Amplitude Modulation on Frequency Locked Extended Cavity Diode Lasers

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Abstract The increase in low frequency amplitude noise on several extended cavity diode lasers was measured when frequency or phase lock servos were applied using the injection current as the feedback channel. The AM noise increase inside the FM servo bandwidth is approximately that expected from the suppression of frequency noise uncorrelated with the inherent amplitude noise of the laser.

I. Introduction

The noise characteristics[1] of semiconductor diode lasers are relevant to a number of applications, including communications and spectroscopy. The noise can be quite complex due to optical feedback and the well known AM to FM coupling, and is an area of active research.[2] Diode lasers are often used with extended cavities to provide wavelength tunability and to narrow the linewidth. It is now common practice to use active (electronic) control systems to suppress portions of either the AM or FM noise. The coupling between AM and FM in the semiconductor laser complicates the noise characteristics in these active feedback control systems. For example, in many systems the feedback path is via the laser's injection current, which simultaneously alters both the amplitude and frequency of the laser.

In previous experiments we studied some of the limitations of using active electronic control of the injection current to suppress AM noise on the output of an extended cavity diode laser (ECDL).[3] The fundamental shot-noise-limit may be approached (fig. 1), but only by using most of the laser output for the feedback control channel. The photo-current signal-to-noise (s/n) of the useful experimental beam reaches a maximum in between the extremes of using most of the light for the experiment (in which case the technical AM is not suppressed) or for the servo control (in which case the shot s/n level is relatively high).

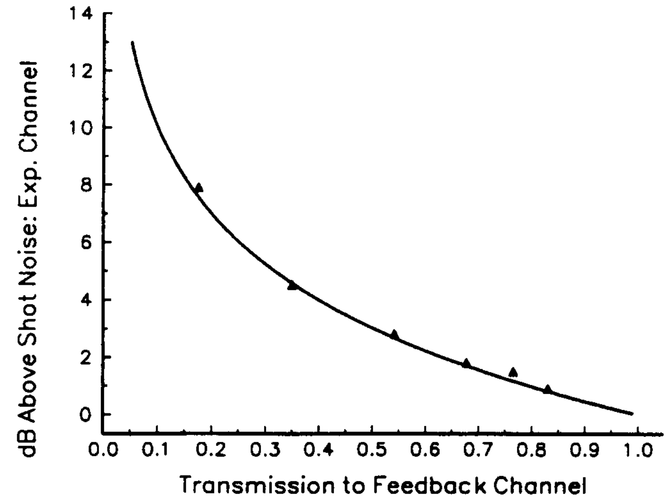

Fig. 1 The performance of an AM feedback loop to the injection current of an ECDL. The residual AM noise of the experimental beam photo-current is plotted versus the beamsplitter transmission to the servo detector.

In some applications both the AM and FM laser characteristics are important. For instance in very high-resolution spectroscopy, it is desirable to have a narrow linewidth laser with low AM noise, zero frequency drift, and precise tunability. Towards this goal we have phase-locked (with a tunable offset frequency) an ECDL to a stable low-drift reference ECDL, by using feedback to the slave injection current. However the injection current feedback path cannot also be used for AM control, and furthermore the FM control adversely affects the laser's AM. In this paper we report measurements of the power fluctuations when frequency control is employed.

In the case of a frequency servo acting through the injection current, the output power is affected primarily by the injection current

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fluctuations. More generally, for any method of feedback the changes induced in the FM noise by the servo will also be mapped to amplitude noise by any element in the extended cavity that has a frequency dependent gain or loss. The amount of FM to AM conversion is dependent on the dispersion of the longitudinal mode selector (usually a diffraction grating), and the lasing wavelength with respect to the mode selector, as well as the chip facet reflectance and alignment effects.

When diode lasers are built into extended cavities of moderate lengths (≈10 cm), the inherent frequency noise is reduced so that a relatively low bandwidth (≈1 MHz) electronic feedback loop is sufficient to frequency lock the laser.[4] At low Fourier frequencies piezo-electric elements may be used to adjust the cavity length, while higher bandwidths require feedback either to the laser injection current, or to intra-cavity tuning elements.[5] Most often the slow piezo feedback loop is necessary to keep the higher bandwidth loop in the center of it's dynamic range.

We can make an estimate of the AM induced by a frequency control servo that uses the injection current by assuming no correlation between the inherent FM and AM fluctuations of the ECDL. In this case the induced AM will add in a root mean square fashion to the inherent amplitude noise. We can estimate the induced power fluctuation $\Delta P(f)$ (in mW/$\sqrt{\text{Hz}}$) from the frequency noise density $S_{\dot{\varphi}}(f)$ that is suppressed when the loop is closed. The dependence of the output power with current $\Delta p/\Delta i$, and the dependence of the laser frequency with injection current $\Delta \nu/\Delta i$ are used to estimate the induced AM. The ratio $\Delta p/\Delta i$ is assumed flat with frequency, which is justified by noting that we are only interested in the effects within the servo bandwidth (relatively low frequencies). We write

$$\Delta P(f) = \frac{\sqrt{S_{\dot{\varphi}}(f)} \cdot \frac{\Delta p}{\Delta i}}{\left| \frac{\Delta \nu}{\Delta i}(f) \right|} \tag{1}$$

as an estimate for the maximum increase in the output power noise spectrum within the servo bandwidth. The increase of the relative intensity noise (RIN) is then $[\Delta P(f)/P_o]^2$.

II. Experiment

The increase in the AM noise due to frequency control loops using current feedback was measured in two separate experiments. A Littrow type extended cavity laser at 657 nm was frequency locked to an optical cavity by electronic feedback to the injection current and the changes induced in the AM spectrum were measured. Secondly, two grazing incidence ECDL's were slaved to reference lasers with a phase-lock by feeding back to the slave injection current ports.[6] The changes induced in the AM spectrum of the slaves were measured.

The Littrow laser was built using an anti-reflection coated 3 mW laser, and frequency locked to the optical cavity with a Pound-Drever-Hall RF lock scheme.[7] The RF modulation was applied with an external modulator resonant at 20 MHz. In the case of injection-current locking the feedback bandwidth was approximately 500 kHz. The power versus injection current had a slope of 0.09 mW/mA, as shown in figure 2. Also shown in figure 2 is the dc change in frequency with injection current $\Delta\nu/\Delta i$, measured at different bias current levels by sweeping the reference cavity and monitoring the correction signal to the injection current. The laser would lock for a frequency interval which could easily be determined with the help of the modulation sidebands, and during this interval the change of the injection current correction signal was measured. The laser cavity length was 12 cm, and the power output at the normal operating point of $I/I_t \approx 1.16$ was about 1.0 mW.

At this bias-current level the complex frequency dependence of $\Delta\nu/\Delta i$ was measured out to 4 MHz with a network analyzer. The response was flat out to several hundred kHz, decreasing 10 db in magnitude by 1.5 MHz. The phase of the response was nearly constant to 100 kHz, but lagged by approximately 90° at 1.5 MHz.

An alternative method for frequency stabilization of this laser was also used for comparison. An electro-optic modulator (a 1 cm aperture ADP crystal) was used in the extended laser cavity[5] to provide a feedback path to the cavity length that is independent of the injection current (and hence to first order the power). For this path the feedback bandwidth was approximately 1 MHz.

The AM noise with the laser unlocked and locked with the two feedback paths is shown in figure 3. The laser was operating with a dc injection current of I/I_t=1.16, and $\Delta\nu/\Delta i \approx 40$ MHz/mA when the locked data was recorded. No change in AM is observed with feedback to the intra-cavity EO crystal.

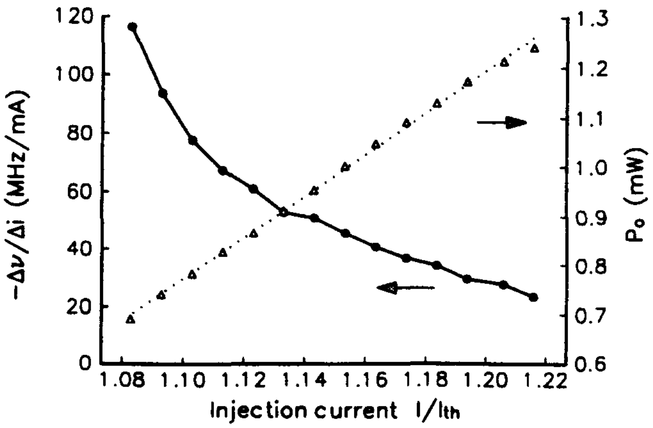

Fig.2 The output power of the Littrow AlGaInP extended cavity laser above threshold and the dc change in frequency with injection current, $\Delta\nu/\Delta i$. The frequency response was also measured (see text).

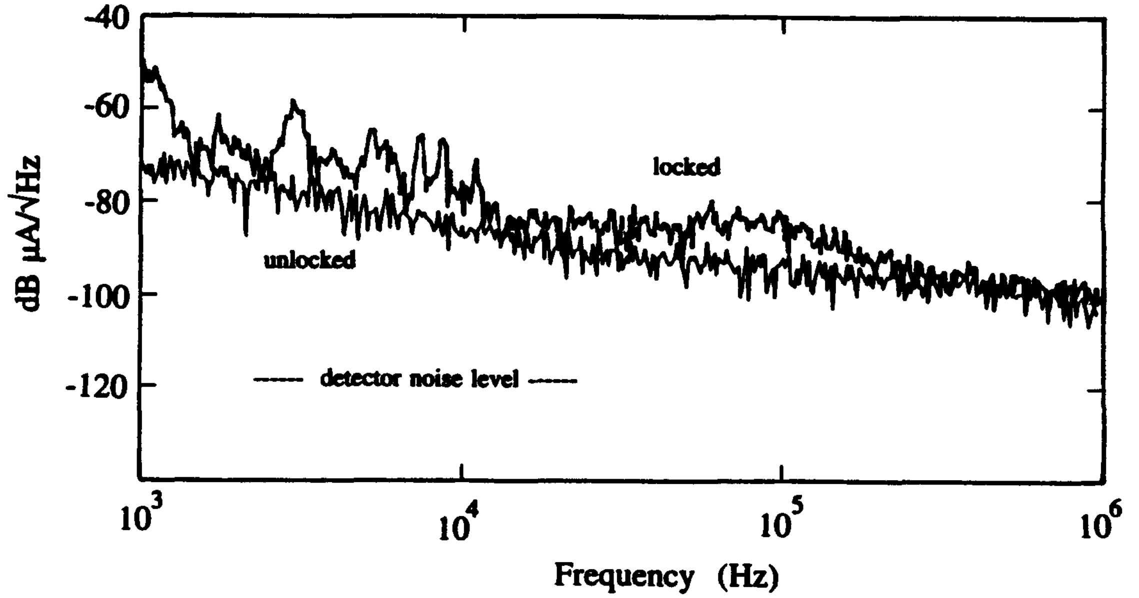

Fig. 3 The low frequency amplitude noise spectrum of the Littrow AlGaInP ECDL. The upper-most trace is the laser locked to an optical cavity by feedback to the injection current. The lower trace is the amplitude noise of the unlocked laser, which on this scale does not change when the laser is locked to the cavity with the intra-cavity electro-optic crystal. The detector noise level is indicated, and the dc photo-current is ≈210 μA.

In the second experiment, a slave ECDL was constructed with an anti-reflection coated 5 mW red diode laser. A diffraction grating with 1800 l/mm was used at a grazing incidence angle of about 85 degrees, and the cavity length was approximately 8.8 cm, resulting in a free spectral range of 1.7 GHz. The output power at the normal operating point was about 2 mW. This laser was phase-locked to the Littrow laser discussed above, and the beat note is shown in figure 4. A significant AM noise increase in the frequency region near the phase-lock servo's unity gain point was observed, i.e. where the noise shoulders appear in the beat note. An example of this induced AM is shown in figure 5.

The other AM measurement of a phase-locked slave was also with a grazing incidence type ECDL, except the laser was a 100 mW AlGaAs laser operating at 792 nm. This ECDL was slaved to a Ti:Sapphire laser with a feedback bandwidth of approximately 800 kHz. The phase-lock on the AlGaAs laser was implemented with a similar degree of phase margin, and a similar increase in the slave's AM noise spectrum was observed.

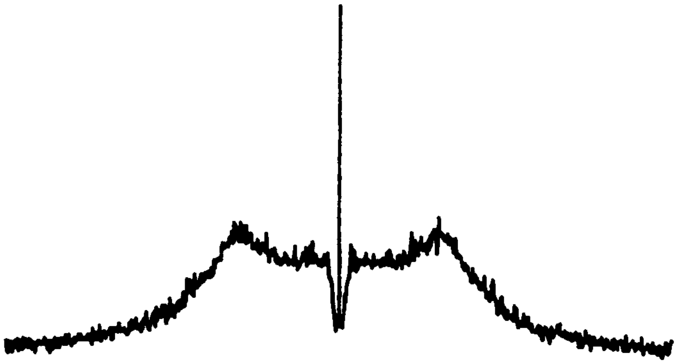

Fig. 4 A beat note between the 657 nm Littrow laser and the phase-locked slave. The offset frequency is approximately 200 MHz. The trace is over a 10 MHz band, and the noise peaks are at 1.5 MHz. The noise close to the carrier peak is -60 dBc.

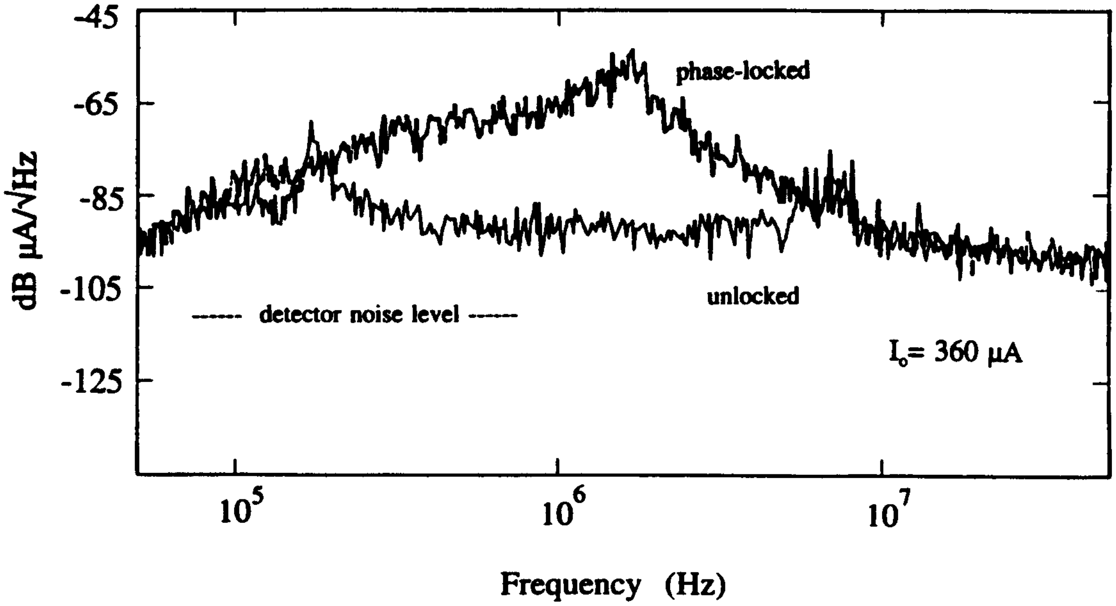

Fig. 5 The AM noise of the phase-locked slave laser (upper trace). The broad noise peak at 1.5 MHz corresponds to the increase in phase noise at the FM servo's unity gain frequency. The peak in the phase noise at this point, combined with the decreasing sensitivity of the laser frequency to injection current, acts to increase the AM noise.

III. Discussion

The frequency locked ECDL noise data (fig. 3) clearly shows a broad-band increase in the AM noise level, and further increases at distinct frequencies. The FM noise spectrum typically exhibited by an ECDL operating in the single-mode regime has a 1/f frequency dependence, reaching a spectrally-white noise-floor at approximately 100 kHz. Structural resonances will cause narrow-band frequency noise, and the FM servo response to this narrow-band noise shows up as AM peaks in the locked spectrum. A noise floor of approximately 10^4 Hz^2/Hz in the frequency noise density was measured in the 12 cm long ECDL.[5] The network analyzer measurement indicates that the current to frequency transfer function value at dc ($\Delta\nu/\Delta i \approx$ 40 MHz/mA) is valid at 100 kHz. The induced AM noise can then be estimated at 100 kHz.

Approximately 50% of the laser output was incident on the AM noise detector, and the detector responsivity at 657 nm was measured to be 0.43 mA/mW. Using equation (1), at 100 kHz the estimated maximum photo-current noise level for the induced AM is -86.3 dBμA/√Hz.

The data of fig.3 shows good agreement with this level, even though we have used a very simplistic model. The current servo-loop bandwidth used was about 500 kHz, and the data shows the locked AM noise approaching the unlocked case at about this frequency.

The AM noise of the phase-locked slave laser (figure 5) displays a large increase in the frequency region near 1.5 MHz. The phase margin of the FM loop at the unity gain frequency was such that the beat note between the two lasers had broad noise sidebands centered at approximately 1.5 MHz from the carrier peak. Only the dc value of the transfer function $\Delta\nu/\Delta i(f)$ of the slave was measured, which was 40 MHz/mA at the operating current level.

However as the laser chip is of the same type[8] and the extended cavity is a similar length as the Littrow laser, we assume that the transfer function $\Delta\nu/\Delta i(f)$ of the slave is similar to that of the Littrow laser. If so, the 10 dB decrease of $\Delta\nu/\Delta i(f)$ together with a 20 dB increase in the phase noise near the FM servo's unity gain point would account for the increase in the AM noise observed in figure 5.

IV. Summary

An increase in the AM noise when an extended cavity diode laser is frequency or phase locked by feedback to the injection current was measured. The increased AM was consistent with a simple model that relates FM noise to AM through the sensitivity of the laser frequency, and power to injection current. The most prominent increases in the AM noise were from low frequency mechanical vibrations that the FM servo suppressed, and from the servo gain peaking near the bandwidth limit, which is accentuated in this frequency region by a decrease in $\Delta\nu/\Delta i$, the dependence of frequency on the injection current.

References

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8. The lasers used were Toshiba TOLD9421 and TOLD9321. This is mentioned only to allow repeatability of experimental results, and does not imply endorsement of these products.

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