Minimum line width of an injection laser

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The lower limit on the line width (Γ) of a semiconductor laser in a single-frequency operation is set by the quantum noise[1]:

$$\Gamma = \pi h \nu \gamma^2 / P \quad , \tag{1}$$

where γ is the cavity line width and P is the output power. Because of the low Q values of semiconductor lasers, the width Γ is comparatively large[2] and restricts the applications of such lasers. A much narrower line can be achieved if γ is reduced. In the present letter we report an experimental confirmation of this idea.

The width of the output line of a semiconductor laser has only been measured with high resolution in a few cases. Hinkley and Freed[1] carried out such measurements on the basis of the beat spectrum produced by a semiconductor laser and a CO_2 laser, but this approach is only feasible for certain kinds of lasers. It is simpler to use beats between longitudinal modes for the measurements,[3] but steady-state multimode output may not be realized in a homogeneous active medium.[4] The use of a Michelson interferometer[5] with a baseline $\gtrsim$ 1 km suffers from technical difficulties. In the present work, for the first time the width of the output line has been measured using beats between two tunable semiconductor lasers. The Q of the cavity is increased by external feedback.

Characteristics of the tunable lasers. The semiconductor laser with unbrightened faces, a stripe contact, and a double $Ga_{1-x}Al_xAs$ heterostructure (1 in Fig. 1) operates continuously (at 77°K) in the wavelength range 8080–8150 Å. The length of the "internal" cavity of the laser diode l = 250 μ. The total length of the "external" cavity (mirrors 5–7) is L ≃ 1 m. Objective lenses 2 match the active region with the passive region, which includes a Fabry–Perot interferometer 3 with a baseline d = 5·10⁻³ cm and an etalon 4 with d = 2 cm. The two objective lenses in the cavity increase the output stability. The Fabry–Perot interferometer 3 selects one of the modes of the internal cavity in an interval of 30 Å. The modes of the external cavity are changed by rotating etalon 4. The output frequency of laser B is tuned continuously over an interval ~100 MHz by shifting mirror 5. With synchronous modulation of the injection current and the length L without etalon 4 in the cavity the range of continuous tuning is 2.5 GHz. The number of modes of the external cavity is monitored with Fabry–Perot interferometer 12, with a resolution of 150 MHz (d = 10 cm). When the current is raised a single external mode is excited in all the laser diodes, as long as the selective elements ensure lasing at one resonance of the internal cavity. The ratio of the threshold currents with and without external feedback K = 1.1–1.15; the output power is 0.5–5 mW; and the threshold currents are 50–100 mA. The working currents are higher than the threshold currents by a factor of 1.1–1.4.

Observation of the beat signal. The beams from lasers A and B are brought into coincidence by objective lenses 8 and mirror system 9 and directed to photodiode 14. If the angle between the beams satisfies $\leqslant 10^{-4}$ rad, the diffraction grating makes it possible to monitor the difference between the laser frequencies within an error of 5 GHz. In the course of the search, an alternating voltage is applied to the piezoelectric ceramic, and the angular position of the etalon and the injection current are varied. When beats appear the alternating voltage is removed and the signal is studied with a S4-27 spectrum analyzer at frequencies in the range 200–300 MHz. Continuous observation is carried out for several minutes, for a time governed by mode switching in the external cavity. If the external mode does not jump the drift rate of the beat frequency varies over the range 2–20 MHz/sec; this determines the band covered (5–100 MHz) and the resolution (50 kHz).

Experimental results. The width of the beat spectrum for the lasers with the external cavities is less than 100 kHz at power levels of 1 and 0.7 mW. This spectral width is governed by the width of the laser line and the analyzer resolution, so that the widths of the laser lines are 50–70 kHz. In the operation of one of the lasers without the external feedback the width of the beat spectrum reaches 300 MHz and is governed by the corresponding line width. Let us compare the measured values with the minimum possible width 1. For the internal resonator, Γ = 2 MHz [$\gamma_i = \Delta\nu_{ax}(\alpha l - \ln R)/\pi$ (Ref. 6), with α = 10 cm⁻¹ and R = 0.32]. For the external cavity, for the same power, 1 mW, we have Γ = 0.5–2 kHz [an estimate of the width of the cavity line for $(l/L) \ll R_2 \ll 1$ yields $\gamma_{ex} \simeq \gamma_i l (LRR_2)^{-1}$ = (30–60) γ_i, where R_2, the fraction of the intensity returned from the external cavity, is esti-

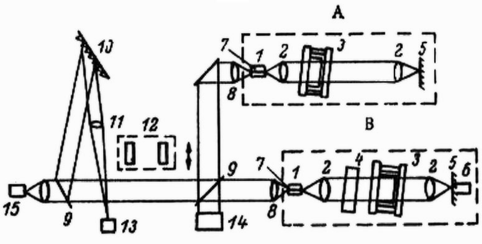

FIG. 1. A, B) Lasers with an external cavity; 1) laser diodes; 2) objective lenses; 3, 4) seletive elements; 5) external mirror; 6) piezoelectric ceramic; 7) output mirror; 8) collimating objective lenses; 9) semitransparent mirrors; 10) diffraction grating; 11) objective lens with a long focal length; 12) Fabry–Perot interferometer; 13) image converter; 14) fast-response photodiode; 15) power meter.

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mated on the basis of the parameter K to be $R_2 = (2-4) \cdot 10^{-2}$].

In both cases the measured width is thus governed by technical fluctuations; for the internal resonator, these are temperature fluctuations, which lead to a change in the optical path length. External feedback reduces these fluctuations by a factor of nl/L, but frequency fluctuations are introduced because of the oscillations in the length of the external part of the cavity. It is important to note that the width of the output line with the external cavity is smaller than the limiting width of an output line with the internal cavity; that is, the contraction due to the decrease in the cavity line width actually occurs. At the attainable values of R_2, $R_2 = 0.5$ (Ref. 7), the extreme line width is ~10 Hz. In other words, this width is limited in practice by apparatus noise, as in the case of gas lasers.

Conclusion. 1. The width of the output line of a semiconductor laser can be reduced by more than two orders of magnitude by increasing the cavity Q. 2. Tunable semiconductor lasers have been developed with a line width smaller than 100 kHz at a power of 1 mW. These lasers can be used for ultrahigh-resolution spectroscopy. 3. A method has been developed for measuring the width of the output line of a semiconductor laser by using an injection laser of the same type as the heterodyne oscillator, but with an external cavity. The increased frequency stability makes it possible to improve the resolution of the method and to study the variation of the shape of the output line as a function of power. This point is of interest in the theory of semiconductor lasers.[8]

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