Suppression of the intensity noise of a laser-diode-pumped single-frequency ring Nd:YVO_4–KTP green laser by optoelectronic feedback

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We investigate the different characteristics of the intensity noise of a laser-diode-pumped single-frequency ring Nd:YVO_4 laser and a Nd:YVO_4–KTP green laser. By use of an optoelectronic feedback circuit connected directly to the pump current of the laser diode, the low-frequency intensity noise of the intracavity frequency doubler was suppressed to some extent.

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Single-frequency light sources with low intensity noise are very useful for many applications, such as high-sensitivity measurements, high-precision interferometry, precision spectroscopy, and optical communications. Laser-diode- (LD-) pumped solid-state lasers and its intracavity frequency doubler are well known as efficient sources for the generation of intensity-stable single-frequency radiation.[1–4] In practical LD-pumped single-frequency laser systems, however, the intensity-noise spectrum has a resonance, that is, an underdamped driven second-order oscillator, known as resonant relaxation oscillation (RRO).[5] The low-frequency part of the intensity-noise spectrum below the RRO is determined by the laser's pump noise, whereas the RRO is driven by vacuum fluctuations, dipole fluctuations, and intracavity losses. Significant suppression of relaxation oscillations in diode-pumped single-frequency lasers has been achieved through different paths, such as stabilizing laser intensity by means of electronic feedback loops,[6–8] injection locking a laser to an intensity-stable master laser,[9,10] and combining these techniques.[11] Intensity noise at low frequencies can be reduced when pump noise is suppressed.[12] Compared with the single-frequency laser, in the intensity-noise spectrum of a single-frequency-doubling laser, RRO is not present, but there is still a large amount of noise resulting from an overdamped driven second-order oscillator during nonlinear conversion.[13]

In this Letter we first analyze a variety of intensity-noise characteristics and give the pump-noise transfer function of a LD-pumped single-frequency Nd:YVO_4 laser and a Nd:YVO_4–KTP green laser and then report on the experimental results of the intensity-noise suppression of the Nd:YVO_4 laser by means of a suitably designed electronic feedback circuit connected to the drive current of the LD. For the first time to our knowledge, the different features of the intensity noise and the pump transfer function of an all-solid-state single-frequency laser and a frequency doubler are analyzed, and the optoelectronic feedback circuit acting directly on the pump current of a LD for reduction of intensity noise is applied to an intracavity frequency doubler.

In the frequency domain the intensity noise can be conveniently described with a transfer function that relates the laser output noise to the various noise sources. The basic approach to obtaining this transfer function is to solve the quantum Langevin equation, including active atoms, the optical cavity mode of the laser, the nonlinear process, and the various coupled external quantum-mechanical reservoirs.[5,13] The external reservoirs produce dissipation and introduce noise into the laser system. By linearizing the quantum Langevin equation, we can obtain the intensity-noise spectrum of the laser output, expressed as the form of a transfer function between the various noise sources and the laser output. The pump-noise transfer function of the single-frequency laser is described by[7,8]

$$F_l(\omega) = [4kk_m{\gamma_t}^2 r(r-1)]^{1/2}/[({\omega_r}^2 - \omega^2) + i\omega\gamma_l], \tag{1}$$

where ω is the noise frequency in radians per second; r is the normalized pump factor, $r = P_{\mathrm{pump}}/P_{\mathrm{th}}$, where P_{pump} is the pump power and P_{th} is the threshold pump power; γ_t is the rate of spontaneous emission between the lasing levels; k is total cavity decay rate, $k = k_m + k_l$, composed of output coupling k_m and intracavity losses k_l; ω_r is the frequency of the RRO; and γ_l is the damping rate of the RRO, expressed as

$$\omega_r = [2k\gamma_t(r-1)]^{1/2}, \qquad \gamma_l = \gamma_t r\,. \tag{2}$$

The function $F_l(\omega)$ in Eq. (1) is a second-order transfer function that is similar to the formula for a damped driven pendulum. Under the operation conditions for a practical solid-state laser, damping rate γ_l is less than ω_r, and the pump transfer function exhibits RRO.[7,8] Since the pump transfer function is the underdamped driven second-order oscillator, an abrupt phase shift of $-180°$ is introduced into the frequency of the RRO.[7,8] The pump-noise transfer function of the single-frequency-doubling laser is described by[13]

$$F_s(\omega) = \frac{[8(k_l + \mu a_0{}^2)\mu a_0{}^2 \gamma_t{}^2 r(r-1)]^{1/2}}{(\omega_r{}'^2 - \omega^2) + i\omega\gamma_l{}'}, \quad (3)$$

where μ is the nonlinear coupling coefficient and a_0 is the amplitude of intracavity fundamental wave:

$$\omega_r{}' = [2\mu a_0{}^2 \gamma_t r + 2(\mu a_0{}^2 + k_l)\gamma_t (r-1)]^{1/2}, \quad (4)$$

$$\gamma_l{}' = 2\mu a_0{}^2 + \gamma_t r\,. \quad (5)$$

The frequency, $\omega_r{}'$, and the damping rate, $\gamma_l{}'$, of the single-frequency-doubling laser include nonlinear conversion $\mu a_0{}^2$, so the doubling process will significantly influence the behavior of the frequency-doubling laser; usually damping rate $\gamma_l{}'$ is larger than ω_r, in which case the pump transfer function is the overdamped driven second-order oscillator and does not exhibit RRO.[13] The plots of the phase and amplitude of the pump transfer function for the single-frequency-doubling laser are shown in Fig. 1. There is no peak of RRO in the amplitude plot of the pump transfer function [curve (1)], and the phase [curve (2)] changes smoothly. The feedback loop should include the second-order oscillator. A requirement for designing a good feedback circuit is to ensure that the magnitude of the open-loop gain G is less than 1 when the phase of the open-loop gain reaches $-180°$. If this required magnitude is not achieved, the feedback loop will be unstable, leading to enhancement of spectral noise. Note also that a stable feedback loop can amplify noise if G approaches -1.

Figure 2 is a schematic of the diode-pumped single-frequency $Nd:YVO_4$–KTP green laser used in our experiments. The unidirectional ring laser is pumped by a laser diode through an optical coupling system. Input mirror M1 has antireflection coating at 808 nm on the internal facet and high-reflectance coating at 1064 nm and high-transmittance coating at 808 nm on the external facet. Concave mirror M4 has high reflectivity at 1064 nm, and concave mirror M3 has high reflectivity at both 1064 and 532 nm. We place a terbium gallium garnet (TGG) crystal and a half-wave plate ($\lambda/2$) in the cavity as an optical diode to enforce unidirectional operation. A type II critically phase-matched KTP nonlinear crystal is used as an intracavity frequency doubler. Output coupler M2 has high reflectivity at 1064 nm and high transmission at 532 nm. The maximum output power of the green light is 150 mW. The rate of spontaneous emission γ_t is $\sim 10^4\ s^{-1}$ for $Nd:YVO_4$. The output coupling, $k_m = Tc/2L$, is $1.7 \times 10^7\ s^{-1}$, where T is the transmission of the output coupler of 4%, c is the speed of light, the length L of the cavity is 350 mm, and k_l is $8.6 \times 10^7\ s^{-1}$ for 2% intracavity losses. The nonlinear conversion $\mu a_0{}^2$ should equal output coupling k_m, as can be determined by measurement of the output power of frequency-doubled light.

The experimental arrangement for noise control and monitoring of the laser is shown in Fig. 3. We monitor the noise of the laser with photodetectors D_1 (in-loop) and D_2 (out-of-loop) (with EG&G FND-100 silicon photodiodes). D_1 (Analog Modules 714A) has a large gain and a broad bandwidth from 10 kHz to ~100 MHz. A transimpedance operational amplifier circuit in D_2 is used to convert the photocurrent to voltage. We inject the error current directly into the diode laser from the driving circuit to minimize the time delays. This circuit consists of a buffer (BUF634) followed by a 100-Ω resistor in parallel with a 1-nF capacitor, followed by a 4-μF capacitor, which ac couples the injected signal to prevent any change in the output power of the diode laser. A noise-reduction circuit is employed to reduce the noise of the laser. First, we measured the pump transfer function from point A to point B in Fig. 3 with a network analyzer (Hewlett-Packard HP4359A). The measured pump-noise function includes all transfer functions of the current driver, the laser diode, the laser, and the photodiode amplifier. The individual

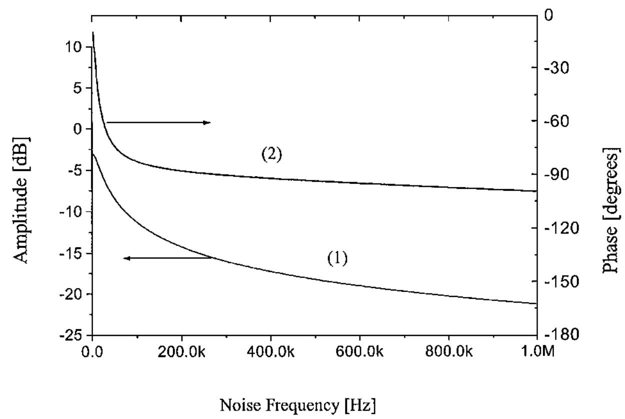

Fig. 1. Amplitude (1) and the phase (2) of the pump-noise transfer function for the single-frequency intracavity frequency-doubling laser.

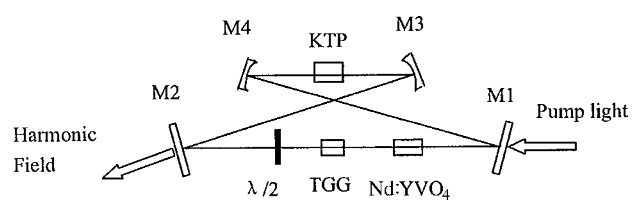

Fig. 2. Schematic of the single-frequency $Nd:YVO_4$–KTP ring laser.

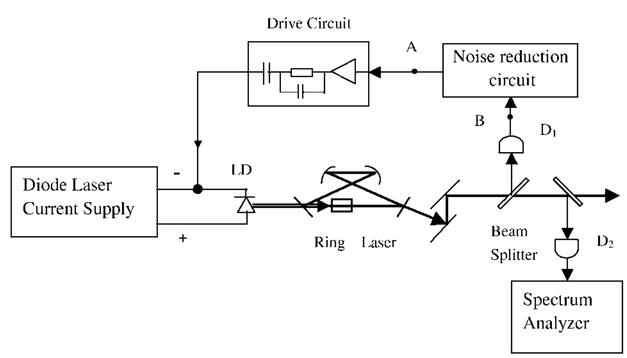

Fig. 3. Experimental arrangement for noise control and monitoring of the laser.

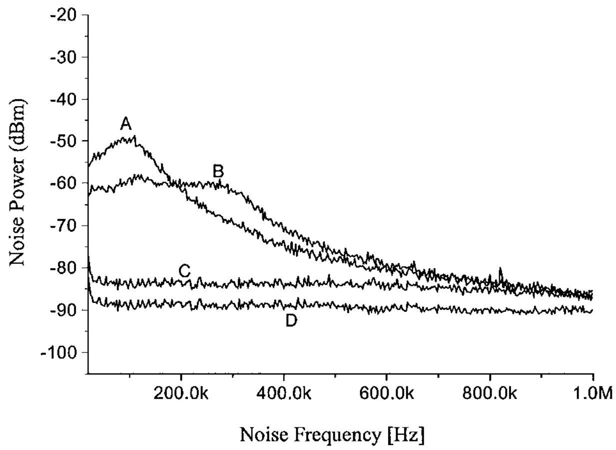

Fig. 4. Experimental noise spectra of the Nd:YVO_4–KTP green laser. A, noise of the free-running laser; B, noise with feedback control; C, superposition of electronic noise and quantum noise for an equivalent Poissonian photocurrent; D, electronic noise floor of the detection system. The detected photocurrents of the two lasers are identical (1 mA).

transfer function of each of the elements was also measured, and it was found that the overall gain and phase change of the pump transfer function result mostly from the laser system itself. The measured pump transfer function of the Nd:YVO_4–KTP green laser is in agreement with Eq. (3). The noise-reduction circuit used in the feedback loop consists of three noninverting amplifiers and a series of active filters to provide phase advance and gain. The phase advance filter can enhance the performance of the control loop, which includes a second-order resonance. For the single-frequency Nd:YVO_4–KTP green laser, the maximum phase advance is 34° at 300 kHz, and the laser's feedback loop is more stable than that of the fundamental laser since the single-frequency intracavity frequency-doubling laser includes an overdamped driven second-order oscillator. The open-loop gain, G, starting from and returning to A in Fig. 3, attained the maximum value of 8 dB at 100 kHz, thus providing an intensity-noise reduction factor $1/|1 + G|$ of ~7 dB and had two unity-gain points, at ~200 Hz and ~200 kHz, with ~20° and ~100° phase margins, respectively. The noise-reduction spectra are shown in Fig. 4. The noise at low frequency is reduced by 7 dB relative to that of the free-running laser (curve A). The noise is amplified near 300 kHz, since that is where G approaches -1.

In conclusion, we have determined the pump transfer function and the intensity noise of a LD-pumped single-frequency Nd:YVO_4–KTP green laser. By means of an optoelectronic feedback circuit, intensity-noise reduction of an intracavity frequency doubler has been demonstrated. For what is to our knowledge the first time, we determined the difference in the intensity noise and the pump transfer function between a fundamental laser and an intracavity frequency doubler and reduced the intensity noise of a single-frequency intracavity frequency-doubling laser with an optoelectronic feedback circuit connected directly to the pump current.

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