Reduction of the intensity noise from an erbium-doped fiber laser to the standard quantum limit by intracavity spectral filtering

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The high frequency intensity noise of a tandem fiber Fabry–Perot erbium-doped fiber ring laser is reduced to the standard quantum limit, with a 0.5 dB experimental uncertainty. Noise reduction of > 14 dB is achieved by intracavity spectral filtering of weak side modes using a narrow-band fiber Fabry–Perot etalon.

Broadly tunable, single-frequency erbium-doped fiber lasers have recently been demonstrated and are potential sources for systems operating near 1.5 μm.[1,2] Measurements of an erbium-doped fiber laser using tandem fiber Fabry–Perot (FFP) filters for mode selection revealed that the intensity noise at high frequency (310 MHz) depended linearly upon laser power, had a resonance structure with the 4 MHz free spectral range of the laser, and could be maintained within 20 dB of the standard quantum limit throughout a 24 nm tuning range.[3] This excess noise power was attributed to the beating of the lasing mode with strongly damped side modes. In this letter, we present an analysis of this side mode beat noise in order to show how it may be reduced in optimized cavity configurations. We then demonstrate noise levels within experimental uncertainty of the standard quantum limit (SQL), by implementing intracavity spectral filtering combined with lower cavity loss.

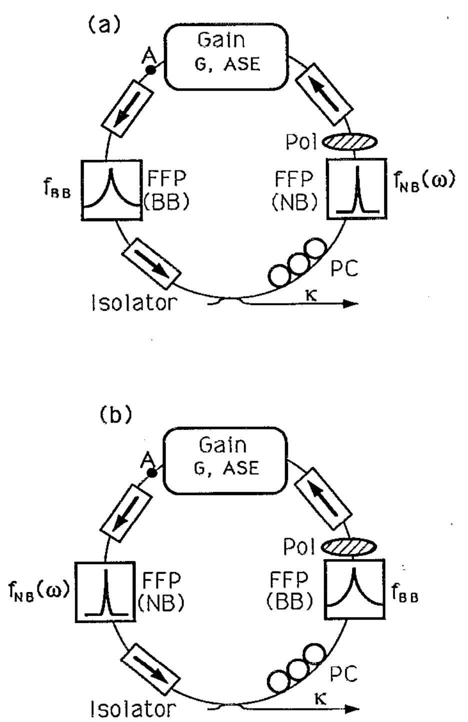

FIG. 1. The tandem fiber Fabry–Perot erbium ring laser in configuration (a) with the narrow-band FFP before the gain medium to increase output power and (b) with the narrow-band FFP after the gain medium to filter side modes (PC:polarization controller; FFP: fiber Fabry–Perot filter).

Consider the two configurations for a tandem fiber Fabry–Perot (FFP) erbium-doped ring laser shown in Fig. 1, where the narrow band FFP, with 130 MHz full width at half-maximum (FWHM) transmission and 10.2 GHz free-spectral range (FSR), selects an individual lasing mode, and the broadband (38 GHz FWHM, 4020 GHz FSR) FFP tunes the lasing wavelength over the erbium gain spectrum. In one pass, the gain medium amplifies the optical power by a factor G and adds amplified spontaneous emission (ASE) power with a spectral density $\tilde{n}_{sp}(G-1)\hbar\omega$, where ω is the optical frequency and $\tilde{n}_{sp}$ is the integrated spontaneous emission factor defined in Ref. 4 and given by

$$\tilde{n}_{sp}=\frac{G}{G-1}\int_0^l dz\, g(z)n_{sp}(z)e^{-\int_0^z g(z')dz'}, \qquad (1)$$

where $g(z)=\sigma_e N_2(z)-\sigma_a N_1(z)$ and $n_{sp}(z)=\sigma_e N_2(z)/g(z)$; σ_e and σ_a are the emission and absorption cross sections, respectively, and N_2 and N_1 are the upper and lower state population densities, respectively. (When n_{sp} is independent of z, $\tilde{n}_{sp}=n_{sp}$.) The FFP filters have intensity transfer functions $f_{NB}(\omega)$ and f_{BB}, where the frequency dependence of the broad-band filter can be neglected in determining the side mode powers. For both configurations, the steady-state electric field of the weak side modes

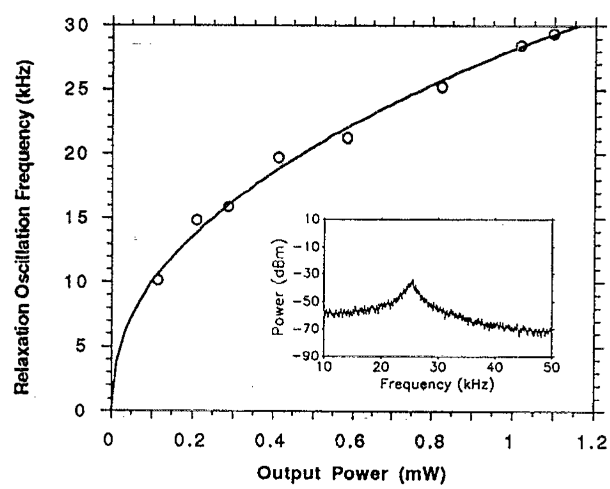

FIG. 2. Relaxation resonance frequency vs laser output power (50% output coupler). Inset: Intensity noise power vs frequency for 820 μW laser output power (35 dB amplifier, 1 kHz resolution).

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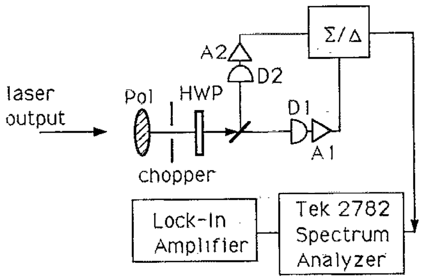

FIG. 3. Balanced homodyne detection system to determine laser noise level relative to the SQL (shot noise floor). The SQL is measured when the photocurrents are differenced; the laser noise is measured when the photocurrents are summed. (HWP: half-wave plate; D1 and D2: BT&D PDH0004 detectors; A1 and A2: Avantek ACT10-213-1 amplifiers).

immediately after the gain medium (at point A) has an optical power spectral density:

$$|\tilde{E}_A(\omega)|^2=\frac{\tilde{n}_{sp}(G-1)\hbar\omega}{1-2\gamma\cos(kl_c)+\gamma^2}, \qquad (2)$$

where l_c is the length of the fiber laser cavity; $k=(n\omega)/c$, and γ^2 is the net round-trip power gain, given by

$$\gamma^2(\omega)=f_{NB}(\omega)(1-\kappa)f_{BB}G(1-\epsilon), \qquad (3)$$

κ is the power output coupling and ϵ is the round-trip loss due to other cavity components.

The intensity noise power spectral density outside the laser ring arising from beating between the lasing mode at frequency ω_0, with output power $\kappa f(\omega_0)E_0^2$, and amplified spontaneous emission at frequencies $\omega_0+\Omega$ and $\omega_0-\Omega$, with optical output power spectral densities $\kappa f(\omega_0+\Omega)\tilde{E}_+^2(\Omega)$ and $\kappa f(\omega_0-\Omega)\tilde{E}_-^2(-\Omega)$, respectively, is

$$W_{PP}(\Omega)=2E_0^2[\tilde{E}_+^2(\Omega)+\tilde{E}_-^2(-\Omega)]\kappa^2 f(\omega_0+\Omega)f(\omega_0), \qquad (4)$$

where E_0^2 is the optical power in the lasing mode at point A, and $\tilde{E}_+^2$ and $\tilde{E}_-^2$ are the optical power spectral densities at point A of the amplified spontaneous emission at frequency offsets of Ω and $-\Omega$ from the lasing mode, respectively. The filter response f represents f_{BB} for configuration (a) and represents f_{NB} for configuration (b) in Fig. 1, and a small asymmetry that may arise in $f_{NB}(\omega)$ about ω_0 due to detuning of the lasing mode from the narrow-band FFP transmission peak has been neglected. Using Eq. (2) and normalizing to the shot noise power spectrum of $2\kappa f(\omega_0)E_0^2\hbar\omega$ gives

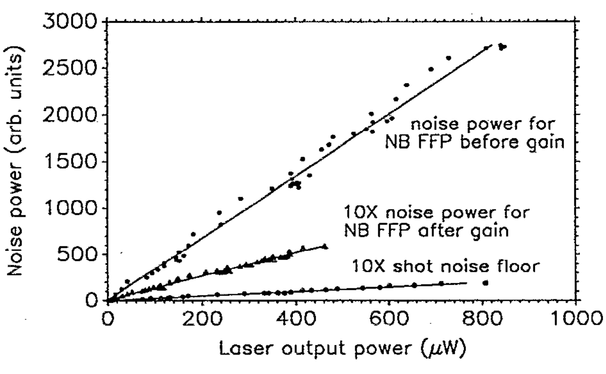

FIG. 4. Laser noise power at 307.5 MHz with 90% output coupler and narrow-band FFP before gain medium (upper trace) and narrow-band FFP between gain medium and output coupler (middle trace.) The noise power in the middle trace and the SQL are multiplied by 10.

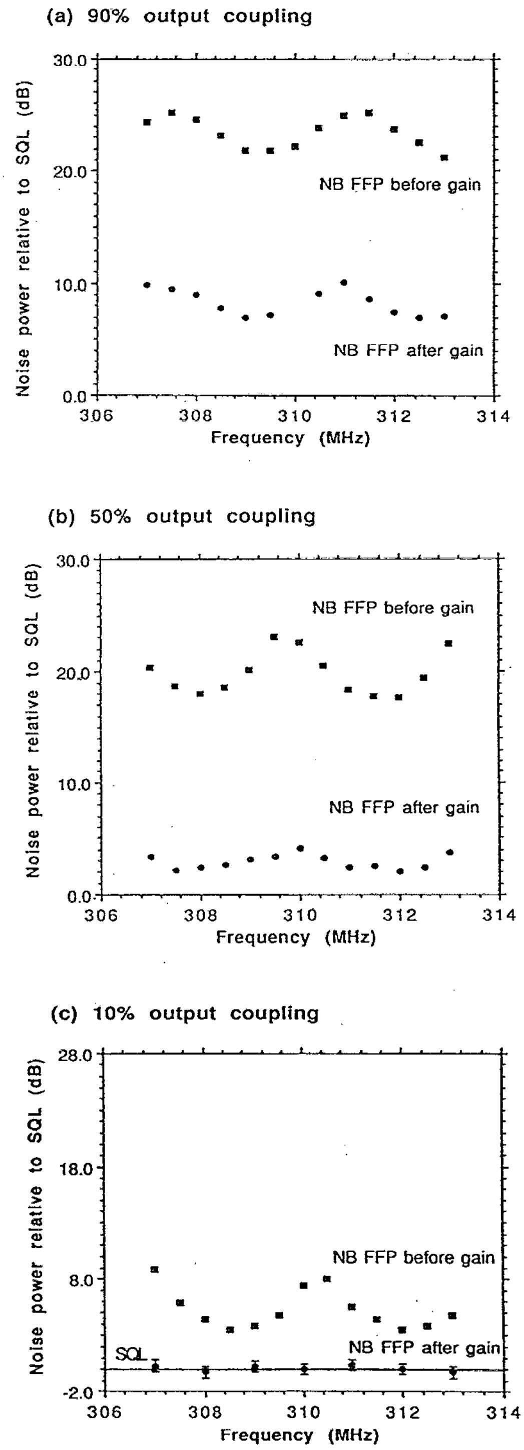

FIG. 5. Laser noise power spectra relative to SQL around 310 MHz for (a) 90% output coupling, (b) 50% output coupling, and (c) 10% output coupling. With the narrow-band FFP after the gain medium, the intensity noise power reaches the SQL for 10% output coupling.

$$\frac{W_{PP}}{W_{\rm SQL}}(\Omega)=\frac{2\tilde{n}_{\rm sp}(G-1)\kappa f(\omega_0+\Omega)}{1-2\gamma\cos[(n\Omega l_c)/c]+\gamma^2}. \quad (5)$$

A resonance structure of the intensity noise power, as discussed in Ref. 3 and shown in Fig. 5, is apparent from the denominator of Eq. (5). The average noise level over a free spectral range of the fiber laser is determined by $\tilde{n}_{\rm sp}$, the single pass gain, the output coupling, and the transfer function of the FFP filter after the gain medium. The noise power can be significantly reduced by placing the narrow-band FFP between the gain medium and the output coupler and by reducing the output coupling to lower the single pass gain. An analysis of the spatial variation of the inversion is required to determine $\tilde{n}_{\rm sp}$,[4,5] and it is expected to increase as the inversion at threshold is reduced by lowering the output coupling.

If the noise from beating of the lasing mode and side modes can be adequately reduced, then shot noise in the lasing mode will be the dominant source of intensity noise, and the total intensity noise level will approach the standard quantum limit. Excess noise due to inversion dynamics and pumping is expected to be negligible at high frequencies, due to the low relaxation resonance frequency of the erbium laser. Figure 2 shows the measured relaxation resonance spectrum near 25 kHz for an 820 μW laser output power and that this resonance frequency occurs in the tens of kilohertz, increasing as the square root of the laser power, in accordance with theory.[6]

Measurements of the SQL and laser intensity noise power versus laser output power are performed using the balanced homodyne detection (BHD) system shown in Fig. 3, balanced to give a common-mode rejection >40 dB. The laser gain medium used throughout the experiments is a Corning Fibergain module with 20 m of Er^{+3}-doped fiber co-doped with aluminum; the amplifier pump beam co-propagates with the lasing mode. The laser intensity noise power at 307.5 MHz and SQL measurements as a function of optical power at the ring output are shown in Fig. 4 for 90% laser output coupling and the two configurations of Fig. 1. With the narrow-band FFP placed between the gain medium and output coupler, as in Fig. 1(b), a 15 dB noise reduction is observed compared with configuration (a). This reduction is comparable to the 17 dB of additional filtering provided by the narrow-band FFP, as compared to the broadband FFP at 310 MHz. Because the narrow-band FFP has 3 dB higher insertion loss at the transmission peak than the broad-band FFP, the laser output power is slightly reduced for the lower noise configuration, as shown in Table I.

TABLE I. Power at output of laser ring for configurations: (a) narrow-band FFP before gain medium and (b) narrow-band FFP between gain medium and output coupler.

Output coupling	Pump laser current	Power (a)	Power (b)
90%	150 mA	710 μW	450 μW
50%	250 mA	1230 μW	730 μW
10%	300 mA	360 μW	200 μW

The intensity noise power near 310 MHz relative to the SQL is shown in Fig. 5 for output couplings of 90%, 50%, and 10%, with both configurations (a) and (b) of Fig. 1. Over a 6 MHz frequency span, 14–16 and 16–20 dB reductions in noise power are observed in changing from configuration (a) to configuration (b) for the 90% and 50% output couplings, respectively. The intensity noise power actually reaches the SQL in configuration (b) with the 10% output coupler. All of the data shown in Fig. 5 have been corrected, as described in Ref. 3, to give the noise power at the fiber laser output by accounting for the 40% to 48% total measurement quantum efficiencies, which include both the detector efficiencies and losses before the BHD system. Experimental uncertainty in the lowest noise measurement is 0.2 dB, which increases to 0.5 dB when corrected for the optical losses.

We have shown how the high frequency intensity noise arising from side modes in an erbium-doped tandem FFP fiber laser can be greatly suppressed by intracavity spectral filtering between the gain medium and the laser output. By employing this technique in a laser with reduced output coupling losses, intensity noise was reduced to the standard quantum limit.

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