obtained. It was realized by slightly changing the phase matching temperature of nonlinear crystal.

As potential applications, we believe that this technique will be widely used to prepare light sources for high precision spectroscopy and high precision measurement experiments. For example, to measure intercombination transition of atom, whose linewidth is usually tens of kHz, the linewidth of prepared light source must be narrower than the transition linewidth. At present, these kind laser sources are usually prepared by transferring the frequency stability of high stable laser with an optical frequency comb. In this system, the best candidate for the high stable laser is the NPRO laser. However the cost of NPRO laser is usually ten times of ECDL laser. It restricts applications. Here, we give a convenient way to improve the laser quality of ECDL to the level of NPRO laser. It will open new applications of ECDL.

4. Conclusion

In summary, a stable single-frequency operation at 540 nm with power of about 20 mW is stably obtained by frequency doubling a noise suppression of a commercial ECDL. The intensity noise and the linewidth reach to the noise level of NPRO laser, which is well-known for its extraordinarily narrow linewidth and extremely low noise among available single-frequency operating lasers. Using this system, 22 absorption lines of iodine molecular were observed around 540 nm. We believe this gives another method to prepare lights for high precision spectroscopy and measurement.

Acknowledgments

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