Comments on "Intensity noise of an injection-locked Ti:sapphire laser: analysis of the phase-noise-to-amplitude-noise conversion"

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An analysis showing that phase noise in a master diode laser is converted to amplitude noise in an injection-locked Ti:sapphire power amplifier was recently published ["Intensity noise of an injection-locked Ti:sapphire laser: analysis of the phase-noise-to-amplitude-noise conversion," J. Opt. Soc. Am. B, **23**, 1276–1286 (2006)]. As this analysis might discourage the broad implementation of injection locking, we report amplitude noise and laser linewidth measurements in such a system and note that these lasers have sufficiently low noise to be useful in a wide range of experiments in atomic, molecular, and optical physics. A low-power diode laser is amplified to 1.6 W at 846 nm. Amplitude noise is measured using a high-speed photodiode. Frequency noise is measured relative to a low-noise commercial Ti:sapphire laser using an offset lock and heterodyne technique. Under optimal conditions, the relative rms amplitude noise is 1%. The linewidth of the injection-locked laser is 300 kHz. As others in this field have shown, the amplitude and frequency noise characteristics depend critically on the lock circuit characteristics.

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Injection locking can be used to amplify low-power lasers to watt-level output powers [1–9]. In Ti:sapphire, this method can be used across the entire Ti:sapphire gain bandwidth, from 700 to 1100 nm. Watt-level output power at a handful of wavelengths in this spectral range can be achieved using tapered diodes or broad-area diode lasers. However, injection locking in Ti:sapphire offers the advantage of wavelength flexibility and superior spatial mode quality.

An analysis of the phase and amplitude noise of an injection-locked Ti:sapphire laser has been published [6], similar in spirit to the analyses of other injection-locked systems [1,2]. In that analysis, it was shown that the phase noise inherent in diode laser (master) sources increased the amplitude noise in the amplified output. This behavior limited the potential usefulness of their system for certain kinds of quantum optics experiments.

We show here that these lasers have sufficiently low noise to be useful in a wide variety of experiments in atomic, molecular, and optical physics. We report amplitude and frequency noise measurements of an injection-locked Ti:sapphire laser. The amplitude noise is measured using a high-speed photodiode. Frequency noise is measured relative to a low-noise commercial Ti:sapphire laser using an offset lock and heterodyne technique. Under optimal conditions, the rms amplitude noise is 0.26% in a measurement bandwidth of 0.03 Hz to 100 kHz and 1.04% in a measurement bandwidth of 0.1 to 70 kHz. The linewidth of the injection-locked laser is 300 kHz. Recent work has shown that this linewidth can be reduced to 1 kHz [9].

Our experiment is similar to what we described previously [3]. A low-power diode laser (New Focus Vortex, 846 nm, 17 mW) is amplified to 150 mW using a tapered amplifier. This output is then injected into a four-mirror Ti:sapphire laser cavity. The cavity has no additional optical elements—no Lyot filter, no Faraday isolator—just four mirrors and the gain crystal. The crystal is pumped using 7 W at 532 nm (Coherent Verdi V-10). The cavity produces up to 1.6 W at 846 nm. A high-speed feedback circuit is used to lock the diode laser to a resonance in the Ti:sapphire laser cavity.

In our experiment, the rms amplitude noise of the amplified laser is only weakly influenced by the gain achieved in the injection-locking process. In a measurement bandwidth from 1 kHz to 70 MHz, the relative rms amplitude noise increases from about 1% to about 2% as the injection power measured at the input of the Ti:sapphire laser cavity is reduced from 100 to 10 mW. Stable operation at low injection power is similar to reports in the literature [8].

A more detailed study of the amplitude noise reveals that the noise increases in certain frequency ranges as the injection power changes. In Figs. 1 and 2, we plot the power spectrum of the amplitude noise when the Ti:sapphire laser is injected at high power (black curve) and low power (medium gray curve). At low power, the amplitude noise increases for frequencies above 250 kHz. This coincides with an apparent phase shift in our feedback system. The diode laser current modulation input, which we use to control the diode laser frequency on a fast time scale, displays a 3 dB roll-off in the transfer function at 1 MHz. However, the phase shift in the transfer function is not as easily measured. Based on our experience using a variety of different high-speed feedback circuits, it appears a phase shift occurs in the current modulation circuit in the diode laser controller near 250 kHz. Our measurements suggest that the noise increase with low injection power is not fundamental per se, but rather related to the limitations of our feedback circuit. This can also be inferred by looking at Fig. 12 in [6], where the amplitude noise is shown to be related

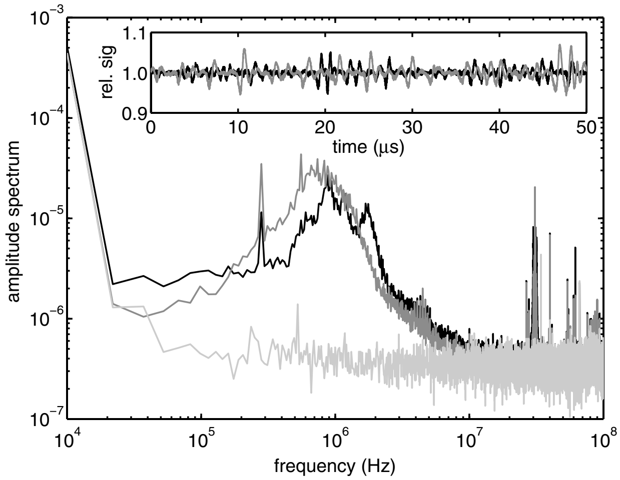

Fig. 1. Amplitude spectrum showing amplitude noise in the injection-locked laser system under different locking conditions. Black curve, 80 mW injection power; medium gray curve, 15 mW injection power; light gray curve, noise floor of our high-speed detection system. As the injection power decreases, the noise above 250 kHz increases. In this frequency range, our feedback system displays a phase shift, limiting our ability to eliminate noise at high frequencies. The amplitude noise of the pump laser and the commercial Ti:sapphire laser used in this experiment are both below the measurement noise floor. The noise floor is relatively high due to the 8 bit analog-to-digital (A/D) resolution in the high-speed data acquisition system. A Hanning window is used in the fast Fourier transform (FFT) analysis. The amplitude spectrum is smoothed using a moving average to produce an effective measurement bandwidth of 15 kHz. The 45 mV signal used in this analysis corresponds to 1.4 W of laser power. Inset: 50 μs of data showing the amplitude noise on the injection-locked laser. Black curve, 80 mW injection power; medium gray curve, 15 mW injection power. The relative rms noise of this data is 1.0% and 1.7%, respectively.

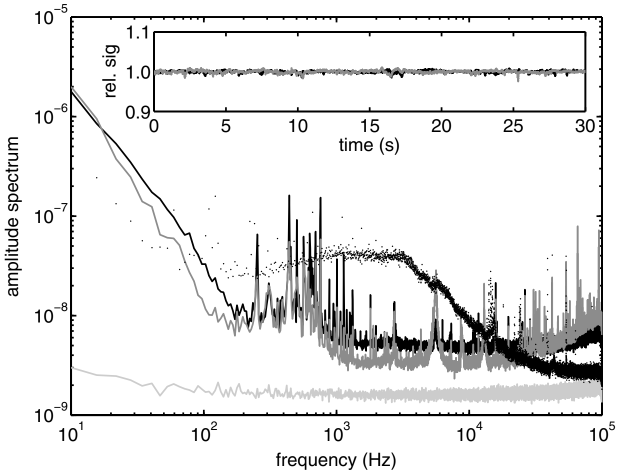

Fig. 2. Amplitude spectrum of the injection-locked laser system at low frequencies for the same conditions as plotted in Fig. 1. Black curve, 80 mW injection power; medium gray curve, 15 mW injection power; light gray curve, noise floor of our low-speed detection system. The noise floor is limited by the 24 bit A/D resolution of the low-speed data acquisition system. The amplitude noise of the commercial Ti:sapphire laser is plotted as black dots in this figure. Above 50 kHz, the noise in that laser approaches the measurement noise floor. A Hanning window is used in the FFT analysis. The amplitude spectrum is smoothed using a moving average to produce an effective measurement bandwidth of 6.25 Hz. The 45 mV signal used in this analysis corresponds to 1.4 W of laser power. Inset: 30 s of data showing the amplitude noise on the injection-locked laser. Black curve, 80 mW injection power; medium gray curve, 15 mW injection power. The rms noise of this data (measurement bandwidth 0.03 Hz to 100 kHz) is 0.26%.

to the feedback gain. This result is not surprising given the analysis in [1]. We note that the amplitude noise can be reduced further by stabilizing the laser power, e.g., by using an acousto-optic modulator.

We measure the frequency noise by comparing the injection-locked Ti:sapphire laser output with a commercial single-frequency low-noise Ti:sapphire laser (M-squared Lasers, SolsTiS, linewidth <50 kHz). The two laser beams are attenuated and overlapped on a high-speed photodiode (Newport 818-BB-21, 1.2 GHz bandwidth). The beat note is high-pass filtered and amplified and sent to a microwave interferometer. The interferometer is similar to the one described in [10]. A radiofrequency power splitter is used to send the signal into two delay lines of 3 cm and 4 m. The signals are then recombined using a double-balanced mixer and low-pass filtered. The interferometer produces an error signal with a zero-crossing when the frequency difference between the two lasers is 10.2 MHz. This error signal is integrated using a high-speed servo controller (New Focus LB1001) feeding back to the injection-locked laser system.

In the top panel of Fig. 3, we show the power spectrum of the laser heterodyne beatnote between the master laser and the M-squared laser. For this measurement, the high-speed integrator mentioned in the previous paragraph offset locks the diode laser to the M-squared laser. The width of the beatnote is a measurement of the master laser linewidth compared to the M-squared laser. The FHWM of this beatnote is around 65 kHz with sidebands at ±270 kHz. These sidebands are generated by the high-speed integrator and are not inherent in either laser.

In the bottom panel of Fig. 3, we show the power spectrum of the laser heterodyne beatnote between the injection-locked Ti:sapphire laser and the M-squared laser. For this measurement, the high-speed integrator feeds back to the cavity length of the injection-locked Ti:sapphire laser. The width of the beatnote has increased to 300 kHz in the amplification process. It seems likely that the increase is due to the phase-to-amplitude noise conversion mentioned in [6]. However, other factors appear to be important. Our measured linewidth is similar to the ~500 kHz linewidth reported in [9], where the

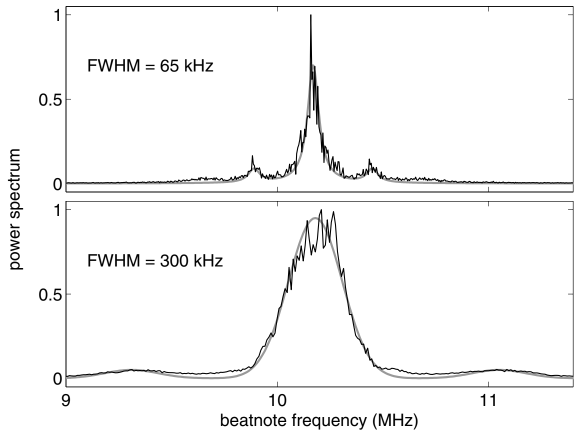

Fig. 3. Beat note signal of the master laser with the M-squared laser (top panel) and the injection-locked laser with the M-squared laser (bottom panel). The thin black lines are experimental data and the thicker gray lines are Lorentzian (top panel) and Gaussian (bottom panel) fits of the data. The amplification process increases the laser linewidth. Advanced techniques can be used to reduce the frequency noise to 1 kHz [9].

master laser was already a low-noise Ti:sapphire laser. In that reference, additional steps were taken to reduce the beatnote to 1 kHz. In our system, as the power in the master laser decreases, the linewidth of the amplified laser does not change. However, as shown in Figs. 1 and 2, the amplitude noise does increase.

In summary, we report amplitude and frequency noise characteristics of an injection-locked Ti:sapphire laser. The relatively low noise characteristics (1% rms amplitude noise, 300 kHz linewidth) make this source ideal for a number of applications in laser science and atomic physics.

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