Narrow linewidth, single frequency semiconductor laser with a phase conjugate external cavity mirror

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We measure the spectral characteristics of an external cavity semiconductor laser which uses a phase conjugate mirror for its external reflection. This device has significant advantages over the conventional external cavity system owing to the self-aligning nature of the phase conjugate mirror. The fiber delay line self-heterodyne technique is used to measure the fundamental linewidth for single mode operation of this device. It shows the linewidth to be at least as narrow as the instrumental resolution of 100 kHz.

The fundamental linewidth (i.e., phase noise) of single mode semiconductor lasers is a subject of considerable practical importance. Devices having linewidths as narrow as 10 kHz are required in certain coherent communication systems and a variety of sensing systems.[1,2] The fundamental linewidth of a single mode semiconductor laser is given by the following expression[3–5]:

$$\Delta\omega = (\theta/2P)(1+\alpha^2), \quad (1)$$

where θ is the spontaneous emission rate into the lasing mode, P is the lasing mode photon number, and α is the linewidth enhancement factor resulting from the detuned nature of the semiconductor laser gain spectrum. Conventional devices exhibit linewidths which are typically 100 MHz at an output power of 1 mW per facet and vary inversely with the output power as indicated by Eq. (1). A well established technique for narrowing the linewidth of these devices is to use long cavities as can be done by antireflection coating one or both facets of the device and forming the cavity with external reflectors (one reflector is often a grating to achieve frequency selection).[6,7] This results in narrowing since a much larger photon population P can exist in the lasing mode. Linewidths as narrow as 10 kHz have been demonstrated using external cavities.[7] Extreme care must be taken in the construction and operation of these systems, however, as their performance is critically dependent upon mechanical misalignment of the external cavity due to thermal variation or microphonics.

Recently, Cronin-Golomb *et al.* reported operation of a passive (self-pumped) phase conjugate mirror (PPCM) using a GaAlAs semiconductor laser.[8] These devices have the property of returning an incident beam back onto itself independent of the angle of incidence. In this paper we examine the spectral characteristics of an external cavity semiconductor laser which uses a PPCM for its external reflector.[9] This system has the advantage over conventional external cavity systems of being self-aligning because of the action of the phase conjugate mirror. It thus maintains alignment once oscillation is established, even in the presence of mechanical variations of the cavity, provided these variations are slower than the response time of the phase conjugation medium. We show that this system can lase in a single longitudinal mode and measure the field spectrum linewidth of this mode using the fiber delay line self-heterodyne technique.[10] We also estimate the theoretically expected field spectrum linewidth for this system.

The experimental setup is shown in Fig. 1. The gain element was an Ortel semiconductor laser having one facet antireflection coated. The emission spectrum of this device is shown in Fig. 2(a) at an injection current of 46 mA which corresponds to a power of a few milliwatts from the low-reflectivity facet. The line center of this emission is at 8362 Å. The external cavity mirror is a ring PPCM using a $BaTiO_3$ crystal.[11] The output from the low-reflectivity facet of the laser was collimated using a small glass sphere (antire-

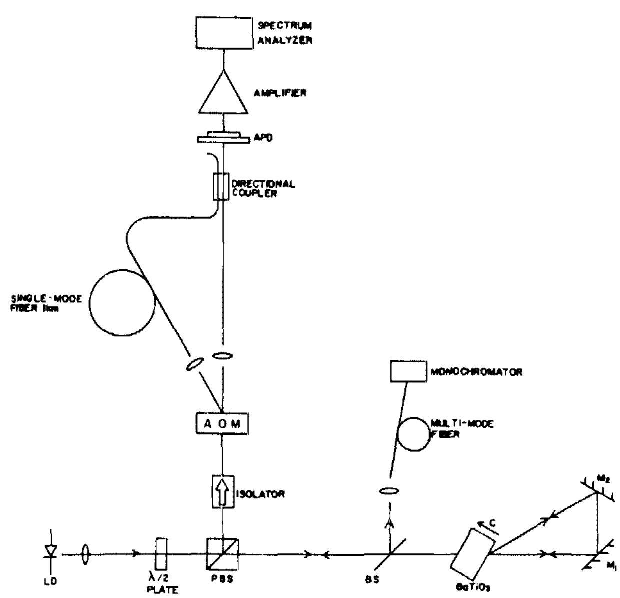

FIG. 1. Experimental arrangement.

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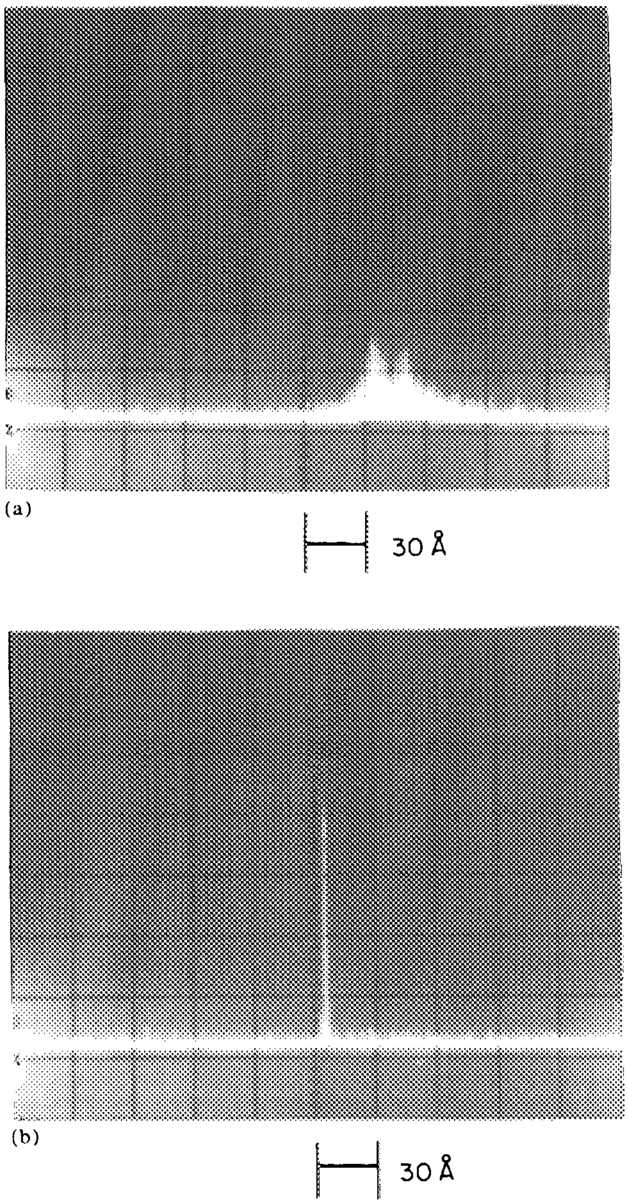

FIG. 2. (a) Output spectrum from antireflection coated laser measured with the grating spectrometer. (b) Output spectrum from the phase conjugate external cavity laser measured with the grating spectrometer.

flection coated). Before arriving at the PPCM the beam was sampled at two locations. First, a half-wave plate and polarizing beam splitter operated in tandem to allow a variable sampling port. This port served as input to the fiber delay line interferometer and alternately as input to a scanning Fabry–Perot interferometer. Next, a pellicle beam splitter was inserted in the path to enable measurement of the phase conjugate reflectivity and to observe the laser spectrum using a grating spectrometer. The total round trip path length in this system was measured to be 46 cm.

The system was aligned by first biasing the semiconductor gain element to achieve an output power of several milliwatts from the antireflection coated facet. The phase conjugate reflectivity was then monitored using the pellicle beam splitter while adjustments were made to the PPCM. The buildup of the phase conjugate reflectivity would usually require about one minute owing to the slow response time

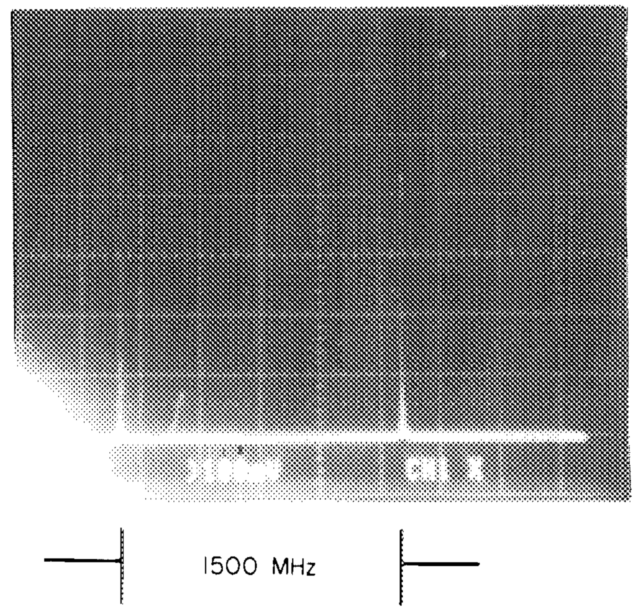

FIG. 3. Output spectrum from the phase conjugate external cavity laser measured with the scanning Fabry–Perot étalon and showing single mode operation of the laser. The trace encompasses approximately two free-spectral ranges of the étalon.

of the $BaTiO_3$ medium. At some point during the buildup of phase conjugate reflectivity system loss is reduced enough to allow lasing oscillation in the external cavity. The resulting spectrum as measured on the grating spectrometer is shown in Fig. 2(b). The lasing wavelength is 8327 Å. The grating spectrometer used has an instrumental bandwidth of 0.2 Å and therefore does not give a true indication of single mode oscillation in this system. To check this we employed a scanning Fabry–Perot étalon having a free-spectral range of 1500 MHz and an instrumental resolution of 10 MHz. This showed that the oscillation was in fact single mode, but remained at a given mode for only a brief period (we estimate approximately 10 ms) before jumping to another longitudinal mode of the cavity. A Fabry–Perot scan showing single mode oscillation is displayed in Fig. 3. The scan encompasses approximately two free-spectral ranges of the Fabry–Perot étalon.

Mode selectivity provided by the gain spectrum is not sufficient to explain this single mode behavior. In the present case there is an additional selection mechanism resulting from the phase conjugate mirror. The buildup of phase conjugation involves the formation of index gratings in the $BaTiO_3$ crystal. Reflection from the PPCM actually involves Bragg diffraction from these index gratings. Subsequent passage back to the gain element occurs only for a narrow band of wavelengths satisfying the Bragg condition. The Bragg selectivity of the 2 μm period grating over its 2 mm interaction length is about 10 Å. This is too broad to explain the observed single mode behavior. This behavior has also been observed in conventional external cavity systems.[6,7] A theoretical explanation has been proposed based on an intermode interference effect.[12] We are continuing to investigate this and the mode hopping effect mentioned above.

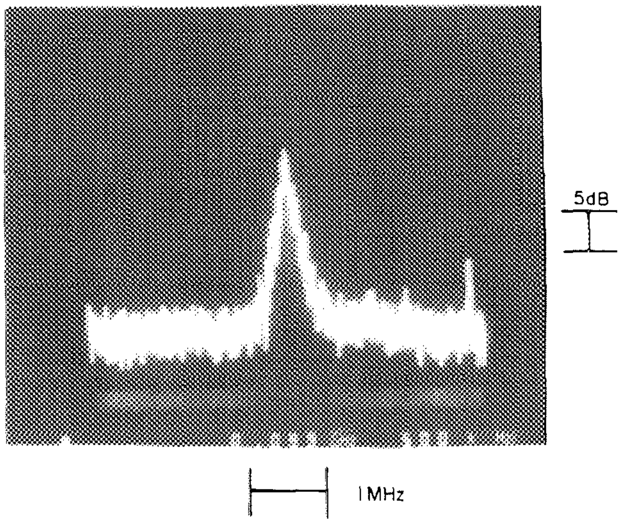

FIG. 4. Self-heterodyne spectral line shape function measured for the phase conjugate external cavity laser at an injection current of 35 mA. The pip at the far right of the trace is picked up from a local radio station.

We also measured the linewidth of the single mode system using a fiber delay line self-heterodyne system. The length of fiber employed to achieve the delay was 1 km. This gives the system a resolution of approximately 100 kHz. An acousto-optic modulator was used to shift the frequency in one path of the interferometer relative to the other by 100 MHz. A typical electronic spectrum analyzer trace is shown in Fig. 4. The half-power point is near the system resolution bandwidth limit caused by the fiber length of 100 kHz (note: the electronic spectrum analyzer resolution bandwidth was well below this value at 20 kHz). Signal to noise in this measurement was limited by our ability to sample power in the external cavity while maintaining lasing action. Measurements were repeated for several bias levels of the diode, but always with the same result.

We now estimate the theoretical linewidth for this system using Eq. (1). The required gain G to achieve laser oscillation in this system is given by the expression,

$$G = s - \frac{1}{2l_A} \sum_i \ln c_i , \qquad (2)$$

where s is the scattering losses within the gain element waveguide, l_A is the length of the active section of the cavity, and the c_i's are the various coupling coefficients experienced by the lasing mode as it completes one round trip of the cavity (mirror and facet losses included). This expression assumes that the gain is spatially uniform in the gain element. G is related to the spontaneous emission rate θ [appearing in Eq. (1)] as follows:

$$\theta = 2\xi n_{sp} v_g G, \qquad (3)$$

where n_{sp} is the spontaneous emission factor, v_g is the group velocity in the gain element, and ξ is a factor which accounts for decreased spontaneous emission coupling into the lasing mode as a result of the large passive section.[13] Using $n_{sp} = 2.5$, $v_g = c/4.5$, $l_A = 300$ μm, $s = 10$ cm^{-1}, $\xi = 0.006$, $R = 0.4$ for the facet reflectivity, $R_\phi = 0.14$ for the phase conjugate mirror reflectivity, and the c's measured for the other coupling losses in the system gives $\theta = 12.6$ ns^{-1} from Eq. (3). The phase conjugate reflectivity was determined at a pumping current of 35 mA. At this same pumping level we estimated $P = 1.3 \times 10^7$ photons. Using $\alpha = -4$ for the linewidth enhancement factor gives $\Delta\nu = \Delta\omega/2\pi = 1.2$ kHz, which is much narrower than the measured value.

In conclusion, we have measured the spectral properties of an external cavity semiconductor laser which utilizes a phase conjugate mirror for its external reflector. This system has the advantage over conventional external cavity semiconductor lasers of being self-aligning. We observed using a scanning Fabry–Perot étalon that the system would lase for short periods of time (10 ms) in a single longitudinal mode and then jump to another longitudinal mode of the system. At this time we are not certain whether this behavior is intrinsic to this kind of resonator or whether it results from another (external) source. We are continuing to investigate. We attempted to measure the linewidth of these modes using a fiber delay line self-heterodyne system and determined that the linewidth was at least as narrow as the instrumental bandwidth of the fiber interferometer (100 kHz). This result is consistent with a calculation of linewidth we presented based on measured coupling losses and optical power in the cavity.

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