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Frequency and intensity noise of an injection-locked Nd:YAG ring laser

D.J. Ottaway, P.J. Veitch, C. Hollitt, D. Mudge, M.W. Hamilton, J. Munch

Department of Physics and Mathematical Physics, The University of Adelaide, Adelaide SA 5005, Australia
(Fax: +61-8/8232-6541, E-mail: pveitch@physics.adelaide.edu.au)

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Abstract. Measurements of intensity and frequency noise of an injection-locked 5-W Nd:YAG laser are presented and compared with the predictions of models. We show that the output of the injection-locked laser has very low levels of noise, and that the measurements support the predictions of the models. Thus these models can confidently be used to predict the performance of high-power, injection-locked lasers being developed for gravity wave detection.

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High-power, single-frequency, low-noise, solid-state lasers that produce diffraction-limited output are required for a wide range of precision metrology applications, of which laser interferometers to detect gravitational waves (GW) are the most demanding [1–4]. A strategy for producing such a laser is to amplify a low-noise, single-frequency laser without introducing significant additional noise, and this can be achieved using one of several techniques, including a master-oscillator-power-amplifier (MOPA) system, a below-threshold, regenerative amplifier or an injection-locked power oscillator. All three concepts have the potential to satisfy the stringent amplitude and frequency noise requirements for GW interferometry. The choice of technology depends on the stability, power level, efficiency and reliability. At very high powers, where the gain medium is fully saturated, the MOPA is preferable because it is simple, reliable and low risk. At low and intermediate powers (up to approximately 100 W), where it is difficult to saturate an amplifier, the injection-locked oscillator is preferable because it is expected to have lower noise and be more efficient. However, injection-locked oscillators are perceived to be complex and risky. Current research efforts are therefore concentrating on both the MOPA architecture and injection-locked oscillators, in efforts to gather sufficient detailed understanding to determine the optimum laser approach for the next generation GW interferometer [5–11].

In our laboratory we are working on the injection-locked oscillator approach. The purpose of our work is to determine if the approach is practical and reliable when scaled to high power. The major issues are to determine if the current detailed understanding of noise in injection-locked oscillators is valid when scaled to high power, and to demonstrate a scalable laser architecture. In this paper we shall concentrate on the former issue, whereas our approach to the latter has been described elsewhere [10, 11] and will be summarized only very briefly here.

Although injection locking of Nd:YAG lasers has previously been demonstrated at significant power levels [6–9, 12–15], the detailed comparison of theoretical predictions and experimental measurements of frequency and amplitude noise is far from complete and inadequate for confident power scaling of the concept. In this paper we shall describe for the first time the detailed comparison of theory and performance of an injection-locked oscillator system with significant power gain (100 mW amplified to 5 W).

Our approach to the high-power injection-locked oscillator is an injection-locked chain, shown schematically in Fig. 1. It was chosen to improve the reliability of the injection-locking process, as the power gain per stage is decreased and the injection-locking range thus increased [16]. We have already demonstrated an injection-locked 5-W Nd:YAG laser that reliably produces a diffraction-limited TEM_{00} mode that has low frequency and intensity noise [9]. This laser was injection-locked to a monolithic non-planar ring oscillator (NPRO)[1] equipped with a 'noise eater' for suppression of the relaxation oscillation. The laser design used is directly scalable to 10–20 W if required [17, 18]. The high-power laser will use a stable/unstable resonator [10, 11] which is scalable to output powers greater than 100 W.

The frequency noise of the injection-locked 5-W laser was found to be due primarily to that of the NPRO master laser at low frequencies, with the contribution from the frequency noise of the slave laser being negligible below 50 kHz [9]. The LIGO-I frequency noise specification, that it be less than $500 \times (100/f)\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ for the frequencies between 100 Hz and 10 kHz [19], was thus easily satisfied. Consistent with most other reports describing point designs in injection locking, the actual performance was emphasized, without deter-

[1] Manufactured by Laser Zentrum Hannover (LZH), Hannover, Germany

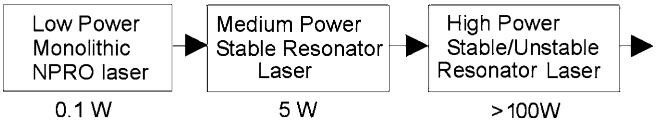

Fig. 1. A three-stage injection-locked architecture. Each stage is individually optimized for mode control and efficiency. The laser powers shown in the figure are indicative only

mining if the measure noise agreed with the predictions by current models, thus verifying the models. This verification is essential for confident use of the models to predict the noise of the 100-W laser. In Sect. 1 of this paper we show for the first time that the contribution is consistent with the predictions of the models.

There are also stringent requirements on the intensity stability of the laser for gravitational wave detectors [19]. In the GW frequency band, 40 Hz to 10 kHz, the amplitude spectral density of relative intensity noise (RIN) must be less than $10^{-5} \times (100/f)^2 /\sqrt{\text{Hz}}$ between 40 Hz and 100 Hz, and less than $10^{-5} /\sqrt{\text{Hz}}$ between 100 Hz and 10 kHz. Furthermore, at the RF frequencies used in the Pound–Drever–Hall frequency-locking servo controls, the RIN must be less than 1.005 times the shot-noise limit for 600 mW of detected power. The relative intensity noise in the GW band should be able to be further reduced to $10^{-6} /\sqrt{\text{Hz}}$ by feedback.

It has been predicted that the intensity noise at low frequencies of an injection-locked laser is caused primarily by the fluctuations in the power of the slave laser pump diodes [15, 20, 21]. Thus, intensity stabilization by feedback to the drive current of the slave laser pump diodes would be preferred and convenient. Intensity stabilization of low-power lasers by feedback to a single-emitter pump diode has been reported [22–25] but there have been no publications that describe intensity stabilization by feedback to the multi-emitter, high-power diode laser arrays that pump a high power slave laser. In Sect. 2 we remedy this situation by including what we believe to be the first published account of intensity stabilization of an injection-locked multi-watt laser by feedback to the high-power pump diode arrays, and show that the approach meets the requirements for GW interferometry.

We have previously reported that our injection-locked laser is shot-noise limited for frequencies above 1 MHz when detecting 75 μW of power [9]. In Sect. 3, we present measurements of high-frequency intensity noise when detecting 66 mW, and compare the measurements with the predictions of the fully quantum mechanical theory [20, 21]. To our knowledge, this is the first time the high-frequency noise of an injection-locked solid-state laser has been characterized at these power levels.

1 Frequency noise

1.1 Theoretical predictions

The contributions to the frequency noise of an injection-locked laser can be determined by following the approach used by Adler [16] for microwave oscillators. The Adler equation [26] can be solved using Laplace transform analysis to yield the transfer functions for the frequency noise of the master and slave lasers to the output of the injection-locked laser [15]:

$$H_{\mathrm{m}}(\omega) = \frac{\phi}{\phi_{\mathrm{m}}} = \frac{1}{1 + j\frac{\omega}{\omega_{\mathrm{lock}}\cos[\Delta\phi(t)]}} \,, \tag{1}$$

$$H_{\mathrm{s}}(\omega) = \frac{\phi}{\phi_{\mathrm{s}}} = \frac{j\frac{\omega}{\omega_{\mathrm{lock}}\cos[\Delta\phi(t)]}}{1 + j\frac{\omega}{\omega_{\mathrm{lock}}\cos[\Delta\phi(t)]}} \,, \tag{2}$$

where ω_{lock} is the half-width of the locking range, and $\Delta\phi(t) = \arcsin\left[\frac{(\omega_{\mathrm{m}}-\omega_{\mathrm{s}})}{\omega_{\mathrm{lock}}}\right]$, where ω_{m} and ω_{s} are the frequencies of the master and slave lasers.

If the frequency noises of the master and the slave lasers are uncorrelated, then the frequency noise of the injection-locked laser is given by

$$S_{\mathrm{f,il}}(\omega) = |H_{\mathrm{s}}(\omega)|^2 S_{\mathrm{f,s}}(\omega) + |H_{\mathrm{m}}(\omega)|^2 S_{\mathrm{f,m}}(\omega) \,, \tag{3}$$

where $S_{\mathrm{f,il}}(\omega)$, $S_{\mathrm{f,m}}(\omega)$ and $S_{\mathrm{f,s}}(\omega)$ are the spectral densities of frequency noise for the injection-locked, master and slave lasers respectively.

Equations (2) and (3) predict that the frequency noise of the free-running slave laser should couple only weakly to the noise on the output of the injection-locked laser at modulation frequencies less than ω_{lock}, if the slave laser is held near the centre of the locking range. If the slave laser is not held at the centre of the injection locking range then the band of modulation frequencies for which the master laser controls the phase of the injection-locked laser will be reduced, and thus there will be less attenuation of the slave laser frequency noise.

In most practical injection-locked lasers a Pound–Drever–Hall (PDH) servo system, which adjusts the length of the slave resonator and hence its resonant frequency, is used to enable long-term injection locking. The effect of the servo system is not included in (2) however. Thus, Barillet et al. [7] expanded on the approach taken by Farinas by introducing the properties of this servo. The frequency noise of the servo-controlled slave laser is given by

$$S_{\mathrm{f,s\text{-}servo}}(\omega) = \left|\frac{1}{1+G(\omega)}\right|^2 S_{\mathrm{f,s}}(\omega) + S_{\mathrm{f,servo}}(\omega) + S_{\mathrm{f,m}}(\omega) \,, \tag{4}$$

where $G(\omega)$ is the loop gain of the servo loop and $S_{\mathrm{f,servo}}(\omega)$ is the frequency noise that is produced by the electronic noise in the servo. In our system, only the first term is significant for the modulation frequencies of interest (< 10 kHz). The contribution by the slave laser to the frequency noise of the injection-locked laser is thus given by

$$\begin{aligned} S_{\mathrm{f,il(slave)}}(\omega) &= \left|\frac{j\frac{\omega}{\omega_{\mathrm{lock}}\cos\Delta\phi(t)}}{1+j\frac{\omega}{\omega_{\mathrm{lock}}\cos\Delta\phi(t)}}\right|^2 S_{\mathrm{f,s\text{-}servo}}(\omega) \\ &= \left|\frac{1}{1+G(\omega)}\frac{j\frac{\omega}{\omega_{\mathrm{lock}}\cos\Delta\phi(t)}}{1+j\frac{\omega}{\omega_{\mathrm{lock}}\cos\Delta\phi(t)}}\right|^2 \\ &\quad\times S_{\mathrm{f,s}}(\omega) \,, \end{aligned} \tag{5}$$

and this term should replace the second term on the right-hand-side of (3).

Since ω_{lock} is generally much larger than 10 kHz and the frequency of the slave laser is actively controlled such that it is close to the frequency of the master laser, the above equation can be simplified to

$$S_{\mathrm{f,il(slave)}}(\omega) = \left| j \frac{1}{1+G(\omega)} \frac{\omega}{\omega_{\mathrm{lock}}} \right|^2 S_{\mathrm{f,s}}(\omega) \ . \qquad (6)$$

If the measurement frequency is within the servo bandwidth then this equation can be further simplified to

$$S_{\mathrm{f,il(slave)}}(\omega) = \frac{1}{|G(\omega)|^2} \left(\frac{\omega}{\omega_{\mathrm{lock}}} \right)^2 S_{\mathrm{f,s}}(\omega) \ . \qquad (7)$$

1.2 Measurements

While the frequency noise of injection-locked solid-state lasers has been measured by several groups [7, 15], there has been no comparison of a sensitive measurement of frequency noise with theoretical predictions. In a previous paper [9] we described the measurement of the contribution of the servo-controlled slave laser to the frequency noise of the injection-locked laser using an out-of-loop technique [12]. In this technique the output of the injection-locked laser is heterodyned with frequency-shifted power from the master laser, thereby allowing the contribution of the slave laser to be determined accurately and unambiguously. In this section we compare those results with the contribution predicted by (7), and with the contribution inferred from the error signal of the PDH servo used to stabilize the injection-locking.

A plot of the gain of the PDH servo loop is shown in Fig. 2. The free-running frequency noise of the slave laser at frequencies within the servo bandwidth was determined by analyzing the signal fed back to the piezoelectric actuator on which one of the slave resonator mirrors is mounted. The results are shown in Fig. 3. These results can be combined using (6) to determine the expected contribution of the slave laser to the frequency noise of the injection-locked laser. The measured injection-locking range is $\omega_{\mathrm{lock}} = 1.9 \times 10^7 \ \mathrm{s}^{-1}$.

The predicted, measured and error-signal inferred contributions of the slave laser to the frequency noise of the injection-locked laser are plotted in Fig. 4. At frequencies above 300 Hz all three curves are in excellent agreement. Below 300 Hz the out-of-loop heterodyne measurement is believed to be limited by mechanical vibrations of the beam-steering mirrors, which causes a time-dependent wavefront mis-match between the beam from the injection-locked laser and the frequency-shifted beam from the master laser. The predicted and error-signal inferred curves are in good agreement below 300 Hz, except where pickup of 50 Hz radiation and its harmonics contaminates the latter curve.

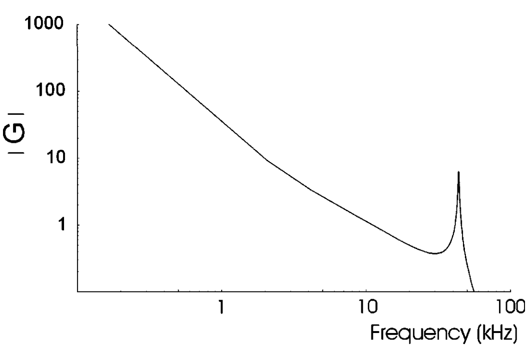

Fig. 2. The magnitude of the PDH servo loop gain

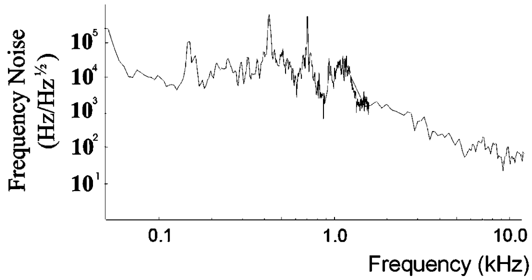

Fig. 3. The free-running frequency noise of the slave laser

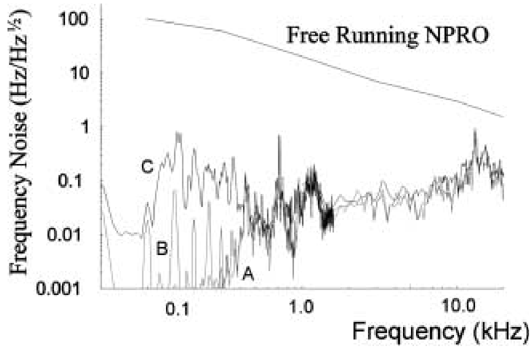

Fig. 4. A comparison of the predicted and measured contributions of the slave laser to the freqency noise of the injection-locked laser: (A) is the theoretical prediction, (B) is the contribution inferred from the PDH error signal and (C) is the frequency noise measured using the heterodyne technique

Also shown in Fig. 4 for reference is the typical frequency noise of a free-running monolithic NPRO [8]. The frequency noise of the injection-locked laser is limited by the NPRO master laser at frequencies below 50 kHz.

2 Intensity noise

2.1 Reduction of low-frequency intensity noise

The block diagram of the intensity noise reduction servo is shown in Fig. 5. The error signal is generated by measuring the intensity of a small fraction of the output of the injection-locked laser using a low-noise detector. The signal from the photodiode is amplified by the preamplifier, which also tailors the loop gain to ensure stability, and then fed back to the diode laser driver.

The diode driver was an SDL 830 from Spectra Diode Labs, which allowed feedback to the laser diode at relatively low frequencies only. The transfer function from the driver input to the pump intensity modulation is shown in Fig. 6. Also shown is the transfer function from the driver input to the intensity modulation of the injection-locked laser. This figure

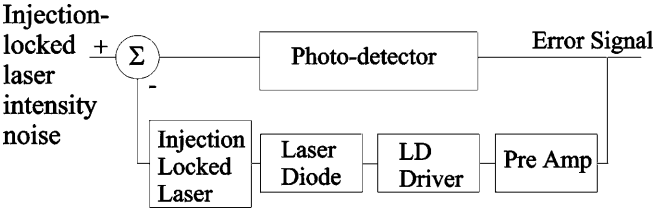

Fig. 5. A block diagram of the intensity noise reduction servo

shows that the servo-bandwidth is limited by the diode driver and not by the injection-locking process.

The transfer function of the pre-amplifier is shown in Fig. 7 and the total loop gain is shown in Fig. 8. The pre-amplifier was ac coupled to prevent dc offsets in the feedback electronics from changing the average diode current suddenly when the loop was closed, as this would change the temperature of the gain medium and thus the natural frequency of the slave laser.

The effectiveness of the feedback is evaluated by measuring the intensity noise of the stabilized laser using an out-of-loop detector; the results are shown in Fig. 9. It shows that feedback to a multi-emitter pump diode laser array can be used to reduce significantly the intensity noise of an injection-locked laser. The reduction factor is limited by the loop gain of the servo above 250 Hz. Below 250 Hz it is believed that the reduction was limited by beam jitter or vibration of the beam-steering mirrors and photodiode, which results in spurious error signals due to variation in the responsivity of the photodiode across its surface [27, 28]. The slight increase in intensity noise between 9 kHz and 30 kHz is due to lack of phase margin at the unity gain frequency. The gain of the servo and the phase margin could be improved by directly injecting the correction current into the diode laser, as has been demonstrated for low-power systems [23].

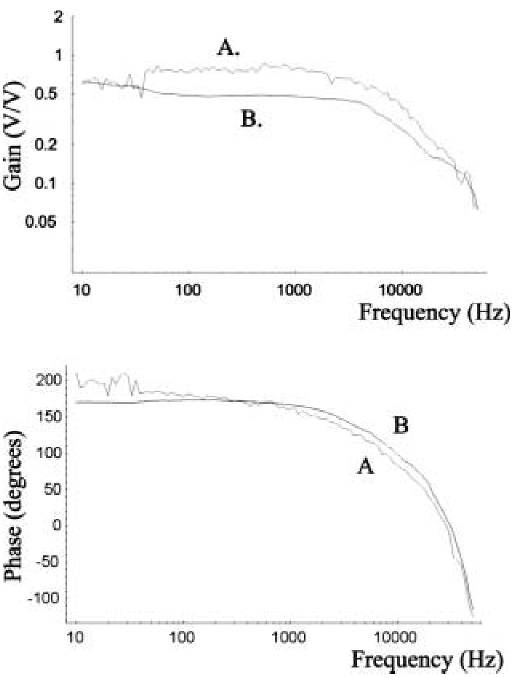

Fig. 6. The transfer functions for the low-frequency modulation port of the laser diode driver to the laser diode output (B) and the output of the injection-locked laser (A)

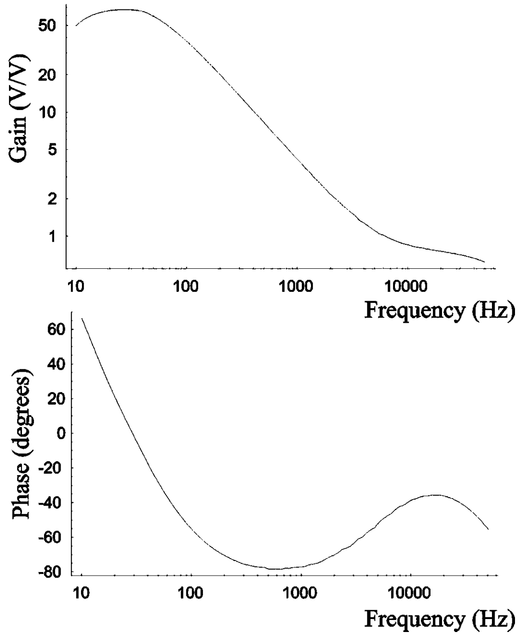

Fig. 7. The transfer function for the pre-amp used in the intensity noise reduction servo

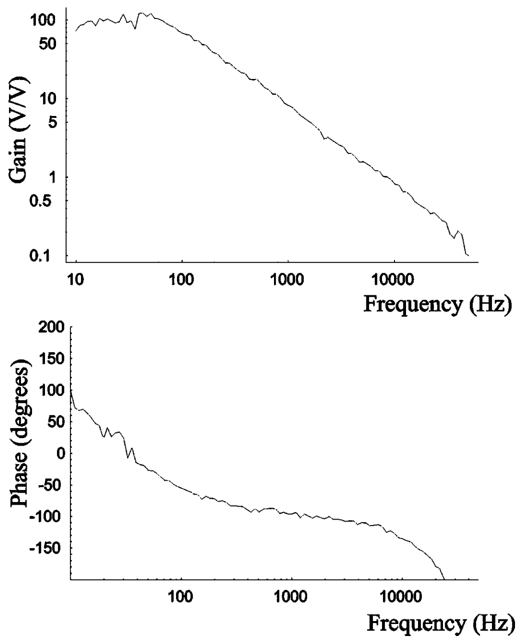

Fig. 8. The loop gain of the intensity noise reduction servo

2.2 Intensity noise at high frequencies

At frequencies around the relaxation oscillation frequency of the free-running slave laser, $\omega_R \approx 2\pi \times 300$ kHz, the amplification of the intensity noise of the master laser by the slave laser should be the dominant contribution to the intensity noise of the injection-locked laser [20, 21]. In this band of frequencies, the RIN spectra of the injection-locked and master lasers should be the same.

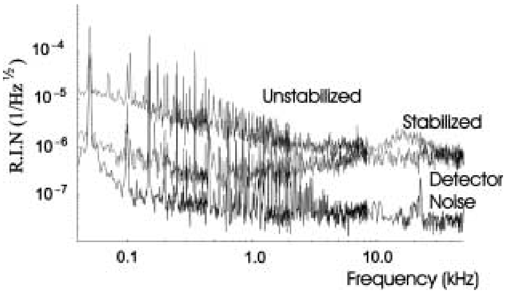

Fig. 9. Intensity noise reduction by feedback to the pump diodes of the slave laser

At higher frequencies, the amplification is predicted to decrease as the intensity noise from the master laser is reflected by the slave resonator. The relative intensity noise of the injection-locked laser, RIN_{il}, should then be given by

$$RIN_{\text{il}}^2\,(f) = \frac{2e}{I} + \frac{RIN_{\text{m}}^2\,(f)}{F_{\text{R}}}\ , \tag{8}$$

where RIN_{m} is the relative intensity noise of the master laser, e is the charge on an electron, I is the detected photocurrent and F_{R} is given by

$$F_{\text{R}} = 1 + \frac{\left(\omega_{\text{R}}^2 - \omega^2\right)^2}{\omega^2\omega_{\text{lock}}^2}\ . \tag{9}$$

If $\omega \gg \omega_{\text{R}}$ then (9) can be simplified to

$$F_{\text{R}} = 1 + \left(\frac{\omega}{\omega_{\text{lock}}}\right)^2\ . \tag{10}$$

We have measured the intensity noise of the master laser and the injection-locked laser at frequencies above 100 kHz using a broadband, high power photo-detector[29] and a Tektonix 497 P spectrum analyzer. The results are plotted in Figs. 10 and 11. The spectra in Fig. 10 were measured using the same amount of optical power and thus confirm that the RINs of the injection-locked and master lasers are identical at frequencies near ω_{R}. The peaks below 400 kHz in the noise spectrum for the injection-locked laser are due to resonances in the PZT-actuated mirror on the slave resonator, which produce phase noise that is weakly coupled into the intensity noise of the injection-locked laser [7, 21]. At higher frequencies, the noise power of the injection-locked laser is less than that of the master laser, as expected.

An expression for RIN_{m}^2 at frequencies above about 1 MHz can be obtained from Fig. 10:

$$RIN_{\text{m}}^2\,(f) = 9.4\times10^{-15}\,(f\ /1\ \text{MHz})^{-(3.0\pm0.2)}\ . \tag{11}$$

The frequency dependence of this equation does not agree with the predictions of any current theory: semi-classical rate equation analysis [30] predicts that the RIN^2 should decrease as f^{-4} at frequencies above the relaxation oscillation, whereas a fully quantum mechanical model [31] predicts a f^{-2} roll-off. The dependence also does not agree with an earlier measurement of the intensity noise of a low-power NPRO laser [31] which shows a f^{-2} roll-off. At present we do not have an explanation for this discrepancy.

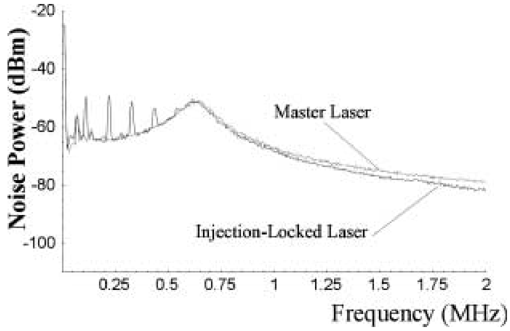

Fig. 10. The medium frequency intensity noise of the injection-locked slave and master laser. Measurement parameters: 9.5 mA photo-current, transimpedance gain $= 500$ V/A, detection bandwidth $= 10$ kHz, detector response $= 0.7$ A/W

Figure 11 shows the measured intensity noise power of the injection-locked laser at RF frequencies when detecting approximately 66 mW of optical power. Note that the measurement is well above the detector noise floor, and that the shot noise begins to mask the roll-off of the contribution due to the master laser at about 5 MHz. The measured noise power and the noise power predicted by (8) are plotted in Fig. 12.

Equation (8) can be used to estimate the relative intensity noise of the injection-locked laser at higher powers and frequencies. For 600 mW of detected optical power, the RIN of the injection-locked laser should be 1.006 times the shot noise

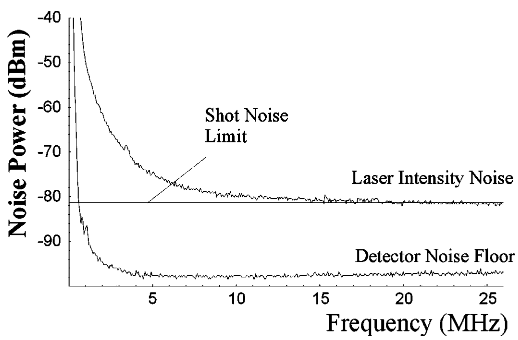

Fig. 11. High-frequency intensity noise with measurement parameters: photo-current $= 46$ mA, transimpedance gain $= 500$ V/A, detection bandwidth $= 100$ kHz, detector response $= 0.7$ A/W

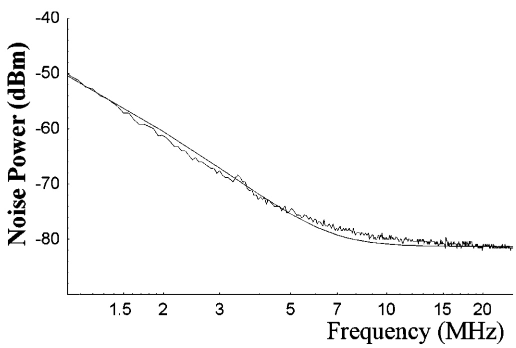

Fig. 12. A comparison of the measured intensity noise of the injection-locked laser and that predicted by (8). The measurement parameters are as for Fig. 11

limit at the lowest LIGO-I modulation frequency (24.5 MHz), assuming a photodetector response of 0.7 A/W.

3 Conclusion

We have presented detailed measurements of the frequency and intensity noise of a diode-pumped, 5-W Nd:YAG laser that is injection-locked by a monolithic NPRO. The frequency noise at measurement frequencies of interest to gravitational wave interferometers is dominated by the frequency noise of the master laser and thus easily satisfies the LIGO-I requirement. The contribution of the slave laser to the frequency noise of the injection-locked laser is negligible at these frequencies, and is accurately predicted by the model discussed in Sect. 2.

We have also shown that relative intensity noise in the GW band can be reduced to less than $10^{-6}/\sqrt{\mathrm{Hz}}$ by feedback to the multiple-emitter pump diodes of the slave laser. The reduction factor was limited by the bandwidth of the diode driver and additional reductions can be expected in the future. A further consequence of our results is that the scheme for broadband intensity stabilization as demonstrated by Huntington et al. [25] for low-power injection-locked Nd:YAG lasers can be applied to higher power lasers.

Finally, the high-frequency intensity noise of the injection-locked laser has been measured for relatively large photocurrents (46 mA). The noise at 24.5 MHz and 600 mW of detected power is thus expected to be only 0.6% above the shot-noise limit, which essentially satisfies the LIGO-I specification.

The injection-locked 5-W laser is thus eminently suitable for use in high-precision metrology experiments such as gravitational wave detection. Further, we have demonstrated that the models used to estimate the noise of injection-locked lasers are valid for 5-W slave lasers, and thus can be used for even higher power slave lasers with more confidence.

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