Quantum noise in a continuous-wave laser-diode-pumped Nd:YAG linear optical amplifier

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We present measurements of the power noise that is due to optical amplification in a laser-diode-pumped Nd:YAG free-space traveling-wave linear amplifier in a master-oscillator–power-amplifier configuration. The quantum noise behavior of the optical amplifier was demonstrated by use of InGaAs photodetectors in a balanced detection configuration, at a total photocurrent of 100 mA and in a frequency band from 6.25 to 15.625 MHz. The experimental results are in good agreement with predictions. © 1998 Optical Society of America

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High-power, low-noise lasers are required for laser interferometric gravitational-wave detection[1,2] and free-space optical communication.[3] The advanced detector in the Laser Interferometer Gravitational Wave Observatory (LIGO) program will require a low-noise, continuous-wave (cw), 100-W, single-frequency, diffraction-limited TEM_{00} mode laser.[4] High single-pass gains demonstrated in cw laser-diode-pumped zigzag slab lasers[5] indicate that cw amplification in a Nd:YAG master-oscillator–power-amplifier (MOPA) configuration is a feasible design for a power-scalable, single-frequency, diffraction-limited TEM_{00} mode laser.[4,6,7] Suitable master oscillators are available in the form of monolithic Nd:YAG nonplanar ring oscillators,[8] which have demonstrated power and frequency noise levels that meet the initial LIGO noise requirements. However, the MOPA design approach raises the question of the power noise properties of optical amplification and the potential need for power-noise reduction by use of passive mode filtering with a premode cleaner[9] after the power amplifier.

Laser interferometric gravitational-wave detectors typically require that one use rf modulation and demodulation techniques to avoid the effects of low-frequency laser power noise and $1/f$ noise in the photodetector. A noise-budget analysis of these interferometers indicates that the detector sensitivity for gravitational-wave signal frequencies above 300 Hz will be limited by photocurrent noise at the rf modulation frequency. Therefore the laser power noise must be essentially shot noise limited at the rf modulation frequency for a photocurrent corresponding to the output power at the interferometer output port.

In this Letter we confirm experimentally the predicted noise performance of a free-space Nd:YAG traveling-wave amplifier operating in the linear gain regime. In previous work on the photon statistics of linear traveling-wave amplifiers,[10] researchers considered primarily high-gain, single-spatial-mode guided-wave semiconductor[11] and fiber laser amplifiers[12] used in long-distance optical transmission systems. In studies of argon-laser amplifiers existing noise theories were applied to free-space amplifiers.[13] However, the multiline operation of the argon-ion laser system required a detailed analysis of the spontaneous emission factor. The four-level nature of the Nd:YAG laser system simplifies this analysis because of the complete inversion of the gain medium. To our knowledge we present the first quantitative measurement of the quantum noise of a linear free-space Nd:YAG optical amplifier.

The theoretical analysis developed by Shimoda *et al.*[10] defines a photon statistics master equation that describes the evolution of the photon-number probability distribution as a function of stimulated emission, stimulated absorption, and spontaneous emission along the amplifier. Starting with the photon statistics master equation, and following the treatment of Desurvire,[12] the mean output photon number of the amplifier, $\langle n_{\mathrm{amp}}(z_o)\rangle$, and its variance, ${\sigma_{\mathrm{amp}}}^2(z_o)$, for a single spatial mode propagating in the z direction, normalized to a 1-s measurement time, are given by

$$\langle n_{\mathrm{amp}}(z_o)\rangle = G(z_o)\langle n(0)\rangle + f_{\mathrm{sp}}[G(z_o) - 1], \quad (1)$$

$$\begin{aligned}{\sigma_{\mathrm{amp}}}^2(z_o) = {} & G^2(z_o)[{\sigma_{\mathrm{in}}}^2(0) - \langle n(0)\rangle] + G(z_o)\langle n(0)\rangle \\ & + 2G(z_o)\langle n(0)\rangle f_{\mathrm{sp}}[G(z_o) - 1] \\ & + \{f_{\mathrm{sp}}[G(z_o) - 1]\}^2 + f_{\mathrm{sp}}[G(z_o) - 1]. \quad (2)\end{aligned}$$

Here $\langle n(0)\rangle$ and ${\sigma_{\mathrm{in}}}^2(0)$ are the mean and the variance in the photon number per second in a single transverse mode at the input to the amplifier, respectively. The amplifier output is taken at distance z_o. The amplifier power gain for the uniformly pumped

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gain medium is given by $G(z_o) = \exp[(\sigma_e N_2 - \sigma_a N_1 - \alpha)z_o]$, where N_2 and N_1 are the atomic population densities (in atoms/cm^3) in the upper and lower laser levels, respectively, σ_e and σ_a are the emission and absorption cross sections (in cm^2) for the lasing transition, respectively, and α is the distributed power loss per unit length in the zig-zag slab amplifier that is due to loss at the total internal reflections. The amplifier spontaneous emission factor is defined as $f_{\text{sp}} = \sigma_e N_2/(\sigma_e N_2 - \sigma_a N_1 - \alpha)$.

If the amplifier input signal is shot noise limited, then $\sigma_{\text{in}}{}^2(0) = \langle n(0)\rangle$. Additionally, if the mean amplifier input photon number is much larger than the spontaneous emission factor ($\langle n(0)\rangle >> f_{\text{sp}}$), Eq. (2) simplifies to

$$\sigma_{\text{amp}}{}^2(z_o) = G(z_o)\langle n(0)\rangle\{1 + 2f_{\text{sp}}[G(z_o) - 1]\}. \tag{3}$$

Experimentally the variance in the electrical-noise power from the photodetectors, $\sigma_{\text{det}}{}^2$, is the measurable quantity. Equation (3) must be modified to include the optical transmission efficiency between the amplifier and the photodetectors, η_{tr}, and the photodetector quantum efficiency, η_{det}. The transmission efficiency and photodetection processes are described as Bernoulli random deletion processes, and the variance of these processes is given by[12]

$$\sigma_\eta{}^2 = \eta^2\sigma_{\text{amp}}{}^2 + \eta(1 - \eta)\langle n_{\text{amp}}\rangle, \tag{4}$$

where $\eta = \eta_{\text{tr}}\eta_{\text{det}}$.

The variance in the electrical-noise power at the output of the photodetectors is given by the relationship $\sigma_{\text{det}}{}^2 = 2e^2\eta\sigma_\eta{}^2 B_o B_e$, where e is the charge of an electron, B_o is the optical bandwidth of the amplifier, B_e is the detector electronic bandwidth, and $B_e \ll B_o$. The shot noise associated with a dc photocurrent is defined as $\sigma_{\text{shot}}{}^2 = 2eI_{\text{dc}}B_e$, where $I_{\text{dc}} = G(z_0)\langle n(0)\rangle eB_0$. Therefore the variance of the measured electrical-noise power from the photodetectors, $\sigma_{\text{det}}{}^2$, normalized to the shot noise limit of the dc photocurrent, $\sigma_{\text{shot}}{}^2$, is given by

$$\sigma_{\text{det}}{}^2/\sigma_{\text{shot}}{}^2 = \{1 + 2\eta f_{\text{sp}}[G(z_o) - 1]\}. \tag{5}$$

The right-hand side of Eq. (5) describes a gain-dependent excess-noise factor that predicts the increase in power noise that is due to optical amplification of a shot noise limited master oscillator in a MOPA laser, compared with the noise of an equivalent-power shot noise limited laser.

Figure 1 shows the experimental apparatus, which consists of a master oscillator, a power-amplifier, and a detection apparatus. The master oscillator is a monolithic, single-frequency, TEM$_{00}$, laser-diode-pumped Nd:YAG nonplanar ring laser (Lightwave Electronics Model 126-1064-700), locked to a Fabry–Perot ring cavity by a rf locking technique.[14] The Fabry–Perot ring cavity reduces the master oscillator power noise to the shot noise limit at the amplifier input as required by Eq. (5). Additionally, the ring cavity acts as a spatial filter to ensure TEM$_{00}$ mode input to the optical amplifier. The transfer function for power noise suppression by the Fabry–Perot ring cavity is $H(f) = 1/[1 + (f/f_c)^2]^{0.5}$; the 3-dB cutoff frequency f_c for the s-polarization input field is 87 kHz.[9] The power noise of the laser at the output of the Fabry–Perot ring cavity was measured to be shot noise limited above 5 MHz for a dc photocurrent of 100 mA.

The laser-diode-pumped Nd:YAG zigzag slab amplifier pump source consists of 21 fiber-coupled laser-diode arrays, each with a maximum power of 10 W.[3] The angle-multiplexed configuration[15] shown in Fig. 1 provides a convenient technique for multipass operation of the zig-zag slab with Brewster angle end faces. The triple-pass configuration provides a total power gain of 4.5 and 126 W of laser-diode pump power.

The detection system consists of two identical ETX2000 Epitaxx InGaAs photodiodes operating with a 5-V bias voltage, ac coupled to high-current transimpedance amplifiers, and a HP 70000 rf spectrum analyzer. The balanced detector configuration provides a simultaneous measurement of the total power noise on the sum signal and of the uncorrelated shot-noise level for the total photocurrent on the difference signal. For each measurement we attenuated the amplifier input signal to ensure that the same optical power was incident upon the photodetectors for each amplifier gain setting. Thus all measurments were made with a constant 50 mA of photocurrent from each photodiode, for a total photocurrent of 100 mA. Measurements were averaged over a frequency range of 6.25–15.625 MHz; this range was

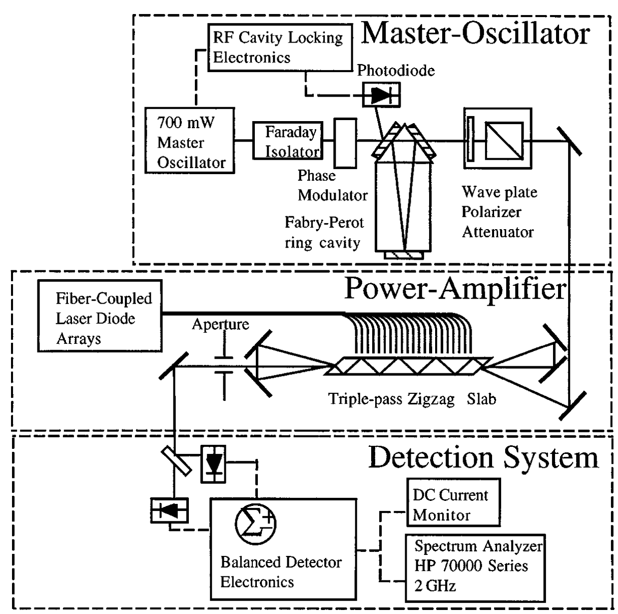

Fig. 1. Schematic of the power-noise measurement apparatus. The master oscillator is locked to the Fabry–Perot ring cavity by a rf modulation locking technique. Above 5 MHz, the output of the Fabry–Perot ring cavity is shot noise limited at 100-mA photocurrent. The Nd:YAG zigzag slab amplifier is pumped with 126 W of fiber-coupled laser-diode power. The output of the amplifier is measured with a balanced pair of InGaAs photodetectors and a rf spectrum analyzer.

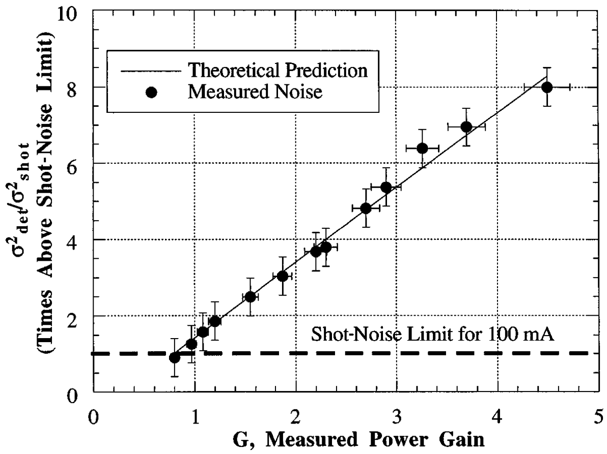

Fig. 2. Power noise as a function of amplifier power gain G compared with the theoretical prediction. The noise is presented in units of times above the shot noise limit, and this provides a measure of the gain-dependent power noise that is due to optical amplification normalized to the shot noise level for the 100-mA photocurrent.

limited by the bandwidth of the photodetectors and the transimpedance amplifiers.

Figure 2 shows the measured power noise of the amplified signal relative to the shot noise limit for the 100-mA photocurrent versus the measured amplifier power gain G. The theoretical prediction of the power noise that is due to optical amplification given by Eq. (5) is shown as the solid line. All factors in the theoretical prediction are calculated from values measured in the experiment; there are no free parameters. The measured optical transmission and the quantum efficiency of the photodetectors were $\eta_{tr} = 0.95$ and $\eta_{det} = 0.97$, respectively. The spontaneous emission factor, f_{sp}, can be calculated from the measured amplifier power gain G and the measured transmission loss of $\alpha = 0.95\%/\mathrm{cm}$ for the triple-pass amplifier. In the regime in which the amplifier is being optically pumped by the laser diodes but remains below the amplifier transparency point (gain < loss), both the amplifier spontaneous emission factor, f_{sp}, and $(G - 1)$ have negative values. Therefore, Eq. (5) correctly predicts power noise above the shot noise limit when the amplifier is operating below the transparency point.

In summary, we have measured the high-frequency power noise of a free-space linear optical amplifier. The experimental results are in excellent agreement with quantum-noise theory. Additionally, we demonstrated the reduction of power noise by use of a passive Fabry–Perot ring cavity as a temporal filter. Shot noise limited measurements at 100-mA photocurrent, equivalent to 130 mW of optical power, demonstrated the operation of the high-current, high-quantum-efficiency photodetectors. Future experiments will evaluate the power noise characteristics of saturated optical amplifiers for high-power applications. These techniques for power noise measurement and reduction are key steps toward the design of a 100-W MOPA system capable of meeting the requirements for use in an advanced gravitational-wave interferometer.

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