Oscillation frequency stabilization and narrowing of a laser diode by using an external cavity

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ABSTRACT

External cavity diode laser (ECDL) systems are presently experiencing a surge in popularity as laser light-sources, in advanced optical communications- and measurement-applications. Because such systems require that their external reflectors be precisely controlled, to eliminate low frequency fluctuations in optical output, we conducted experiments with a two-cavity version of the ECDL system for a vertical cavity surface emitting laser (VCSEL). This technique brings the added advantages of a narrower linewidth than would be achievable via a single optical feedback. VCSELs are characterized by wider oscillation linewidths than edge emitting types, so the larger effect of double optical feedback system is expected.
Keywords : VCSEL, ECDL system, frequency stabilization, oscillation linewidth

1. Introduction

Semiconductor lasers outperform competing technologies on a number of well-known fronts; lower cost, greater efficiency and durability. While they are expected to be the lead technology, in next-generation optical communications- and measurement- applications, certain issues still beg a solution; -problems that have, in fact, confronted researchers from the start; spectra that are neither as stable, nor as pure as those of other types of lasers; susceptibility of their oscillation frequencies to fluctuations in driving current and ambient temperature. Experiments now underway in our facility involve the stabilization of a temperature-controlled diode laser's oscillation frequency, through the management of its driving current.

The ECDL systems being used as laser light-sources, in optical communications- and measurement-applications bring the added advantage of a much narrower linewidth. However, the susceptibility of their oscillation frequencies to fluctuations in driving current and atmospheric temperature result in changes to the refractive index and the external-cavity. We made every effort to maintain the length of the ECDL cavity, while evaluating oscillation-frequency stability.

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The vertical cavity surface-emitting laser (VCSEL) is now commercially available, and the ECDL systems using them are expected to improve their frequency stability. The VCSEL's oscillation linewidth is, however, originally very wide, so we expect that the VCSELs with our double optical feedback system will make their oscillation frequency narrow and stable.

2. Principle

2.1 Single optical feedback system

Figure 1 describes a model of an elementary ECDL system. The external mirror reflects a diode laser's output back to the source, whereby the diode laser oscillates in "coupled" (internal/external) cavities. Where this happens, the diode laser's output will be altered significantly, even if feedback light is weaker than that produced by the beam. Because laser operations depend on cavity-length, feedback-light strength, and the electron's excitation-level, both oscillation linewidth and output power fluctuate unpredictably[1]. And, when the ECDL system oscillates at frequencies where internal- and external cavity modes coincide, around the center of the gain-curve, the oscillation frequency of the ECDL system is locked to one of the external cavity modes, as shown in Fig. 2. If the length of an external cavity can be held in stasis, the ECDL's oscillation frequency stability is assured. In addition, the efficiency of the lasing process increases, due to the concentration of the light's energy near the center oscillation frequency. This exerts a narrowing influence on diode lasers' oscillation linewidth, significantly increasing peak output-power.

Variations in optical output power (-referred to as Low-Frequency Fluctuations (LFFs)) occur, when both stable- and unstable modes locate adjacent one-another, -essentially creating competing oscillation modes. Though ordinary semiconductor lasers are described by a two-variable rate-equation, and oscillate at a predetermined rate of output, the ECDL, under the same conditions, becomes a three-variable rate-equation; one which operates with a low level of stability.

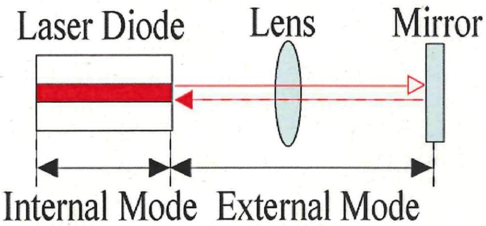

Fig.1 ECDL system

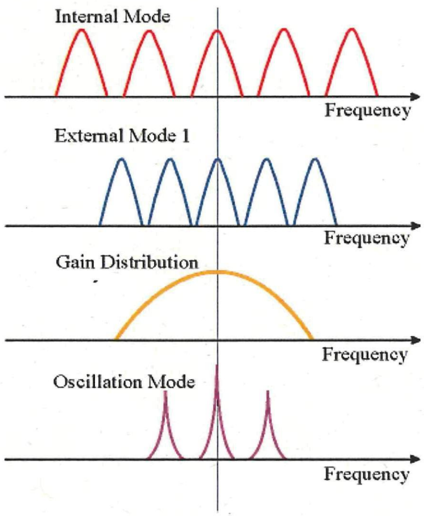

Fig.2 Oscillation mode
(Single optical feedback)

2.2 Double optical feedback system

The Lang-Kobayashi equation is introduced, here, to help describe the sequence of events that take place, when a single-mode semiconductor laser is exposed to appropriate feedback light. F. Rogister et al. extended the equation to the double optical feedback ECDL system, wherein

$$\frac{dE}{ds} = (1+i\alpha)NE + \kappa_1 E(s-\tau_1)\exp(-i\Omega\tau_1) + \kappa_2 E(s-\tau_2)\exp(-i\Omega\tau_2) \qquad (1)$$

$$T\left(\frac{dN}{ds}\right) = P - N - (1+2N)|E|^2 \qquad (2)$$

-"s" represents a unit of a photon's lifetime; $E(s)=A(s)\exp[i\varphi(s)]$ expresses averaged measurements of an electric field; $N(s)$ is an averaged, excited carrier number; κ_1 and κ_2, the averaged strengths of the light fed back from each of the two external cavities; τ_1 and τ_2, the ratios of photon lifetime to round-trip times, in two external cavities; α, the broadening factor of the oscillation linewidth; Ω, the lasing angular frequency; P, diode laser threshold current, and finally, T, the ratio of photon : carrier lifetimes. The stationary solution to equation (2) is given as $E = A_s \exp[I(\Delta\cdot\Omega)s]$, $N = N_s$, where $\Delta =$ constant angular frequency, A_s and N_s are constants.

$$\Delta = \Omega - \kappa_1[\alpha\cos(\Delta\tau_1)+\sin(\Delta\tau_1)] - \kappa_2[\alpha\cos(\Delta\tau_2)+\sin(\Delta\tau_2)] \qquad (3)$$

$$A_s^{\ 2} = \frac{P-N_s}{1+2N_s}$$

$$N_s = -\kappa_1 \cos(\Delta\tau_1) - \kappa_2 \cos(\Delta\tau_2) \qquad (4)$$

According to equation (3), the stationary solution in the double optical feedback system shows that stable- and unstable modes are produced simultaneously, in a manner similar to that used in the single optical feedback process.

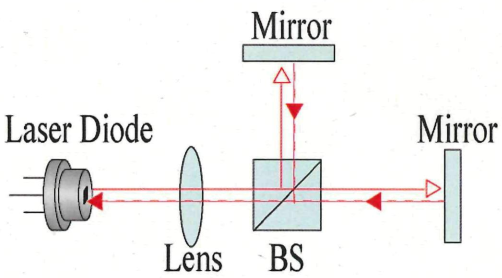

Fig3. Double optical feedback

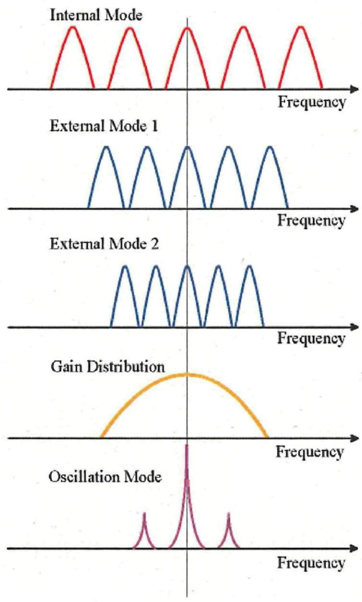

Fig.4 Oscillation mode
(Double optical feedback)

In double optical feedback systems, however, when secondary light feedback intensity κ_2 increases, the paired stationary solutions may move away from each other. So, taking that theory into consideration, we assembled the double external cavity diode laser system shown in Fig.2; a system designed for eliminating LFF. A bit later in this discussion, we describe how, under conditions in which the intensity of one feedback light is constant, LFF is eliminated by adjusting the intensity of the other feedback light. As shown in Fig.3, when a second external mirror is added to an ECDL system, the supplementary external mode shown in Fig. 4 effectively restricts the lasing environment; a condition marked by a narrower oscillation linewidth-, and a more stable oscillation frequency-, than those obtainable using single optical feedback systems.

2.3 VCSELs and external cavities

Over the past few years, VCSELs have received considerable attention because of such intrinsic advantages as; -low threshold current, single-longitudinal-mode operation, high-speed modulation (because of a short cavity length), a circular output beam cross section, wafer-scale integration, and almost none of the temperature fluctuation-induced mode-hopping so often seen in other semiconductor lasers. They now enjoy broad acceptance in optical communications and information processing.

While they enjoy broad acceptance in optical communications and information processing, VCSELs are somewhat handicapped by their broad oscillation linewidth, an impediment we believe we can overcome by means of the ECDL system. Because the VCSEL's output power is considerably lower than that of the Fabry-Perot design, we added an RF amplifier to the arrangement.

3. Experiment

3.1 Experimental setup

By using double optical feedback to encourage an unstable mode to move away from its stable counterpart, we simultaneously stabilized and narrowed the oscillation frequency of a VCSEL. We assume its linewidth to be narrower than those of single optical feedback setups, due to the restrictions imposed on them, by the added optical feedback effect.

Figure 5 shows optical setup used in this study. Beam splitters (BS1) divide the output beams of VCSEL1 and VCSEL2. The resulting beams are further divided by beam splitters (BS2), and fed back to the diode lasers from mirrors of Littrow arrangements. Two laser beams are further introduced to an avalanche photo diode (APD) that produces the beat-note originating from two laser beams directed toward the APD along the same optical path. Figure 6 shows our experimental setup.

We measured the beat-note frequency between the two identical systems with the universal-counter, with the resulting information being exported to a data logger. We calculated the square root of the Allan variance from this information, in order to evaluate the frequency stability of our system. The beat-note was simultaneously introduced to the universal-counter and the spectrum-analyzer, in order to evaluate its oscillation linewidth.

In constructing our ECDL systems, we mount two systems on a 400 mm×400 mm, iron/nickel alloy, super-invar "breadboard", to eliminate the influence of atmospheric temperature on resonator-length. The ECDL diode laser systems are temperature controlled within 1/100 K variation. After measuring the weak RF-amplified beat-notes of the two ECDL systems from the APD, we evaluated the relative frequency stability of two ECDL systems. The signal produced by the VCSELs was also "less than robust".

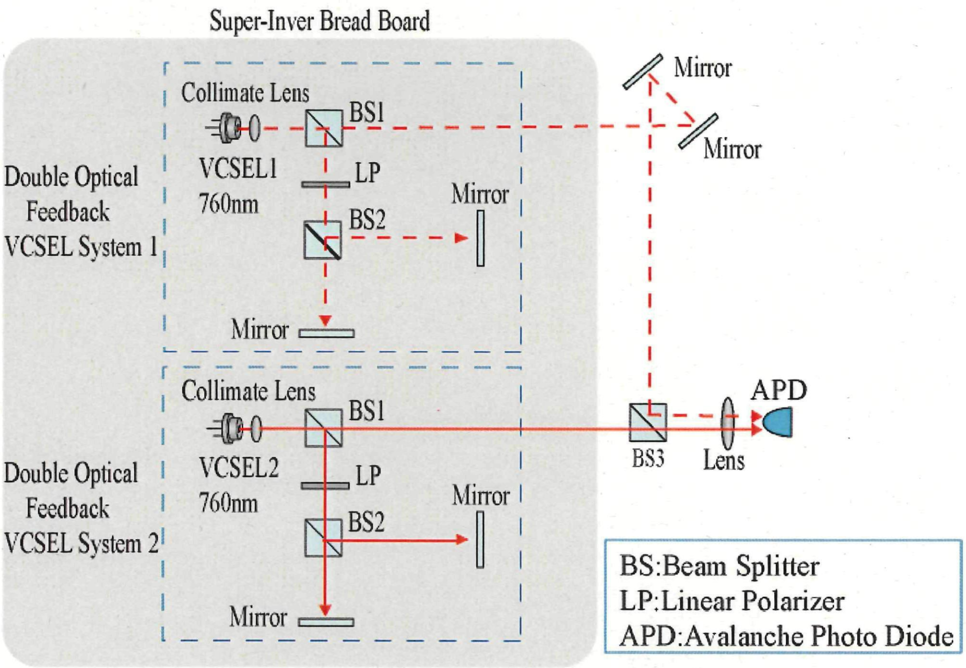

Fig.5 Optical setup

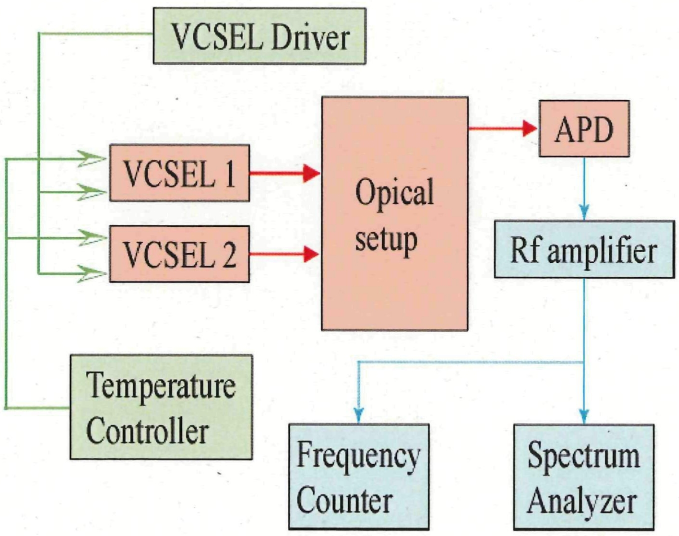

Fig.6 Experimental setup

3.2 Experimental result

Figure 7 shows the square root of the Allan variance, using the Fabry-Perot laser. Clearly, optical feedback had a positive impact on oscillation-frequency stability. And the superiority of the double optical feedback system made it the only logical choice, where our purposes were concerned.

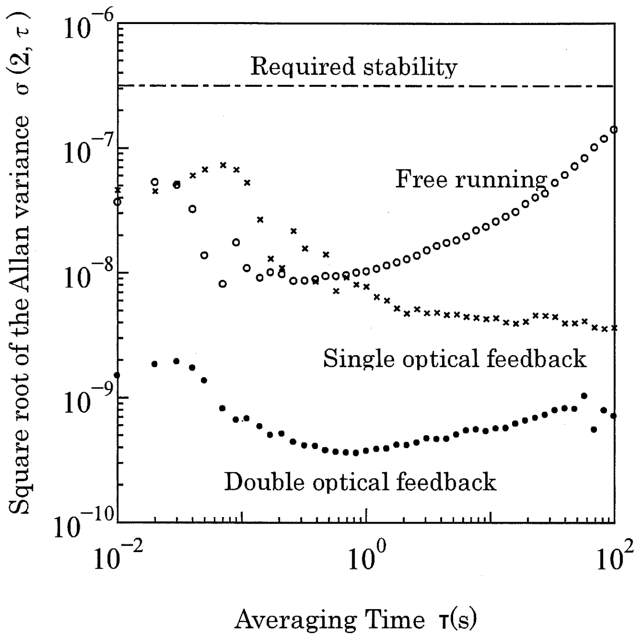

Fig. 7 Frequency stabilities (Fabry-Perot type laser)

Figure 8 compares oscillation spectra. The horizontal axis of the "Free Running" result is 100 MHz/div. and that of the "Double Optical Feedback" result is 10 MHz/div. The oscillation linewidth of a beat signal between two VCSELs was 150MHz, during a free-run, but our ECDL system narrowed linewidth to a mere 3MHz. The overall improvement in oscillation-frequency stability is readily apparent (Fig.9), but optimum stability can be obtained, only when temperatures are precisely controlled. Evaluating oscillation frequency stability at this point, we confirmed that double optical feedback improved stability by roughly one order of magnitude, in the longer averaging time region. We built our double-external-cavity optical setup on a "Super-Invar" board, and controlled atmospheric temperature to within ±0.1 K. The stability of our two external cavities showed marked improvement as we expected.

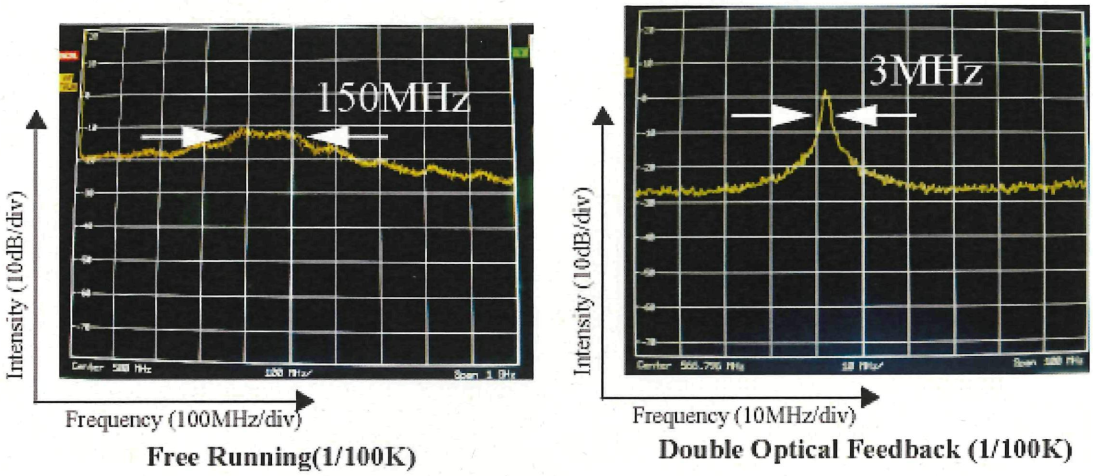

Fig.8 Comparison of oscillation spectra

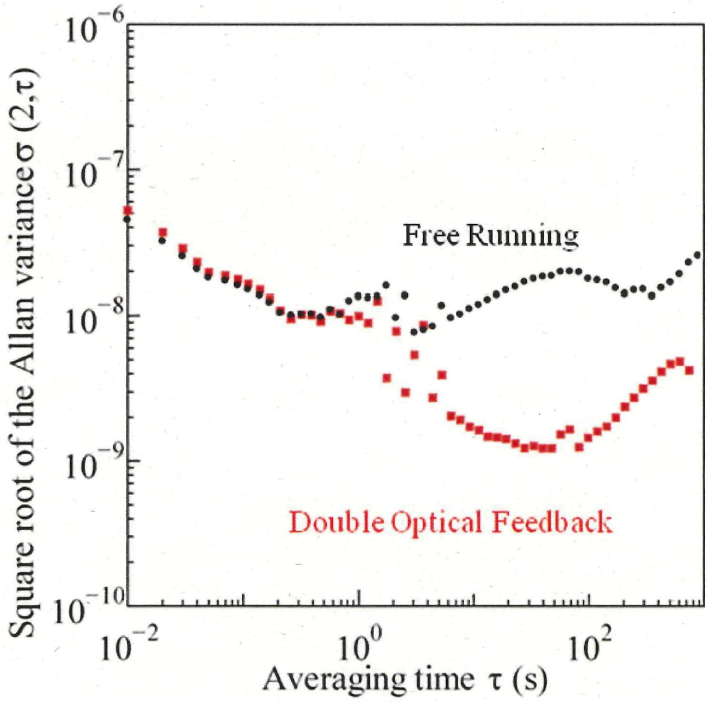

Fig.9 Frequency stabilities (VCSEL)

4. Conclusion

The goal of the present undertaking was to stabilize the oscillation frequency of an External-cavity diode-laser. We set about the task, by first constructed a "Compact double optical feedback ECDL" system on a Super-Invar optical board; a device that held the promise –and in the end, proved itself uniquely capable, of accurately maintaining external cavity length. For this reason, we strongly advocate its use in related equipment, such as lens holders and optical bases.

The stabilization of oscillation frequency and the narrowing of linewidth have been realized simultaneously in our system. Furthermore the DFB laser currently used for optical communications has a linewidth of about 3 MHz, so we had the narrower oscillation linewidth completed to the same extent. As this project moves forward, we will replace VCSEL2 (the reference laser) with a Fabry-Perot type device having a narrower oscillation linewidth to improve resolution and stability.

The ECDL uses a simple system of external mirrors and beam splitters that require no direct current modulation to achieve stability. So, it is possible to stabilize the oscillation frequency collaborating with other techniques. So improving the technique of using external cavities would support the broadening of semiconductor laser's application fields.

ACKNOWLEDGMENT

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