Frequency Stabilization of Laser Diodes at 0.83 μm Using a Fiber Optic Coupler

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***Abstract*—We report a novel frequency stabilization scheme for laser diodes. The frequency discriminator is simply a fiber optic coupler which acts as a nearly-balanced-arm fiber-optic Michelson interferometer. It is estimated that the frequency fluctuation of our test laser (λ = 0.83 μm) stabilized by this method is less than ± 4 MHz. This scheme is applicable to longer wavelength (1.2–1.6 μm) laser diodes and the stabilized lasers can be packaged easily.**

FREQUENCY stabilized laser diodes have found many applications in lightwave communication and fiber sensor systems. For example, they have been used as optical transmitters and local oscillators in coherent optical communication systems [1]–[3]. In optical fiber sensors systems, it is also well known that the frequency stability of the laser diode used would affect sensor sensitivity [4], [5]. Typical frequency discriminators used for laser diode frequency stabilization include Fabry–Perot interferometers [6], [7] and atomic or molecular absorption lines [8]–[10]. Residual frequency fluctuations less than 1 MHz have been achieved in systems using the Fabry–Perot interferometer. In this letter, we report for the first time frequency stabilization of a fiber pigtailed laser diode (λ = 0.83 μm) by using a fiber coupler as the frequency discriminator. The fiber coupler has not been modified in any way, e.g., high relectivity coating on the fiber ends. It acts as a nearly-balanced-arm Michelson interferometer of which the peak transmission signal is used for feedback control of the injection current of the laser diode. Because the sensing port can be isolated from the signal transmission port, the package design is very simple and can be implemented in an all fiber fashion.

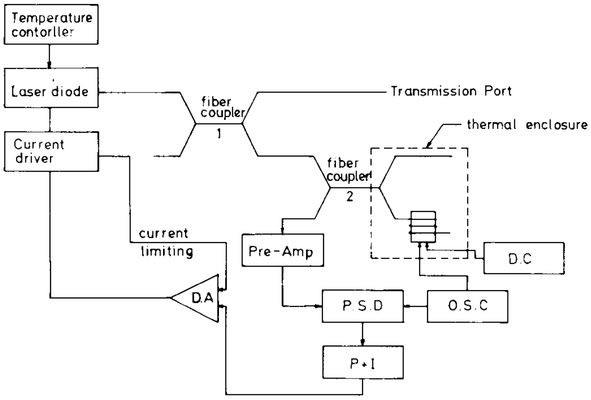

Fig. 1. Experimental setup used to stabilize the laser diode using a fiber optical coupler: DA: differential amplifier; PSD: phase sensitive detection; OSC: sinusoidal signal generator; DC: dc voltage supply; $P + I$, proportional and integrating compensating circuit.

A block diagram of our experimental setup is shown in Fig. 1. A single-mode fiber pigtailed laser diode (Seastar PT-450, λ = 0.83 μm) was mounted on a thermoelectrically cooled copper heat sink. Its temperature was controlled by a P + I + D compensating network to within 0.01 °C. The laser diode output fiber pigtail was spliced to a single-mode (nonpolarization maintaining) fiber coupler. The fiber end was as cleaved without modification. The arm length of the output ports of the coupler was adjusted such that the signal at the preamplifier output was stable [see Fig. 2 (a)], when an appreciable amount of dc ramp voltage was applied to the PZT. In other words, the optical path difference of the interferometer was adjusted to less than the coherence length of the laser diode. Our experiments showed that the interference signal was stable, indicating that the optical feedback effect did not affect the spectrum of the single-mode laser. This agreed with our estimation that the effective reflectivity of our system (pigtailed laser with as cleaved fiber ends) was of the order of $10^{-4} - 10^{-5}$ and was consistent with results of previous studies on the optical feedback effect [11]. The use of nonpolarization-maintaining fiber may results in signal fading [5]. This can be corrected using appropriate compensation circuits. The fiber coupler sensing port was enclosed in a thermally isolated package and stabilized to within 0.01 °C also. One arm of the sensing fiber was wrapped on a PZT 2 cm in diameter for about four turns. DC voltage applied to the PZT was used for frequency tuning, while a sinusoidal signal at 100 kHz was also applied as the reference for the phase sensitive detector (PSD). When a dither modulation signal was applied to the PZT, the output signal of the detector can be written as

$$\begin{aligned} I = I_0[1 &+ J_0(\phi_m)\ \mathrm{Cos}\ \Phi - 2J_1(\phi_m)\ \mathrm{Sin}\ \Phi\ \mathrm{Cos}\ \omega_m t \\ &+ 2J_2(\phi_m)\ \mathrm{Cos}\ \Phi\ \mathrm{Cos}\ 2\omega_m t \\ &- 2J_3(\phi_m)\ \mathrm{Sin}\ \Phi\ \mathrm{Cos}\ 3\omega_m t + \cdots] \end{aligned} \tag{1}$$

where $\phi = 2\pi nL/\lambda$ is the optical phase; L is the difference in optical path length of the two arms of the interferometer; ϕ_m is linearly proportional to V_m, ω_m, and V_m are, respectively, the modulation frequency and amplitude of the applied signal. Equation (1) represents the transmission function of the

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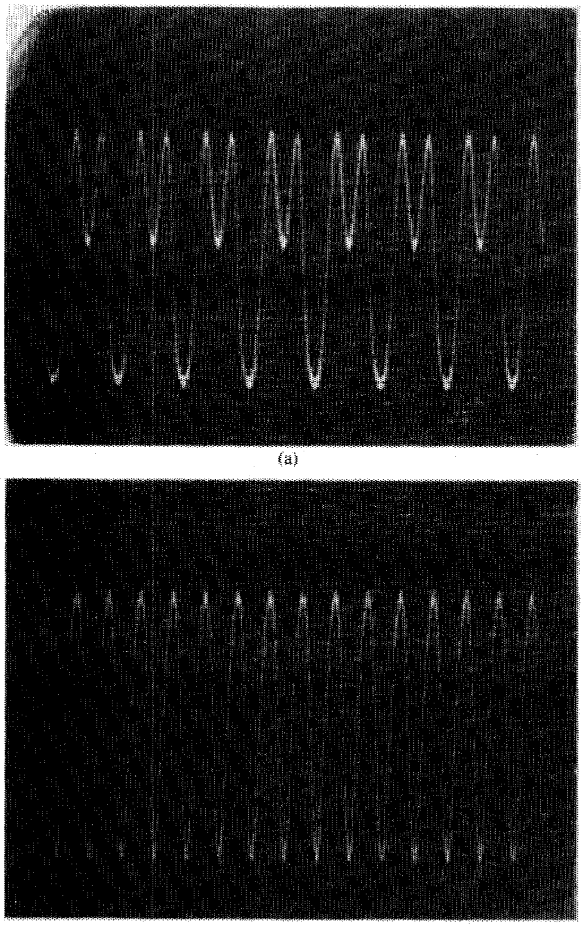

(a)

(b)

Fig. 2. (a) Output signal of the preamplifier for a free-running laser diode. (b) Output signal of the preamplifier for a stabilized laser diode for which the odd harmonic terms of the interference signal have been nulled. The time scale is 10 μs/div.

interferometer used as the frequency discriminator in the stabilization system. With $L = 3$ mm, we found that the FWHM of the transmission function was about 30 GHz. The magnitude of the transmitted interference signal was basically determined by the finite reflectivity of the uncoated cleaved facets of the fiber and was approximately 4% of the incident intensity of light into the fiber. The visibility of the interference pattern was approximately 0.9. The system sensitivity is optimized when $J_1(\phi_m)$ is adjusted to its peak value. In our experiment, $\omega_m = 100$ kHz and the optimized signal amplitude V_m was 2.4 V, corresponding to the peak value of $J_1(\phi_m)$ to achieve the highest possible sensitivity.

The output of the preamplifier was first sent to an active bandpass filter with its center frequency at ω_m and then went on to the phase sensitive detection circuit. The PSD error signal was fed to a $P + I$ (proportional and integrating) compensating circuit for signal nulling by controlling the driving current of the laser diode and thereby stabilizing the frequency of the laser diode output. The system servo loop bandwidth was 10 KHz.

In Fig. 2, we show the preamplifier output for a free running laser diode. When the dither signal at frequency ω_m was applied to the PZT, all the harmonic components in (1) were present. When the frequency of the laser diode was stabilized by this technique, only the even harmonic terms of ω_m were observed since the odd terms including SINϕ were nulled to zero. Typical stabilization results using this technique are presented in Fig. 3. By employing a Fabry–Perot interferometer with a free spectral range, FSR = 30 GHz, we have previously determined that output frequency of the test laser varied with the driving current according to -2.4 GHz/mA. We then adjusted the dc voltage applied to PZT such that interferometer was biased at $1/_2\pi$. A current modulation signal corresponded to 0.5 mA (peak value) was applied to the laser diode. From the mixer output of the PSD circuit we can estimate the corresponding voltage variation of the PSD output. It was thus determined that the amount of change of the interference signal corresponding to a current sweep of 0.25 mA, or approximately 600 MHz shift in the output frequency of the laser diode, as shown in Fig. 3. When the feedback loop

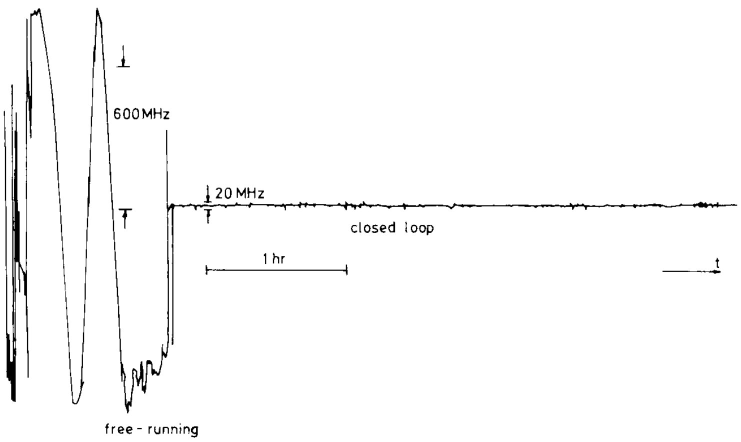

Fig. 3. The PSD output of a free-running laser diode and stabilized laser diode using a fiber optic coupler.

was closed. it was estimated from the interference signal that the peak-to-peak frequency fluctuations of the laser diode was less than ±4 MHz.

In summary, we have demonstrated an effective method for frequency stabilization of laser diodes ($\lambda = 0.83$ μm) by simply using a fiber optic coupler as the frequency discriminator. The peak-to-peak fluctuation of the laser diode when it was locked to the peak of the interference signal is less than 4 MHz. Because of its simplicity and ease for packaging, this new technique should be an attractive alternative to stabilized lasers currently used in fiber optic sensor and coherent optical communication systems.

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