Phase noise characteristics of single mode semiconductor lasers with optical feedback

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The phase noise characteristics of single mode semiconductor lasers with optical feedback have been studied. A correlation is found between the suppression of the low-frequency noise and the enhancement of the high-frequency noise near the relaxation oscillation frequency. Contrary to previous analyses, the low-frequency noise is minimized when the reflected light is 70°–90° out of phase with respect to that inside the diode laser cavity. A calculation of the laser frequency fluctuation spectrum, taking into account the amplitude-phase coupling of the laser field, agrees with the observation. A new explanation is proposed for the feedback-induced phase noise reduction effect.

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The phase noise characteristics of semiconductor lasers are important in determining the performance of coherent optical communication systems and optical fiber sensors. Phase noise, related to laser frequency fluctuations, can be observed as an additional amplitude noise when a laser beam is divided and then recombined after a relative time delay. Many experimental studies have been performed, mostly for low-frequency noise, to evaluate its relevance to interferometric measurements.[1,2] More recently, experimental results show that in the high-frequency regime the phase noise spectrum of a laser without external feedback (referred to as a "solitary laser") exhibits a pronounced peak at the same frequency as the relaxation oscillation[3,4] due to a carrier-fluctuation-induced refractive index change in semiconductor lasers.[3,5] This amplitude-phase coupling is also responsible for the presence of satellite modes separated from the main line by the relaxation oscillation frequency.[6]

In this letter a study of the phase noise characteristics of single mode semiconductor lasers with optical feedback is presented. Previous studies have shown that a weak feedback of 1×10^{-5} can reduce the low-frequency phase noise in semiconductor lasers.[2,7] The present study reveals a new and interesting correlation between the noise suppression in the low-frequency regime and the noise enhancement in the high-frequency regime near the relaxation oscillation frequency. The low-frequency noise is the lowest when the reflected light is 70°–90° out of phase with respect to that inside the laser diode. The result is not predicted from previous analyses which indicate the greatest phase noise reduction under the condition of constructive interference.[2,7] Based on a theoretical analysis which agrees with the observations, a new explanation is proposed for the feedback-induced phase noise reduction effect.

The experimental setup is shown in Fig. 1. The lasers used in this study are single mode channeled-substrate-planar AlGaAs/GaAs lasers made by Optical Information Systems and Hitachi. The lasers are operated at typically 3 mW. The laser current is adjusted to avoid the mode-hopping regime which may complicate the noise measurement. The collimated laser beam is divided by a beam splitter. The reflected beam, approximately 4% of the total power, is reflected back into the laser by a flat mirror. The feedback ratio is controlled by a variable density filter. The phase of the reflected light is controlled by a piezoelectric transducer. The transmitted beam is sent to a Michelson interferometer for noise measurement. To avoid undesired reflections, the mirrors of the interferometer are replaced by corner cubes so that the reflected beams are parallel to, but not collinear with, the incident beams. The recombined beam is detected by a high-speed avalanche photodiode, whose signal is analyzed by an rf spectrum analyzer. The time delay of the interferometer is fine tuned by a piezoelectric transducer to yield a maximum noise signal. Under this condition, the ac component of the photocurrent is directly proportional to the phase difference of the interfering beams.[4] The spectral density of the laser frequency fluctuation, $W_{\Delta\nu}(\omega)$, is related to the spectrum analyzer response $P(\omega)$, by the relation[4]

$$P(\omega)\propto [1-\cos(\omega\tau_M)]\, W_{\Delta\nu}(\omega)/\omega^2, \quad (1)$$

where τ_M is the relative time delay of the interferometer.

Figure 2 shows the measured $W_{\Delta\nu}(\omega)$ vs $\nu(=\omega/2\pi)$ for a laser operated with and without optical feedback. The frequencies below 100 MHz are plotted on a log scale to provide more resolution for the low-frequency regime. The spectrum for a solitary laser exhibits a pronounced peak at the intrinsic resonance frequency, as previously reported.[3,4] In the presence of an optical feedback of 0.3×10^{-4}, the spectrum is

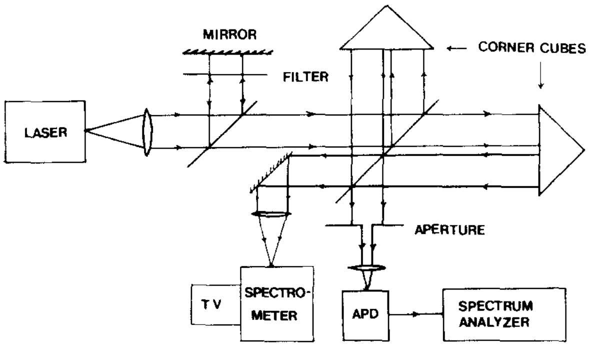

FIG. 1. Experimental setup for the phase noise measurement.

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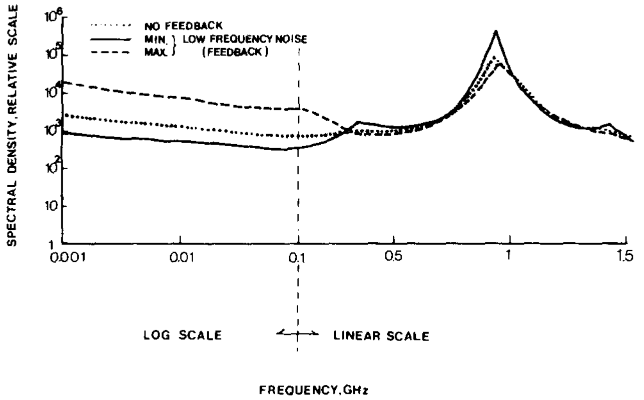

FIG. 2. Measured spectral density of the laser frequency fluctuation for a laser with and without optical feedback. The length of the external cavity is 30 cm. The feedback ratio is 0.3×10^{-4}.

considerably changed. In the high-frequency regime, the feedback induces external cavity harmonics on the intrinsic noise spectrum similar to those found in the intensity noise spectrum.[8] This can be understood in terms of a coupling between the amplitude and the phase of a semiconductor laser through a carrier-density-dependent refractive index change, the same mechanism that gives rise to the noise peak in a solitary laser.[3,5] By changing the phase of the reflected light, the induced noise can be enhanced or suppressed. Interestingly, the noise enhancement (suppression) in the high-frequency regime near the relaxation oscillation frequency is correlated with the noise suppression (enhancement) in the low-frequency regime below 100 MHz. The reflection-induced spectra shown in Fig. 2 correspond to the situations of the maximum and the minimum low-frequency noise. The correlation is more evident in Fig. 3 where the noise powers at 100 kHz and at 1 GHz, as well as the power of the lasing mode, are plotted as a function of the displacement of the external mirror. As the length of the external cavity is varied, the reflected light undergoes alternating constructive and destructive interference with the light inside the laser, giving rise to a periodic variation in the laser power. In the meantime the noise power is enhanced or suppressed depending on the interference condition. The low-frequency noise reaches the minimum when the reflected light is 70°–90° out of phase with respect to that inside the laser diode. The laser frequency is found to be smaller than that of the nearest external cavity mode. The is not consistent with previous theoretical analyses which indicate the greatest phase noise reduction[2,7] under the condition of constructive interference. In actuality, the condition of minimum low-frequency noise does not occur at constructive interference. As will be justified later, this is due to the strong amplitude-phase coupling, which is a major mechanism of spectral line broadening in semiconductor lasers.[9]

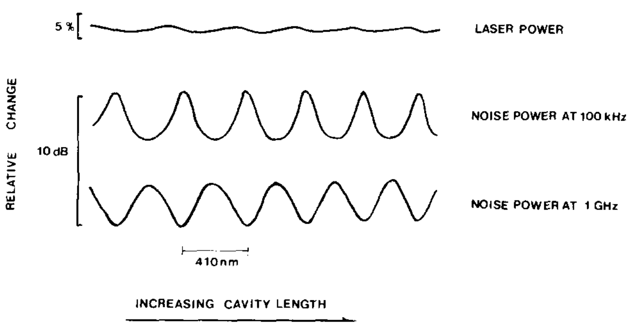

FIG. 3. Measured noise power at 100 kHz and 1 GHz, and the power of the lasing mode as a function of the displacement of the external mirror.

To calculate the spectral density of the laser frequency fluctuation, we adopt the method used by Lang and Kobayashi[10] when they analyze the laser amplitude noise under an external feedback. Two coupled equations are used to describe the carrier density and the complex laser field, $[E+\delta E(t)]\exp(i\phi(t))$, in a compound cavity. The laser frequency is coupled to the carrier density fluctuations through changes in the refractive index of the gain medium. The procedures of the calculation include adding the Langvin noise sources to Eqs. (21), (22), and (24) of Ref. 10 and solving for $\phi(t)$, the phase of the laser field, and $\dot{\phi}(t)=d\phi(t)/dt$. $W_{\Delta\nu}(\omega)$ is then obtained as the Fourier transform of the autocorrelation function $\langle\dot{\phi}(t)\dot{\phi}(t+\tau)\rangle$.[5] The detailed theoretical results will be presented elsewhere. The expression of $W_{\Delta\nu}(\omega)$ for low frequency has the following form:

$$W_{\Delta\nu}(\omega\approx 0) = \frac{W(1+\alpha^2)}{4\omega_m^2\, E_0^2\{1+[\alpha\sin(\Delta\Omega\tau)+\cos(\Delta\Omega\tau)]k\tau\}^2}, \quad (2)$$

where W is the normalization coefficient of the noise source defined in Ref. 5, $\alpha\approx -5$ is the ratio of the derivatives of the refractive index and the gain with respect to the carrier density, ω_m is the laser frequency, $\Delta\Omega$ is the detuning of the laser frequency from the nearest external cavity mode, k is the feedback coefficient,[10] and τ is the round trip time of the external cavity. $W_{\Delta\nu}(\omega\approx 0)$ has a minimum at $\Delta\Omega\tau=\tan^{-1}(\alpha)=-1.37$ rad $=-78°$ and a maximum at $\Delta\Omega\tau=\tan^{-1}(\alpha)+\pi=1.76$ rad $=102°$. The calculated $W_{\Delta\nu}(\omega)$ for the experimental conditions of Fig. 2 is shown in Fig. 4. The calculation agrees with the general feature of the observation. This includes the anticorrelation of the noise power in different frequency regimes, and the phase angle of the reflected light and the detuning of the laser frequency ($\Delta\Omega<0$) when the low-frequency noise is minimum. However, the calculation based on quantum fluctuations caused by the spontaneous emission cannot explain the frequency dependence of the noise power at low frequencies where the

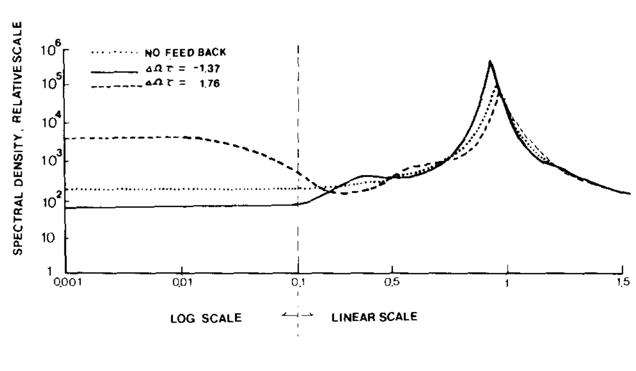

FIG. 4. Calculated $W_{\Delta\nu}(\omega)$ vs frequency for the conditions of Fig. 2. The solid curve is obtained using $\Delta\Omega\tau=-1.37$, and the dashed curve using $\Delta\Omega\tau=1.76$.

contribution from the $1/f$ noise[1] becomes increasingly important with decreasing frequency. Other noise sources, such as random variations in the active region temperature caused by the presence of nonradiative recombination centers,[11] need to be considered.

The physical origin of the experimental and theoretical results can be explained as follows. For a laser in which the refractive index is independent of the carrier density, that is, $\alpha = 0$ in Eq. (2), the greatest reduction in the low-frequency noise occurs at $\Delta\Omega = 0$, meaning that the reflected light is in phase with that inside the laser. This is the same result obtained previously by neglecting the amplitude-phase coupling. However, in semiconductor lasers, α is approximately -5.[9] The strong amplitude-phase coupling modifies the situation considerably. For low-frequency fluctuations with periods much longer than the damping time of the relaxation oscillation, the laser amplitude fluctuation δE and the carrier density fluctuation δn are in constant equilibrium following the relation $\delta E \propto -\delta n$. The greatest noise reduction occurs when the laser frequency is somewhat smaller than that of the nearest external cavity mode. At this point, an increase in the field amplitude caused by a spontaneous emission event reduces the carrier density and increases the refractive index of the diode laser cavity. This process shifts the laser line toward the red (lower frequency) further away from constructive interference and raises the laser threshold of the compound cavity. As a result, the carrier density increases and the laser amplitude decreases, counteracting the amplitude increase caused by the spontaneous emission. The oscillation is therefore damped. The high-frequency fluctuations, however, behave differently because δE responds to δn with a phase retardation following the relation $\delta E \propto \dot{\delta n}$. The increase in the carrier density caused by the red shift described above makes $\delta E > 0$ and encourages further increase in the high-frequency component of the amplitude fluctuation above its stationary value, giving rise to an enhanced oscillation. This explains the anticorrelation in the noise power of the two different frequency regimes.

In summary, it has been shown that reflections induce external cavity harmonics in the phase noise spectrum. The induced noise can be enhanced or suppressed by adjusting the phase of the reflected light. There is a correlation between the noise suppression in the low-frequency regime and the noise enhancement in the high-frequency regime. The greatest noise reduction in the low-frequency noise occurs when the reflected light is 70°–90° out of phase. The results can be described by a calculation taking into account the amplitude-phase coupling in semiconductor lasers. A physical explanation is also provided.

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