Low-noise blue light source with large frequency-scanning range from frequency doubling of a diode laser

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Low-noise cw 8.7-mW blue light is generated by frequency doubling of the output of a Fabry–Perot diode laser in a $KNbO_3$ crystal inside a bow-tie ring cavity. The blue output has a narrow linewidth and a greater than 10-GHz continuous tuning range, with intensity fluctuations of less than 0.02 dB. The blue light has a near-diffraction-limited Gaussian TEM_{00} mode with $M^2 \approx 1$. © 2001 Optical Society of America
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Compact, stable, single-frequency blue lasers are of great interest for many scientific applications. Because blue-emitting diode lasers are currently limited in output power, wavelength range, and reliability, frequency doubling of an infrared diode laser remains a simple alternative method of overcoming these limitations. Efficient frequency doubling has long been achieved by placing the nonlinear crystal inside an external cavity.[1–3] With the availability of high-power diode lasers, higher blue output is easily attainable. For example, with a master oscillator power amplifier, as much as 1 W of single-frequency blue radiation at 465 nm was reported recently.[4] For many applications such as high-resolution spectroscopy, additional properties of narrow linewidth, large frequency-scanning range, and low noise are often required. In previous reports of direct frequency doubling of a diode laser, most of the intensity noise of the harmonic output was at the level of a few percent; for example, the output fluctuation reported in Ref. 4 was less than 10% for 30 min; in Ref. 5, less than 4% for 500 s; in Ref. 6, 5%; and Brozek *et al.* reported an intensity rms fluctuation of 0.6%.[7] The frequency-scanning range is usually a few gigahertz; in Ref. 8 the reported maximum scanning range was 6 GHz; in Ref. 9, 4 GHz.

Usually the diode laser has to have a single spatial mode and a single frequency with a relatively narrow linewidth. In our previous investigation with Switzer,[10] we reported obtaining a blue light source by frequency doubling a high-power Fabry–Perot diode laser. The diode laser operates in single mode, and the frequency locks to the cavity resonance by feedback of the ring cavity transmission after reflection off a grating. In this paper we demonstrate the low noise, excellent beam quality, and large frequency scanning of this blue laser.

Figure 1 shows the experimental setup. The laser used in the experiments is a commercial SDL-6530-J1 InGaAs diode laser without any special preparation. The threshold current is 18 mA, the maximum output power is 200 mW at a 250-mA injection current, and the center wavelength is ~968 nm at 23 °C. The emitting dimensions are 3 μm × 1 μm, and the ellipticity of the transverse mode of the diode laser is 1:2.6. The initial spectrum of the diode laser is multimode.

The external cavity is a bow-tie ring cavity, with two plane mirrors and two spherical mirrors (reflectance R, 25 mm). The first plane mirror (M1) has a reflectance of 97% at 970 nm, and the other three mirrors are high reflectors with reflectance greater than 99.3% at 970 nm. The nonlinear crystal, $KNbO_3$ (3 mm long, b cut), is placed at the midpoint between the two spherical mirrors, where the smaller internal focus is located. Near 970 nm, noncritical type I phase matching requires cooling of the crystal to below 0 °C, so we use critical type I phase matching. The angle of incidence on the crystal is ~40° at 25 °C, and walk-off angle ρ between the fundamental light and the generated blue is 9.58 mrad. Using this walk-off angle and the 3-mm crystal length in the Boyd–Kleinman theory,[11] we get an optimum beam waist of 15 μm for frequency doubling. The distance between the two spherical mirrors is 31.2 mm, and the distance between the two spherical mirrors via the plane mirrors is 111 mm. The incident angle on all four mirrors is 22.5°. This configuration produces a large elliptical beam waist of 69 μm (horizontal) and 194 μm (vertical) between the plane mirrors for efficient mode matching of the diode output, and a small circular beam waist of 19.5 μm inside the crystal, which is not exactly at the ideal beam waist of 15 μm because of the limited radius of curvature available for the spherical mirrors. We use two lenses, L1 ($f = 4.5$ mm; N.A., 0.55) and L2 ($f = 38.6$ mm), separated by 400 mm to focus the output beam into the large beam waist and correct the astigmatism of the diode laser. We have foci in the vertical and horizontal directions located ~510 mm behind the second lens; the beam waists are 69 and 194 μm for the horizontal and the vertical directions, respectively. According to Ref. 5, the small beam waist size is roughly proportional to $\sqrt{R}$, so by using $R = 15$ mm spherical mirrors we could obtain the optimum size.

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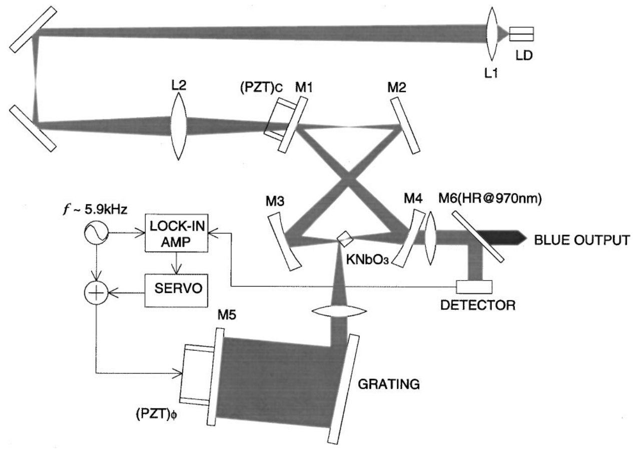

Fig. 1. Experimental setup. The bow-tie ring cavity is formed by two plane mirrors (M1 and M2) and two spherical mirrors (M3 and M4). The reflection off the $KNbO_3$ crystal is reflected back by the grating mirror (M5) to provide the feedback for single-mode operation and frequency locking. Other abbreviations defined in text.

As in our previous investigation, the reflectance from the first surface of the $KNbO_3$ crystal is fed back into the laser after it first reflects off a diffraction grating. The diode laser operates in a single mode and self-locks to the ring cavity resonance. This passive locking method is one of the popular techniques for locking the frequency of a diode laser to the cavity resonance and narrowing the spectral linewidth.[2,4,5,8,12,13] Because our laser has a relatively wide spectrum range and a side-mode suppression ratio of only ~10 dB, an additional grating has to be used. Our setup is similar to that of Kozlovsky *et al.*,[13] but their diode laser was specially antireflection coated (0.1–0.4%) and in their experiment the feedback was rather strong (~3%). In our experiment the feedback is of the order of 10^{-3}. In this feedback regime, optical locking is sensitive to the phase of the feedback light; external perturbations will cause the laser frequency to hop among different cavity resonances. For long-term stable operation and to permit scanning of the laser frequency, the optical path length between the diode laser and the feedback mirror (M5) has to be actively controlled. To control phase ϕ of the feedback phase, a piezoelectric transducer, [(PZT) ϕ, Fig. 1] is mounted upon mirror M5. Modulating the path length at 5.9 kHz and monitoring the transmitted fundamental light with a lock-in amplifier generates the error signal, and this error signal is fed back to (PZT)ϕ via a servo amplifier for active control of the feedback phase.

With 190 mW of pump power, we find that, on resonance, the circulating fundamental power inside the cavity is ~3.1 W. Approximately 40% of the infrared input power is reflected at input mirror M1 owing to a reflectivity mismatch. The calculated mode-matching factor is ~79%. A larger mode-matching factor is important because the stability of the diode laser with feedback depends greatly on the waveform of the feedback light.[14] The enhancement could be further improved by selection of the optimum transmission T_1 of the input coupler by use of this equation[15]:

$$T_1 = L/2 + (L^2/4 + E_{\mathrm{NL}} m P_1)^{1/2}, \tag{1}$$

where L describes all linear losses in the cavity exclusive of T_1, $E_{\mathrm{NL}} = P_2/{P_1}^2$ is the single-pass nonlinear conversion efficiency, m is the mode-matching factor, and P_1 is the fundamental input power. This optimization comes from matching the loss in the cavity and the nonlinear conversion to the reflectivity needed for maximum coupling to the cavity.

The maximum blue output measured after M6 is 8.7 mW. During reflection of the crystal, the spherical mirror, and high reflector M6, we estimate that 35% of the blue light generated is lost, yielding 13.4 mW of generated blue light. This corresponds to a nonlinear conversion efficiency $E_{\mathrm{NL}} = 0.139\%/\mathrm{W}$. Using the equations given by Boyd and Kleinman,[11] we obtained a theoretical nonlinear conversion efficiency of 0.246%/W. This discrepancy is caused mainly by the deviation of the focal position from the center of the crystal, which we correct later to increase the amount of blue light by ~70%. The system is mounted upon a thick aluminum plate and covered with an aluminum box to improve stability by decreasing air flow. The blue output power for 30 min. shown in Fig. 2, with a peak-to-peak fluctuation of less than 0.02 dB. The blue output is focused upon a detector (New Focus 1621); the photocurrent noise is amplified by 40 dB and measured by a spectrum analyzer. With 4.5 mW of blue light, the detector current is 1.01 mA. The noise of a red-filtered halogen lamp (CVI AS250 tungsten-halogen fiber light source, 300–800 nm) is also measured by the detector with a 1.01-mA photocurrent. The relative intensity noise (RIN) is then calculated, as shown in Fig. 2. The shot-noise ratio calculated from this equation is −155 dB:

$$\mathrm{RIN}_{\mathrm{shot}} = 10 \log_{10} \frac{2q}{I_{\mathrm{dc}}}, \tag{2}$$

where q is the electron charge and I_{dc} is the photocurrent.

The highest peak of the blue-light noise is the modulation frequency at 5.9 kHz. At high frequency the blue-light intensity noise is ~10-dB above the shot-noise level. The intensity noise is sensitive to the diode current. For

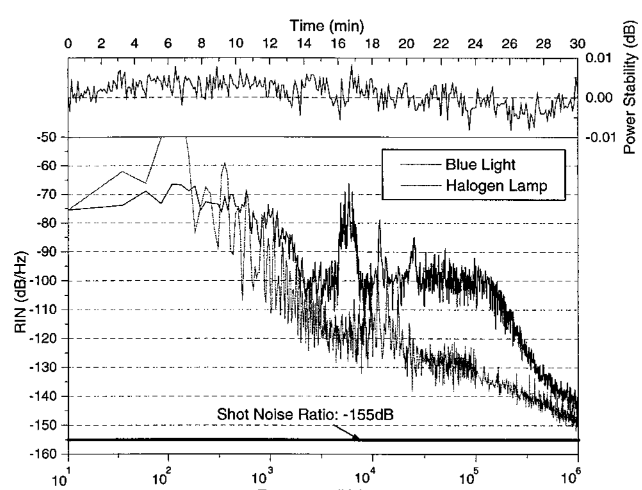

Fig. 2. Output blue-light power fluctuation for 30 min, RIN of the blue light (upper curve), and RIN of a red-filtered halogen lamp (lower curve). The noise of the red-filtered halogen lamp above shot-noise level is mainly 1/*f* noise.

stable optical locking, the feedback from the grating (FWHM, ~6GHz) must fall upon one of the diode's longitudinal modes. When the diode laser current deviates from the optimum value for ~0.3 mA, the diode laser will not lock to the exact peak of the cavity resonance and we will observe a much higher noise at the modulation frequency and increased low-frequency noise. As the current deviation increases, the system will completely lose stable locking and the diode laser will operate in multimode with chaotic behavior.

To measure the frequency noise of the blue light we use a Fabry–Perot interferometer as an optical frequency discriminator to convert the FM noise into AM noise and then measured it with a photodetector and a spectrum analyzer. The interferometer has a free spectral range of 1.5 GHz and a finesse of 44. The single-sided frequency noise power spectrum, $S_{\mathrm{FM}}(f)$, is shown in Fig. 3. The highest peak is the modulation frequency of 5.9 kHz; the peaks near 1 kHz are the acoustic and mechanical vibrations. One can find the linewidth of the blue light by calculating intensity spectrum $I(\nu)$ numerically, using the following equation[16]:

$$I(V) = 4\,\mathrm{Re}\int_0^{\infty} \mathrm{d}\tau \exp[i2\pi(\nu_0 - \nu)\tau] \times \exp\left[-2(\pi\tau)^2 \int_0^{\infty} S_{\mathrm{FM}}(f)\frac{\sin^2(\pi f\tau)}{(\pi f\tau)^2}\mathrm{d}f\right], \quad (3)$$

where ν_0 is the laser frequency. The calculated intensity spectrum is shown in Fig. 4, and the resultant linewidth is 1.25 MHz. The fundamental light with feedback should have a similar linewidth. This linewidth is considerably narrower than that of the original laser, which is 1.3 GHz (measured with a Fabry–Perot interferometer with a free spectral range of 38 GHz and a finesse of 61). These values give a linewidth reduction factor of the order of 10^3. Thus this cavity and feedback can be used to reduce the laser linewidth and suppress the frequency noise.

Inasmuch as the $KNbO_3$ is critically phase matched with a walk-off angle of ~0.55° and the beam has a tight focus, we need to verify the spatial quality of the output blue light, which is important in many applications. To do this, we focus the output blue light with a lens ($f = 123$ mm) that is placed 140 mm behind the center of the crystal to generate a larger beam focus (~200 μm). The beam intensity profile is measured with a beam profiler, and the beam waists of the horizontal and vertical planes with changes of axial position z are as plotted in Fig. 5(a). The data are then fitted with the Gaussian beam propagation equation[17]

$$\omega(z) = \omega_0\left[1 + \frac{(z - d)^2}{{z_0}^2}\right]^{1/2}, \quad (4)$$

where ω is the beam radius at $1/e^2$ intensity, ω_0 is the beam waist radius, the Rayleigh range is

$$z_0 = \frac{\pi {\omega_0}^2}{M^2\lambda}, \quad (5)$$

and M^2 is the beam quality parameter. The result of the fit is also plotted in Fig. 5(a); the beam waist is 95.9 and 91.8 μm for horizontal and vertical planes, respectively, with an astigmatism of 40.2 mm. Using this result, we calculate that the beam waist of the blue light inside the cavity is 13.37 and 13.30 μm for horizontal and vertical planes, respectively, and the astigmatism is 3.4 mm. These values are close to the theoretical result of 13.78 μm with the fundamental beam waist of 19.5 μm. The measured beam quality parameter M^2 is 1.06 ± 0.07 and 1.06 ± 0.06 for the vertical and the horizontal planes, respectively. Thus the output blue light has a near-diffraction-limited Gaussian TEM_{00} mode. Our result is comparable with a similar one from an experiment described in Ref. 18, in which the generated UV light has $M^2 \approx 1$, even with the large walk-off angle, which had been thought to degrade the beam quality in the walk-off meridian. In Fig. 5(b) the captured beam profile of the output blue light at some arbitrary distance is shown. The Gaussian fits for the horizontal and vertical planes are 97% and 96%.

To control the cavity length, we attach a piezoelectric transducer, which we label $(\mathrm{PZT})_C$ (Fig. 1), to cavity mirror M1 such that, by changing the cavity length, the feedback phase, and the injection current of the diode laser synchronously, we can achieve continuous frequency scanning. The main limit to the scanning range is the limited range of $(\mathrm{PZT})\phi$. We apply a sawtoothed voltage across $(\mathrm{PZT})_C$, and the frequency of the fundamental

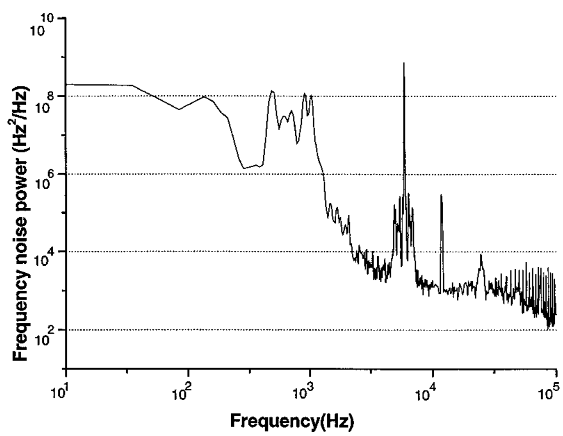

Fig. 3. Single-sided frequency-noise power spectrum of the blue light. The highest peak is the modulation frequency at 5.9 kHz.

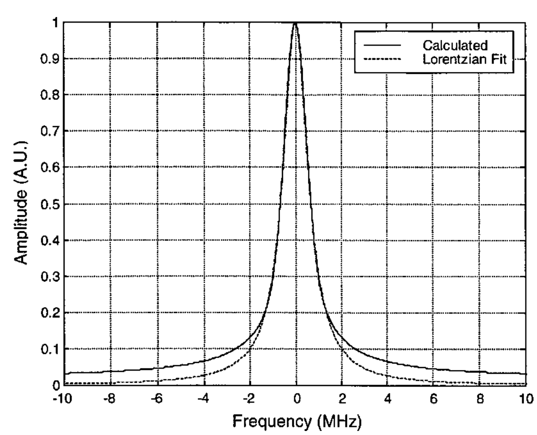

Fig. 4. Calculated field spectrum of the blue light. The resultant linewidth is 1.25 MHz.

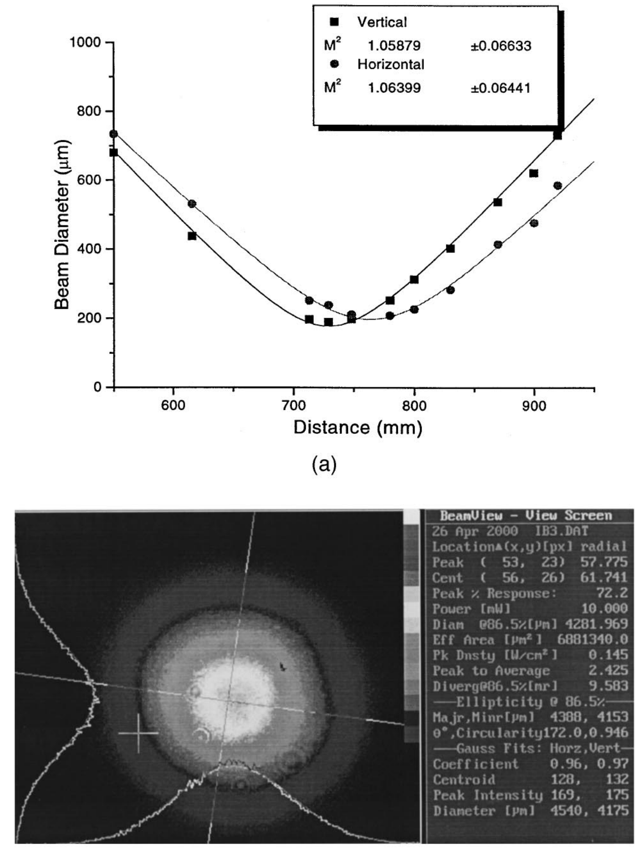

Fig. 5. (a) Beam waists of the horizontal and vertical planes with changes of axial position z. Solid curves least-squares fits. Measured beam quality parameters M^2 of 1.05879 and 1.06399 for horizontal and vertical planes are shown. (b) Beam profile of the output blue light at some arbitrary distance. The Gaussian fits for the horizontal and vertical planes are 97% and 96%, respectively.

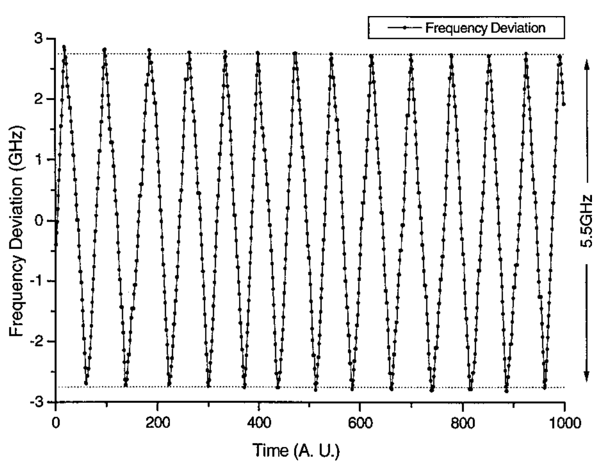

Fig. 6. Measured frequency ramping of the fundament light by a wavemeter. The scanning range is ~5.5 GHz, corresponding to 11 GHz in the blue.

light is monitored by a wavemeter (Burleigh WA-1500). The frequency change with time is shown in Fig. 6, and we can see that the scanning range is ~5.5 GHz, corresponding to 11 GHz in the blue. Because the acceptance bandwidth of the nonlinear generation in our setup is ~66 GHz, the change in the power of the blue light should be less than 3%.

In conclusion, we have demonstrated a low-noise blue laser with a large frequency-scanning range. The noise comes mainly from cavity vibrations and the modulation to generate an error signal. Frequency and intensity stability can be further improved by use of a monolithic, hermetically sealed cavity, and the conversion efficiency can be increased by use of a longer crystal and reduction of the crystal's temperature to reduce the walk-off angle.

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