RF performance of optical injection locking

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ABSTRACT

Coherent photonic systems promise novel functionality and/or improved performance compared to direct detection photonic systems, but have the disadvantage of being sensitive to optical phase noise. The most common approach to this problem is to force one laser to track the phase of the other with a phase locked loop (PLL), so that the phase noise of the lasers cancels out of the RF heterodyne beat note. Although the PLL approach has been implemented for semiconductor lasers, the large linewidth of these lasers and the resulting large PLL loop bandwidth severely constrain the design and limit performance. This disadvantage of the PLL approach is particularly relevant for many applications, since semiconductor lasers are preferred for system insertion.

An alternative approach for establishing coherence between two lasers is optical injection locking. Standard theory indicates that injection locking can act in the same way as a first order PLL with a bandwidth as high as several GHz, which is large enough to achieve state of the art noise levels (e.g. -130 dBc/Hz @ 1 MHz offset) with semiconductor lasers. We present phase noise measurements on the beat note of two injection locked semiconductor lasers. Our results (phase noise @ 1 MHz offset as low as -125 dBc/Hz) indicate that state of the art phase noise performance from injection locked lasers should be obtainable in practice. We found that it is necessary to length match the two paths in the experiment (master -> detector and master -> slave -> detector) to avoid excess noise due to delay decorrelation of the master, and also that environmental noise seems dominant at offsets < 20 kHz.

Keywords: Optical injection, phase noise, optical carrier tracking

1. INTRODUCTION

Analog point-to-point communication applications can be effectively addressed by direct detection analog RF photonic links due to the high dynamic range these links provide. Since only the optical intensity is detected, the performance of these links is not degraded by optical phase noise, provided all optical components are broadband relative to the frequency jitter of the laser, which is nearly always the case in practice. However, there is a growing interest in pushing analog signal processing operations from the RF domain into the optical domain, especially as the RF carrier frequencies and/or RF bandwidths increase significantly beyond the current state of the art. Logically, there are three possibilities for how signal processing can be divided up between the optical domain and the RF domain: 1) Do all processing in the RF domain, which is essentially the current state of the art, 2) Do all processing in the optical domain, which is only possible for a limited subset of the processing functions of interest, and 3) Do some processing in the optical domain, and the rest in the RF domain, which is conceptually more complicated than the other approaches, but is also likely to be the only practical approach for moving sophisticated signal processing (partly) into the optical domain.

An example of the distinction between approaches 2 and 3 is provided by an optical channelizer. If the channelizer simply disperses a modulated optical carrier onto a detector array then all the processing is done in the optical domain (approach 2 above), but all the system can do is give total power in each channel. If the channelizer disperses a modulated optical carrier and a suitable comb of optical LO frequencies onto a detector array, then further electronic signal processing can be performed on the outputs of any or all of the detectors. Thus a coherent optical channelizer is suitable for incorporation into a system where the signal processing task is split between the optical and RF domains (approach 3 above). This example is a clear illustration of the basic principle that coherent optical detection is required in any system where (linear) signal

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processing is split between the optical and RF domains, since the translation from an optical signal to an RF signal is a linear process only for coherent optical detection.

Since coherent detection is a phase sensitive process, the RF beat tone from two independently running lasers will have a phase noise spectrum equal to the sum of the phase noise spectra of the two lasers, and this phase noise will also appear as noise sidebands on every signal of interest if the carrier laser is modulated. Laser phase noise is typically large by RF standards, especially for semiconductor lasers. For example, a semiconductor laser with a linewidth of 1 MHz nominally has L(f) = -68 dBc/Hz at 1 MHz offset while a high performance requirement may be as low as L(f) < -130 dBc/Hz at 1 MHz offset, where L(f) is the SSB phase noise power spectral density (PSD). Fortunately, it is not necessary to reduce the phase noise on each laser individually to such low levels --- it is only necessary to ensure that the heterodyne (or homodyne) beat has low enough noise for the application at hand. This can be done by implementing a "carrier tracking" function that forces the phase of one laser to follow that of the other laser. Since the phase of the heterodyne beat is the difference of the phases of the two lasers, the correlation of the laser phases enforced by carrier tracking leads to a reduction of the beat note phase noise.

2. OPTICAL CARRIER TRACKING

Two approaches that have been demonstrated for performing optical carrier tracking are a phase locked loop (PLL), and optical injection locking (IL). In a (heterodyne) phase lock loop, the beat signal at the photodetector is mixed with an RF reference to produce a low frequency phase signal which passes through a suitable loop filter and is then applied to a tuning input on one of the lasers. A homodyne PLL is the same system without the mixer and RF reference. In either case, when the loop is locked, it acts as a feedback control system that tends to drive the phase difference between the RF reference and the "VCO" (the combination of the two lasers and detector) to zero. Optical injection locking is the coupling of light from the "master" laser into the resonant cavity of the "slave" laser in such a way that the slave output is captured by the master and becomes phase coherent with it. The major necessary conditions for injection locking to occur are that the input light from the master be spatially mode matched to the free running slave mode, and that the frequency of the input from the master be close enough to the free running slave frequency. The frequency range over which injection locking will occur is called the locking range, and can be as much as several GHz for a monolithic semiconductor laser.

The performance of the PLL and IL approaches to carrier tracking (or that of any linear carrier tracking approach) can be quantified by a low pass, unity DC gain, phase transfer function H(f) that essentially describes the strength of the phase correlation between the two lasers induced by the carrier tracking mechanism. The contribution of the laser phase noise to the photocurrent phase noise when carrier tracking is implemented is given by

$$W_{IF}(f) = |1 - H(f)|^2 (W_{L1}(f) + W_{L2}(f)), \tag{1}$$

where W_{IF}, W_{L1}, and W_{L2} are the phase noise PSD [rad^2/Hz] of the photocurrent, laser 1 and laser 2 respectively, and H(f) is the carrier tracking transfer function. For a laser of FWHM linewidth $\Delta\nu$, the (one-sided) phase noise PSD is $W(f) = \Delta\nu/\pi f^2$, provided the laser's frequency noise spectrum is white, which is the usual assumption leading to a Lorentzian lineshape. In applications, the quantity of interest is often L(f), the "SSB phase noise PSD" in dBc/Hz. L(f) is a measure of the effect of phase noise on a carrier, in that it gives the ratio of the noise sideband power density to the carrier power as a function of offset frequency. If the total phase variance is small, then L(f) [dBc/Hz] $\approx$ W(f)/2 [rad^2/Hz]. If the phase variance is not small, the relation between L(f) and W(f) is much more complicated. In Eq. 1, the phase variance of the free running lasers is infinite (assuming white laser frequency noise), but the phase variance of the heterodyne beat is typically small, if the carrier tracking mechanism is performing properly. We will make this assumption in the remainder of the paper, so that Eq. 1 can be used to obtain estimates of $L_{IF}(f)$. As the bandwidth of H(f) increases, carrier tracking performance improves, since the phase noise cancellation is effective over a wider spectrum, and the noise cancellation at low frequencies typically improves.

2.1 PLL carrier tracking

For a PLL, H(f) is the usual loop transfer function which is given by

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$$H(s)=\frac{2\zeta\omega_n s+\omega_n^2}{s^2e^{s\tau}+2\zeta\omega_n s+\omega_n^2}, \tag{2}$$

for a high gain, second order loop, where $s = j2\pi f$, ω_n is the loop natural frequency [rad/s], ζ is the loop damping factor, and τ is the loop time delay, since there is necessarily some time delay incurred in propagation around the loop. The loop time delay is a critical parameter, since it must satisfy the following inequality for a high gain, second order PLL to be stable:

$$\omega_n\tau<\frac{\tan^{-1}\left(2\zeta\sqrt{2\zeta^2+\sqrt{4\zeta^4+1}}\right)}{\sqrt{2\zeta^2+\sqrt{4\zeta^4+1}}}. \tag{3}$$

For the typical case $\zeta = 0.707$, this reduces[1] to $\omega_n\tau < 0.736$. Since the bandwidth scales linearly with ω_n, increasing the bandwidth to provide more noise reduction leads to a more stringent requirement on the time delay τ. Furthermore, if τ is too close to violating Eq. 3, there will be a large peak in the noise spectrum due to inadequate gain and/or phase margins which will often not be acceptable in practice.

The work reported in reference[2] provides a concrete example. In this work, the carrier laser had a linewidth of 2 MHz and the LO laser had a linewidth of 6 MHz. A second order loop was implemented, with $\omega_n = 7.8 \times 10^8$ rad/s and $\zeta = 0.707$, which leads to a time delay requirement of $\tau < 0.94$ ns. The time delay as implemented was only 0.4 ns, which satisfied the stability requirement, but meeting this requirement severely constrained the design, since optical and electrical path lengths had to be kept as small as possible, and loop circuitry that added too much delay could not be employed. A spectrum analyzer trace was given, and assuming the observed noise is entirely phase noise, the results were L(f) = -117 dBc/Hz at 1 GHz offset, L(f) reaches a peak of -102 dBc/Hz between 100 MHz and 300 MHz offset, and the "low frequency" limit (on a GHz span) of L(f) was -125 dBc/Hz. It seems clear from this work that the only approaches for dramatically improving PLL carrier tracking performance are to monolithically integrate the PLL to reduce the loop delay to the maximum extent possible, or to significantly reduce the phase noise of the lasers being controlled by the loop.

Our interest in injection locking for carrier tracking of lasers, especially semiconductor lasers, is motivated mainly by the difficulty of the PLL time delay issue and the absence of a similar time delay issue for injection locking. The reason injection locking has no time delay issue is that it does not depend on feedback through an external loop --- all the action is confined to the cavity of the slave laser, which is typically very small. In the next section, we obtain a simple estimate of the H(f) that may be obtained from injection locking.

2.2 Injection locked carrier tracking

Laser dynamics are frequently described by a set of rate equations for the optical intensity, optical phase, and population inversion. A linearization of these rate equations about a CW operating point gives a transfer function matrix that relates the inputs (injected amplitude, injected phase, slave pump current) to the outputs (slave amplitude, slave phase, slave population inversion). In any case of practical interest, noise induced fluctuations will be small enough to justify the use of a linearized model. Although the basic ideas are always the same, the exact form and complexity of this type of analysis varies widely, depending on the approximations that are made in the development. For our purposes, it is convenient to start from a detailed recent analysis[3] of semiconductor laser injection locking, and identify the additional approximations we make to obtain our estimates.

We neglect optical intensity and population inversion fluctuations. We also assume that the static phase difference between master and slave is zero, which requires the master frequency to be slightly less than that of the free running slave due to phase-amplitude coupling in semiconductor lasers[4]. With these assumptions, the system of linearized rate equations decouples, and the phase equation reduces to

$$\frac{d}{dt}\delta\phi\approx\frac{c}{2nL}\sqrt{\frac{P_i}{P_0}}(\delta\phi_i-\delta\phi)+F_\phi(t), \tag{4}$$

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where $\delta\phi$ is the slave phase, $\delta\phi_i$ is the master phase, P_i is the (mode-matched) injected power, P_0 is the free running slave power, n is the index of refraction of the slave cavity (at its free running operating point), c is the speed of light, L is the cavity length, and F_ϕ is the Langevin phase noise source for the slave laser. For a laser with Lorentzian linewidth $\Delta\nu$, we have $W_F = 4\Delta\nu$ [rad^2/s^2Hz] for the PSD of the Langevin source F_ϕ. Since we refer P_0 and n to the free running slave, we are also assuming a condition of low-level injection, where the injection is weak enough that it does not significantly change the operating point of the slave (i.e. output power and carrier concentration). Although the approximations needed to obtain Eq. 4 are drastic, it is important to note that it was not necessary to assume a negligible phase-amplitude coupling, so Eq. 4 is applicable to a semiconductor laser provided the stated assumptions are valid. From Eq. 4, we can show the photocurrent PSD is given by Eq. 1, as claimed above, with a transfer function given by

$$H_{IL}(f) = \frac{\Delta\omega}{s + \Delta\omega}, \text{ where} \tag{5}$$

$$\Delta\omega = \frac{c}{2nL}\sqrt{\frac{P_i}{P_0}}. \tag{6}$$

We see that Eq. 5 is a transfer function of the same form as for a first order PLL with DC loop gain (~equivalent to bandwidth) $\Delta\omega$. For typical parameters ($L = 300\ \mu m$, $P_i/P_0 = 0.01$, $n = 3.5$), a bandwidth of 1.4×10^{10} rad/s is obtained, which is a bandwidth that is difficult to obtain from a stable PLL.

Given a transfer function for a carrier tracking approach, laser phase noise spectra and photocurrent phase noise requirements, it is possible to derive requirements on the bandwidth of the carrier tracking approach from Eq. 1. For example, suppose the lasers have Lorentzian lineshapes (i.e. white frequency noise) with 1 MHz linewidths, and the phase noise requirement is L(f) < -130 dBc/Hz at offsets $\geq$ 1MHz. For a second order PLL with $\zeta = 0.707$, we obtain $\omega_n > 7.9 \times 10^9$ rad/s to meet the phase noise requirement (assuming the time delay does not significantly affect the performance), which leads to a stringent time delay requirement of $\tau << 90$ ps. For injection locked carrier tracking according to Eq. 5, we obtain $\Delta\omega > 1.12 \times 10^{10}$ rad/s, which is less than the bandwidth estimated above from typical laser parameters. From these estimates, it seems clear that injection locking is a promising approach for carrier tracking of semiconductor lasers, and the remainder of this paper will be devoted to phase noise measurements in support of this claim.

3. EXPERIMENTAL SETUP

Figure 1 gives a simplified schematic diagram of our injection locking experiment. All components in Figure 1 were commercially available fiber coupled components, except the slave laser which was an unpackaged distributed feedback (DFB) device which was fiber coupled via a pickup head. In Figure 1, light from the master laser (an external cavity laser with nominal linewidth of 10 kHz operating at 1.55 μm) was split by a 3 dB coupler into the two arms of the interferometer. In the upper arm, the light passed through an attentuator/isolator unit that also provided an output power readout. The next component was a circulator, which provided additional isolation for the master (ports 1 to 2). After the circulator, the light from the master passed through a polarization controller that aligned the injected polarization with the slave polarization. The output of the slave returned through the polarization controller and the circulator (ports 2 to 3), so it was separated from the injected light. The slave output from port 3 of the circulator passed through a 3 dB coupler to a detector. In the lower arm of the interferometer, the light from the master was coherently frequency shifted by an acousto-optic (AO) frequency shifter driven by an RF reference. The AO frequency shifter that was available could only generate a frequency shift of 55 MHz, which sufficed to demonstrate the concept, although a larger frequency shift is desirable. After the frequency shift, the light passed through a length of fiber intended to equalize the lengths of the two paths in the experiment (master -> slave -> detector and master -> frequency shift -> detector). The necessity for this path length balancing will be explained in the following text. The next components were a polarization controller, 3 dB coupler and detector. The purpose of the polarization controller was to align the polarizations of the two optical signals at the detector to maximize the 55 MHz beat signal. The detected signal was then amplified and input into a demodulating phase noise test set (HP 3048a) for SSB phase noise PSD (i.e. L(f)) measurements. A spectrum analyzer was also used, mainly to determine the presence or absence of injection locking.

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There are several key features of this injection locking experiment. The first is that it was almost completely fiber coupled, and could have been used with a fiber pigtailed slave laser in an unisolated package. The second key feature is the use of an optical circulator that provided an efficient separation of the slave light from the injected master light. A third feature is the use of a demodulating phase noise test set, which provided a considerably lower measurement noise floor than can be obtained with a spectrum analyzer, and also gave about 20 dB of amplitude noise suppression. Finally, fiber coupling reduced the difficulty and uncertainty of the injection ratio measurement. The fiber to slave coupling loss applied equally to the slave output and the injected input. Thus a relatively simple coupling efficiency measurement (we obtained a slave to fiber coupling efficiency of approximately 50%) also gives the master to slave injection efficiency, which is a difficult measurement in free space.

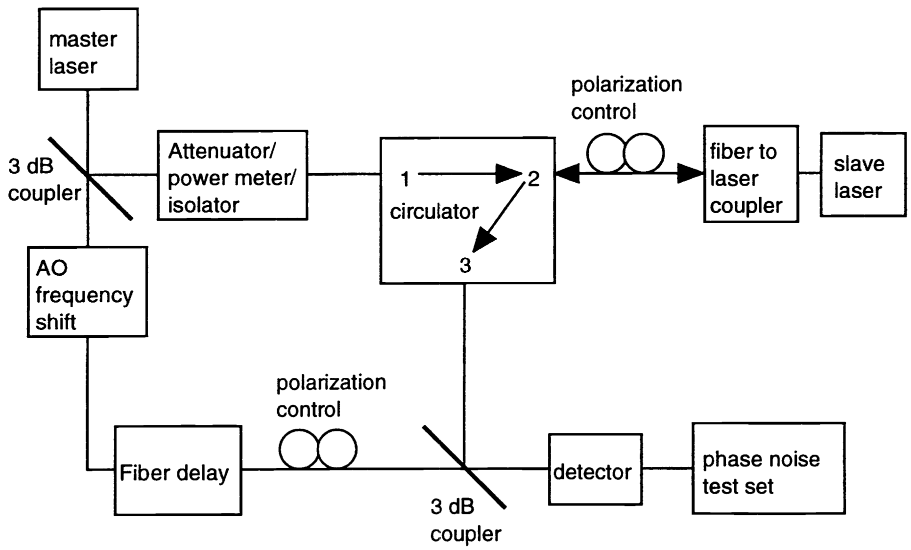

Figure 1: Schematic diagram of injection locking phase noise measurement

Before giving our results, it is necessary to consider some consequences of our measurement approach. The basic idea of the measurement is to form a heterodyne beat note between the injection locked slave laser and a frequency shifted portion of the master laser output, and measure the phase noise on this beat note with a phase noise test set, as seen in Figure 1. This is the same basic arrangement that is used for a self-heterodyne measurement[5] of the linewidth of a single laser, so it follows that the relative time delay between the two arms of the experiment is a critical parameter. If this time delay is too large, the noise induced by decorrelation of the master will swamp the noise due to imperfect master-slave tracking that we are trying to measure. For a laser with white frequency noise and FWHM linewidth $\Delta\nu$, the self heterodyne SSB phase noise $L_{SH}(f)$ is given by[6]

$$L_{SH}(f) = \frac{\Delta\nu}{\pi}\frac{1}{f^2+\Delta\nu^2}\left(1-e^{-2\pi\Delta\nu\tau}\left(\cos 2\pi f\tau + \frac{\Delta\nu}{f}\sin 2\pi f\tau\right)\right), \tag{7}$$

where $\tau \geq 0$ is the magnitude of the time delay difference between the two arms of the experiment. In the limit of small τ (i.e. $\Delta\nu\tau << 1$ and $f\tau << 1$) this reduces to a white L(f) given by

$$L_{SH0} \approx 2\pi\Delta\nu\tau^2. \tag{8}$$

From Eq. 8, we can obtain time delay requirements given the master laser linewidth and a self heterodyne noise floor requirement. For example, if we want self heterodyne noise to be below -140 dBc/Hz (i.e. well below the requirements of interest), and the master laser linewidth is 10 kHz, we obtain $\tau < 0.4$ ns. To obtain the same self heterodyne noise floor with a 1 MHz linewidth master laser requires $\tau < 40$ ps. Since a time delay of 0.4 ns corresponds to roughly 8 cm of fiber, it is not difficult in principle to ensure adequate path length matching in a laboratory scale experiment, especially if the master laser

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has a relatively narrow linewidth. It should be noted that in many applications of phase coherent lasers, such as generation and distribution of RF carriers by optical heterodyne detection, the same requirement for path length matching must be imposed on the two paths to each detector in the system.

The requirement for matched path lengths led to a number of practical difficulties. One problem was that due to the high degree of isolation in this system, it was not possible to use an optical time-domain reflectometer to measure and balance the path lengths. A second issue was that the need for balanced path lengths was not appreciated until the setup had been assembled, and completely tearing down the experiment to physically measure all lengths of fibers was not feasible. Even if this had been feasible, the accuracy of the path balancing would have been marginal at best. As a result, a trial and error procedure for path length balancing was employed. Fortunately, this could be done with only the master laser operating, since the weak reflection of the master from the slave laser facet led to a self heterodyne beat at the detector, with essentially the same relative time delay that would occur in injection locking. The noise floor (presumably due to relative time delay) on this beat note was measured, and the length of the fiber delay was varied in an attempt to minimize the noise floor according to Eq. 8.

The qualitative trend was as expected --- for fiber delays that were clearly too long or too short, the measured noise floor was higher than it was for fiber delays which were closer to the path matching condition. Quantitatively, it was not possible to reduce the noise floor to less than about -127 dBc/Hz, which suggests the presence of another source of phase noise in addition to the path length mismatch. Although it is not known what the source of this excess noise is, some potential sources have been eliminated. The two RF synthesizers (HP 8662) in the experiment (one to drive the AO frequency shifter, the other to serve as a reference in the phase noise test set) both had a noise floor of -140 dBc/Hz over the relevant range of offset frequencies. The thermal noise in the amplifier/attenuator chain between the detector and phase noise test set also appeared to be too low to account for the observed excess noise. A plausible source of the excess noise is multiple reflections from the (FC/PC) fiber connectors in the experiment, since a multiply reflected contribution to the heterodyne beat may have a very substantial path length mismatch that more than makes up for its relatively small power.

4. EXPERIMENTAL RESULTS

As mentioned above, a spectrum analyzer was connected to the detector output mainly to determine whether or not injection locking was occurring. Under injection locked conditions, the spectrum analyzer trace is a clean tone at 55 MHz. As the master laser is tuned away from the slave laser frequency, lock will eventually be lost, and on the spectrum analyzer this appears as a sudden decrease in the power of the 55 MHz tone (recall that there will always be a sharp 55 MHz tone due to reflection of the master from the slave laser end face), combined with the appearance of a broad, fluctuating peak at higher frequencies (typically > 1 GHz), due to the mixing of the master and unlocked slave. The edge of the injection locking regime exhibits hysteresis, where a detuning that will not cause loss of lock is insufficient to establish lock. Due to this behavior, we took the locking range to lie between the two frequencies at which lock is established from an unlocked condition, since in this range, if lock is lost due to some transient effect, it will always be restored. We were mainly interested in the noise performance of injection locking well within the locking range, so approximate measurements of the locking range were adequate for that purpose. The following figures show a set of phase noise measurements where the injection ratio varies as indicated, and the detuning of the master is readjusted for each spectrum such that we are at or near the center of the locking range, where one expects the lowest noise performance.

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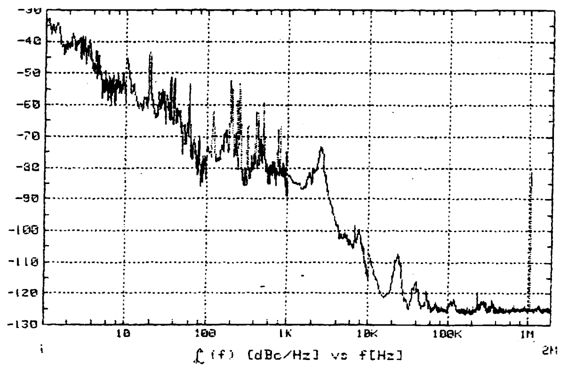

Figure 2: Injection locked phase noise PSD for -16 dB injection ratio

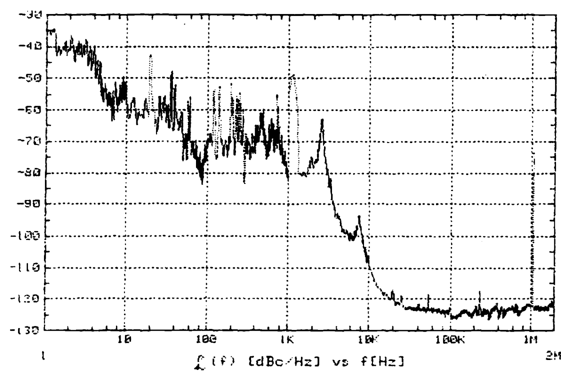

Figure 3: Injection locked phase noise PSD for -21 dB injection ratio

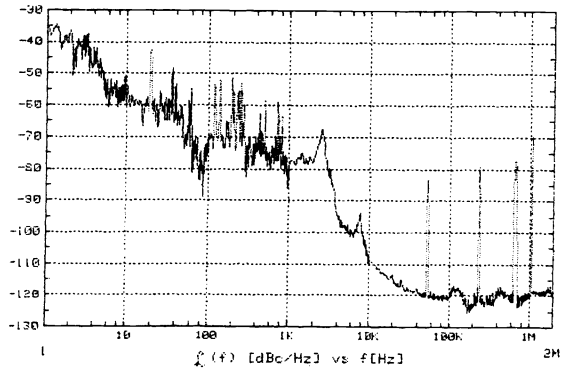

Figure 4: Injection locked phase noise PSD for -26 dB injection ratio

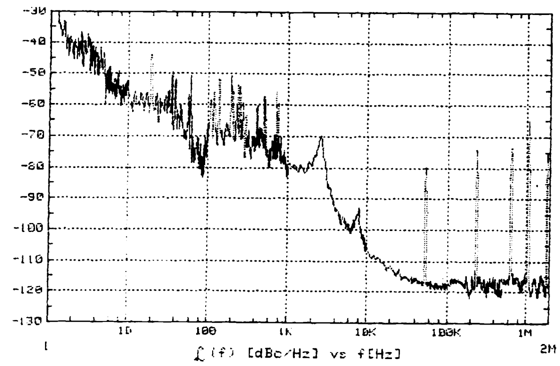

Figure 5: Injection locked phase noise PSD for -31 dB injection ratio

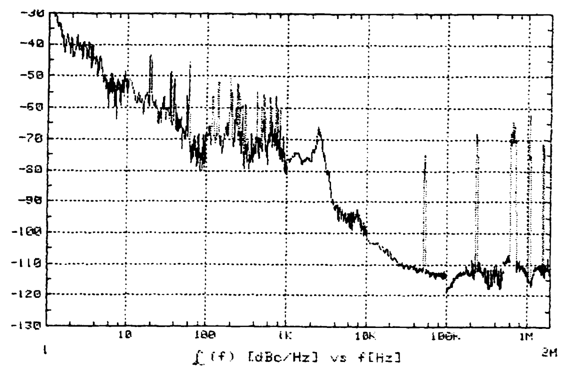

Figure 6: Injection locked phase noise PSD for -36 dB injection ratio

5. DISCUSSION

In Figure 7 we summarize the most significant trend observed in figures 2 through 6, namely that the noise floor at relatively high measured offset frequencies (i.e. 1 to 2 MHz) decreases as the injection ratio increases. From Eqs. 1, 5 and 6 we obtain the following estimate for the phase noise due to imperfect injection locking at low offset frequencies ($f \ll \Delta\omega$):

$$L(f) \approx \frac{2\pi\Delta\nu}{\Delta\omega^2} = \frac{8\pi\Delta\nu n^2 L^2}{c^2}\left(\frac{P_i}{P_0}\right)^{-1}, \tag{9}$$

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where $\Delta\omega$ is the IL bandwidth given by Eq. 5, $\Delta\nu$ is the linewidth of the slave laser, n and L are the slave laser refractive index and length respectively, P_i/P_0 is the injection ratio, and the contribution of the master laser to the heterodyne phase noise is neglected, since the master linewidth is much less than the slave linewidth. Note that Eq. 9 is a low frequency limit compared to the IL bandwidth $\Delta\omega$, so in principle, it should apply over the entire measured range of offset frequencies. In practice, additional sources of phase noise, such as acoustic pickup, are present at offset frequencies less than roughly 100 kHz, so we only expect to see the trend predicted by Eq. 9 at relatively high measured offset frequencies (e.g. 100 kHz to 2 MHz).

The dotted line in Figure 7 is a curve fit to the measured data of the form $L = a\, P_0/P_i + b$, where a and b are the curve fitting parameters. The form of the a term in the curve fit follows from Eq. 9, while an excess noise term b is assumed in the curve fit to account for the data in Figure 7, as well as the observation of excess noise during the path length balancing procedure. The fitting parameters obtained are b = -126.5 dBc/Hz and a = -149 dBc/Hz. The excess noise seen in the curve fit is consistent with the roughly -127 dBc/Hz of excess noise observed when balancing the paths. If we assume plausible laser parameters in Eq. 9 (e.g. $\Delta\nu$ = 10 MHz, n = 3.5, L = 300 μm), we would expect to obtain an a parameter of -145 dBc/Hz, which is quite close to the observed value. An independent measurement of the slave laser linewidth would be a valuable check on the validity of Eq. 9.

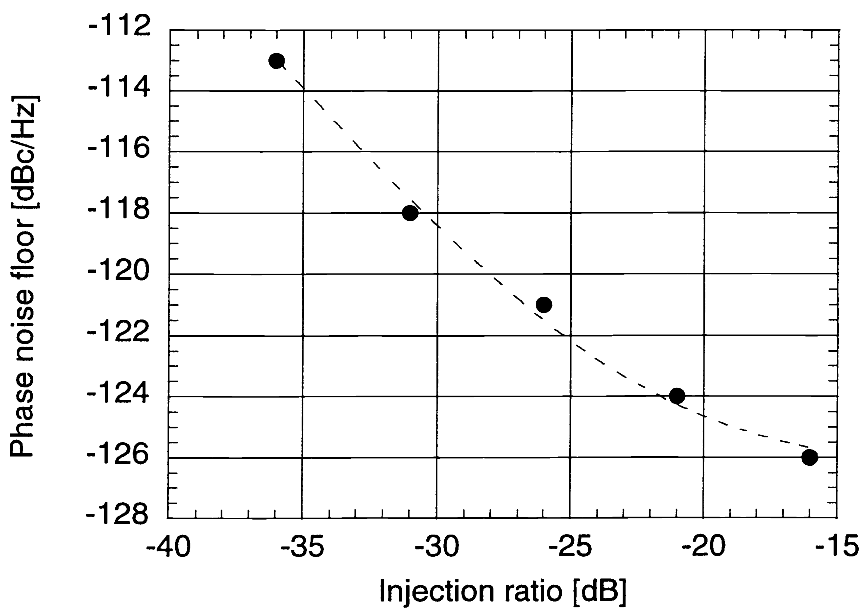

Figure 7: Phase noise floor vs. injection ratio. The solid circles are experimental points and the dotted line is a curve fit.

As seen in figures 2 through 6, the phase noise generally increases as the offset frequency decreases, and no systematic trend in the phase noise data is seen as the injection ratio varies for offset frequencies below several kHz. We believe the measured noise in this frequency range was due primarily to acoustic pickup in the fibers instead of a degradation in the performance of injection locking at lower offset frequencies. Our reasons for this belief are that no special measures were taken to acoustically isolate the experiment, and that the self heterodyne noise spectrum of the master alone had a low frequency noise spectrum essentially identical to that shown in figures 2–6. We also modified the master self heterodyne measurement by significantly decreasing the total length of fiber in the two arms of the interferometer while maintaining an approximate path length match. By doing so, we observed a significant (10–20 dB) reduction of low frequency phase noise, due presumably to decreased acoustic sensitivity, while the high frequency (100 kHz to 2 MHz) noise floor was essentially unchanged.

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6. CONCLUSIONS

In conclusion, this work has demonstrated a very low level of phase noise on the heterodyne beat of optically injection locked semiconductor lasers. To our knowledge, this is by far the lowest reported level of phase noise from injection locked semiconductor lasers. Since the noise floor of -125 dBc/Hz seen in this work appears to be due to an excess noise mechanism unrelated to injection locking, further improvements may be possible, which suggests the consideration of injection locking for the most demanding applications.

We have also seen that time delay noise, and fiber acoustic noise are issues which will usually need to be addressed in applications of phase locked lasers. Usually, time delay noise and fiber acoustic noise are not seen in measurements of PLL performance, but the reason is simply that the PLL acts to enforce phase coherence at the detector, where its performance is typically measured. Thus there is intrinsically no time delay effect in the measurement, and fiber acoustics between the lasers and detector are suppressed by the PLL. In applications, it will frequently be necessary to tap a portion of the output of each laser to make a heterodyne beat at a second detector (e.g. a detector at a remote antenna array element), and time delay noise and fiber acoustic noise along the paths to this second detector are definitely relevant issues. The results shown in figures 2 through 6 give an indication of the level of acoustic pickup that occurs along moderate lengths of connectorized fiber (~20 m or so in each arm of the interferometer) in a laboratory environment, if no attempt is made to isolate the fibers from acoustic disturbances.

Injection locking by itself cannot comprise a complete carrier tracking solution, unless unrealistic requirements are placed on the absolute frequency stability of each laser to ensure the relative drift of the two lasers is an insignificant fraction of the injection locking range. Therefore it is necessary to supplement injection locking with a drift control mechanism. Published methods include an optical PLL[7], and a Pound-Drever-Hall servo loop to lock the master to the slave cavity resonance[8,9]. In principle, the main advantage of injection locking, namely its large noise suppression bandwidth, should be preserved in hybrid schemes of this type, since the drift control mechanism need not have a large bandwidth. In practice, considerable care will be needed to ensure that a practical (i.e. drift stabilized) injection locking scheme really delivers the full performance promised by injection locking.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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