Optical Feedback Phase Stabilization of a Semiconductor Laser

SENG-TIONG HO, SHAOUL EZEKIEL, JOHN R. HAAVISTO, AND JOSEPH J. DANKO

Abstract—**The phase of optical feedback into a semiconductor laser was stabilized to maintain a minimum linewidth of 2 MHz. The scheme makes use of the linewidth information provided by a 1-MHz width external resonator. A further reduction in the laser linewidth to 300 kHz can be achieved and stabilized by using an external resonator with a narrower width.**

SEMICONDUCTOR lasers are important coherent light sources in the near infrared region as very few other kinds of lasers oscillate in these wavelengths. However, a solitary semiconductor laser does not produce a highly coherent light. For example, a typical single-mode GaAlAs semiconductor laser has an intrinsic spectral-linewidth of about 15 MHz at 5 mW [1]. In addition to this broad linewidth, the laser frequency fluctuates due to variations in diode temperature and injection current. Hence, for many applications that need a highly coherent light source, such as ultrahigh resolution spectroscopy, coherent communication, and coherent optical sensors, it is necessary to drastically reduce the intrinsic laser linewidth as well as the laser frequency fluctuations.

The laser frequency fluctuations mentioned above can be reduced by feedback control of the laser current and temperature, using an external Fabry–Perot cavity [2] or an atomic resonance [3] as a frequency reference. On the other hand, the intrinsic linewidth of the laser can be reduced by placing the diode within an external cavity [4], or as it has been demonstrated recently, a reduction of the laser linewidth by as much as a factor of 200 can be achieved by using optical feedback [5]. This latter method is very simple but suffers from the problem that mode-hopping can occur, which depends on the phase and the amount of feedback. Moreover, the degree of linewidth narrowing at a particular feedback level also depends on the phase of feedback. In this letter, we propose a method to control the phase of the optical feedback so as to maintain stable laser operation at the minimum linewidth for a given feedback level and also present preliminary data using this method.

The experimental setup is shown in Fig. 1, where the light from a laser diode (Hitachi 1400) (LD) is fed back by a PZT driven mirror M from a distance of 60 cm via a beam splitter $S1$. The amount of light fedback is controlled by a variable attenuator (ATT). A confocal Fabry–Perot interferometer (CFP) with a 1-MHz resolution (Tropel model 216) is used to measure the linewidth of the laser and also to form part of a feedback loop for the control of the phase of the optical feedback by controlling the position of mirror M. This loop will be referred to as the phase stabilization loop. A parallel plate Fabry–Perot interferometer (PFP) with a 300-MHz resolution is used as a reference for the stabilization of the laser frequency by feedback control of the diode injection current and will be referred to as the frequency stabilization loop. An optical isolator (I) is used to prevent undesired optical feedback from the two Fabry–Perot interferometers. The photodetectors used in the feedback loops consist of a p-i-n photodiode with a bandwidth of 1 MHz (PD_1) and an avalanche photodiode (PD_2) with a bandwidth of more than 40 MHz. Throughout the experiment, the semiconductor laser is operated at 5.6 mW, which gives a solitary laser linewidth of about 13 MHz in the absence of feedback. The temperature of the laser is held within 10^{-3} K using a peltier cooler.

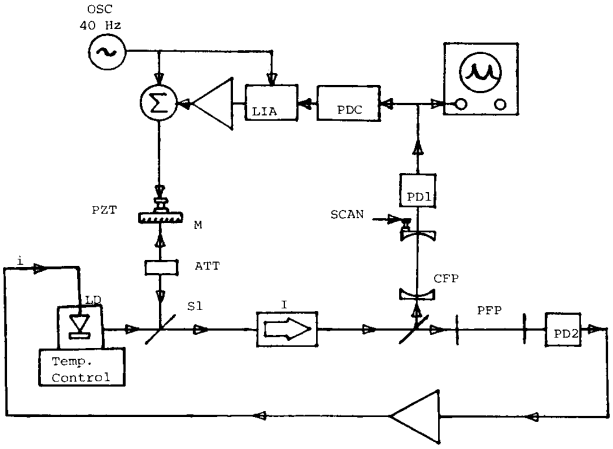

Fig. 1. Experimental setup.

Before discussing the operation of the phase autolocking loop, we shall consider the effect of optical feedback on the laser frequency and the laser linewidth.

The theory of the effect of optical feedback on the laser frequency and the laser linewidth has been studied by

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Goldberg *et al.* [5] and Saito *et al.* [6]. According to their theory, both the laser frequency and the laser linewidth depend on the feedback parameter X and the phase of optical feedback θ given by

$$X = \frac{(1 - R_0)R_m^{1/2} L_2}{R_0^{1/2} n L_1}$$

and

$$\theta = 4\pi \nu_0 L_2/c \pmod{2\pi}$$

where R_0 is the reflectivity of the solitary laser facet, R_m is the fraction of the light fedback, L_2 is the length of the external cavity, nL_1 is the optical length of the solitary laser cavity, and ν_0 is the frequency of the solitary laser without feedback.

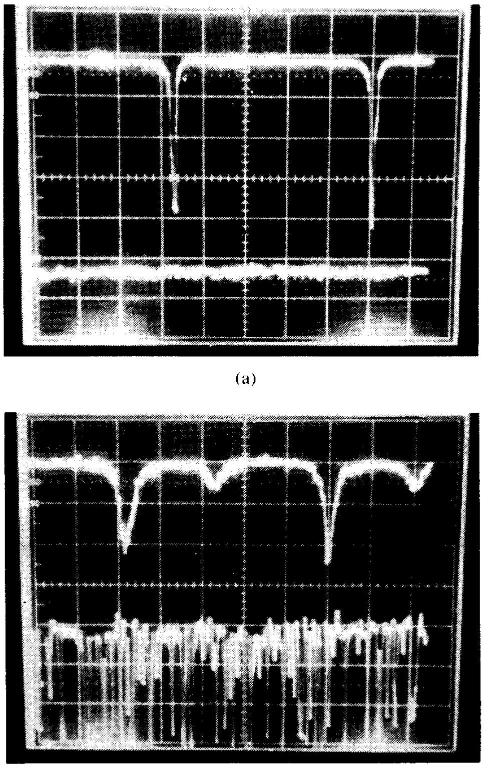
According to the theory, for $0 < X < 1$, the laser linewidth as a function of θ has the minimum value at $\theta = 0$ and the maximum value at $\theta = \pi$. In fact with X close to 1, we have seen linewidth variation from 7 to 90 MHz as θ is tuned from 0 to π, as compared to the solitary laser linewidth of 15 MHz.

For $1 < X \leq 13$, the laser linewidth still has its minimum value at $\theta = 0$, but at θ close to π, there is mode-hopping in addition to a broadening of the linewidth. The magnitude of the laser linewidth at $\theta = 0$ decreases with X in the range $0 < X \leq 13$. In fact, at $X = 13$ the laser linewidth is approximately 200 times smaller than the solitary laser linewidth.

The range of operation with $X > 13$ is of no interest because strong satellite modes begin to appear for all values of θ.

The variation of the laser linewidth with θ and the mode-hopping behavior discussed above are illustrated[1] in Fig. 2(a) and (b) for $X \simeq 1.2$. Fig. 2(a), taken at θ close to zero, shows a single-mode lasing with a 7-MHz linewidth in the upper trace as measured by the scanning Fabry–Perot CFP. The lower trace of Fig. 2(a) shows the intensity transmitted by the Fabry–Perot PFP when the laser frequency is held at the side of the Fabry–Perot resonance. As can be seen, the transmitted intensity is stable, indicating stable laser operation. The upper trace of Fig. 2(b) shows a broadening of the laser linewidth to 22 MHz when $\theta \simeq 0.8\pi$ together with the appearance of a second mode due to mode hopping. The mode hopping is confirmed by the frequency jumps shown in the lower trace of Fig. 2(b).

From the above discussion, it can be seen that in order to achieve a narrow linewidth, the value of X has to be larger than unity but smaller than 13. However, with $X > 1$, we found that mode hopping can occur in a matter of a minute in our laboratory due to the thermal drift of the phase of feedback θ from 0 to π. Hence, in order to maintain a stable narrow linewidth free from mode hopping for a long time, it is necessary to maintain the phase of feedback θ around zero.



(a)

(b)

Fig. 2. (a) Upper trace: Output of confocal Fabry-Perot (CFP) taken with $X \simeq 1.2$ and $\theta \simeq 0$, showing a laser linewidth of 7 MHz. The free spectral range of the Fabry-Perot is 300 MHz. Lower trace: Output of the parallel plate Fabry-Perot (PFP) showing a stable laser frequency. (b) Upper trace: Output of confocal Fabry-Perot (CFP) taken with $X \simeq 1.2$ but $\theta \simeq 0.8\pi$, showing a broadening of the laser linewidth to 22 MHz and a second mode due to mode hopping. Lower trace: Output of the parallel plate Fabry-Perot (PFP), showing frequency jumps due to mode-hopping.

By making use of the θ dependence of the laser linewidth, our phase stabilization loop shown in Fig. 1 achieves the required stabilization of θ by locking the laser linewidth around its minimum value (corresponding to $\theta = 0$). In the phase stabilization loop, the linewidth information is provided by the confocal interferometer CFP operated in the scanning mode. The instantaneous laser linewidth is obtained by measuring the height of the resonance for each CFP scan, which is inversely proportional to the laser linewidth. With this linewidth information, an ac feedback method can be used to maximize the height of the resonance (i.e., minimize the laser linewidth) by controlling the position of the feedback mirror M. In our preliminary experiment, the PZT of mirror M is modulated with a 40-Hz signal, which in turn modulates the laser linewidth. A sample-and-hold digital peak-voltage detection circuitry (PDC) is used to pick up the highest voltage of the CFP scan every 10 ms while the CFP is driven at a rate of 10 ms/scan. The output of the peak-voltage detection circuitry is subsequently demodu-

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[1] The values of X and Rm are only estimates and are adequate in our case. A precise measurement of these parameters is not easy.

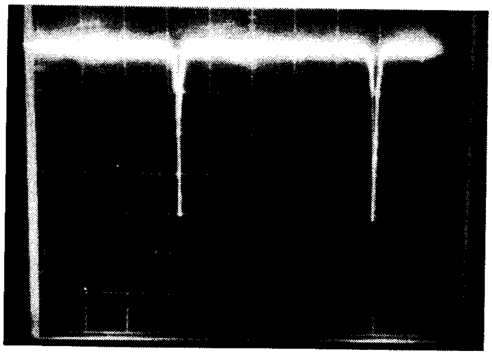

Fig. 3. Output of confocal Fabry–Perot (CFP) demonstrating a stable 2-MHz linewidth achieved with $X = 2$.

Fig. 4. Output of confocal Fabry–Perot (CFP) demonstrating the 30-MHz frequency modulation due to the modulation of the phase of optical feedback.

lated by a lock-in amplifier, which provides an error signal necessary for the feedback control of the mirror M.

The modulation of the position of mirror M or θ is required for the operation of the phase stabilization loop, but as discussed above, the modulation in θ will introduce modulation in the laser frequency, which is undesirable. However, this can be eliminated without affecting the operation of the phase stabilization loop by stabilizing the laser frequency[2] to an external reference such as the Fabry–Perot PFP. In our experiment, the laser frequency is locked to a point on the slope of the PFP resonance using a fast feedback loop with a bandwidth of 500 kHz. Thus, the frequency stabilization loop serves to reduce both the unwanted modulation in the laser frequency and the laser frequency fluctuations.

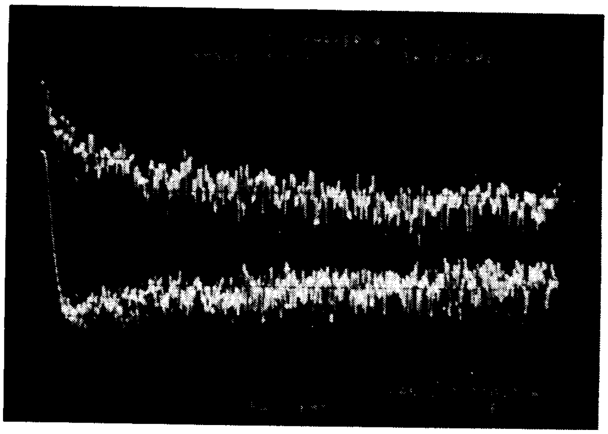

Fig. 5. Power spectrum of frequency noise of a solitary laser (upper trace). Reduced frequency noise power spectrum due to frequency stabilization (lower trace). The horizontal scale is 10 kHz per division, while the vertical scale is 10 dB per division.

By making use of the phase stabilization loop and the frequency stabilization loop, we have achieved a stable 2-MHz linewidth with an optical feedback level of $Rm \simeq 10^{-5}$ ($X \simeq 2$). The stable 2-MHz linewidth is shown by the CFP scan in Fig. 3, whereas Fig. 4 shows a 30-MHz p–p frequency modulation of the laser due to the modulation in Θ when the frequency stabilization loop is switched off. The noise power spectrum of the laser frequency fluctuations is measured by the fast photo detector PD_2 in Fig. 1. A section of the frequency noise spectrum from 0 to 100 kHz is shown in Fig. 5, where the upper trace in the figure shows the frequency noise level of a free running solitary laser and the lower trace shows the reduced noise level, indicating that the laser frequency noise power spectral density below 100 kHz has been substantially reduced by the feedback loop.

The 2-MHz linewidth could be maintained stable for a period of more than 1 h. The period of stability was limited by the dynamic range of the control loop. The bandwidth of the phase stabilization loop in our present set up is not very large and is limited to a few hertz by the slow scanning rate of the confocal Fabry–Perot interferometer (CFP). It is clear that a larger bandwidth would be required in a more noisy environment. There is another way of detecting the minimum linewidth of the laser by monitoring the small intensity variation of the laser output as a function of the phase of optical feedback. This alternative method could provide us with a larger bandwidth and is being investigated in our laboratory.

The 2-MHz linewidth obtained in our setup is not the minimum possible. In fact, with a larger amount of feedback ($X \simeq 7$), we have achieved a linewidth of 300 kHz. The narrow linewidth was measured by using a long fiber spectrum analyzer [7]. However, in order to stabilize the phase of the feedback in this case, we would require a Fabry–Perot linewidth of less than 300 kHz or we may try to extract the laser linewidth information from the fiber spectrum analyzer.

In conclusion, we have proposed a scheme of locking the phase of optical feedback to a value that gives the minimum linewidth. The method employs a high resolution scanning Fabry–Perot and a peak-voltage detection circuitry for linewidth measurement. Such a method is particularly useful because it can be used with "off the shelf" lasers since it does not require antireflection coat-

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[2] Since, for low feedback levels, the feedback phase is determined primarily by the external cavity and is negligibly affected by small variations in the laser frequency.

ing of the laser facet as in the case of the external cavity scheme [4].

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We are grateful to C. J. Nielson for pointing out to us, recently, that a similar scheme was described in [8].

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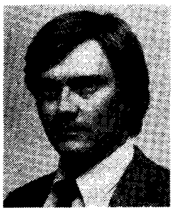

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