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ACTIVELY MODE-LOCKED SEMICONDUCTOR LASER WITH FEEDBACK AT AN INTERMODE FREQUENCY

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This is a study of an active mode synchronization regime (mode locking) in a three-mirror semiconductor laser obtained by modulation of the laser current at the frequency of intermode beating of the external laser cavity through a feedback circuit. Under certain conditions stable active mode-locking is observed, and when the length of the external cavity is varied, corresponding tuning of the intermode beat frequency occurs. The main conditions under which this regime is attained are determined. The width of the intermode beating spectrum is found experimentally to be ~300 Hz for an intermode frequency of 300 MHz. The half width of the optical spectrum is ~4 nm.

Keywords: *semiconductor laser, mode-locking, intermode beating, microwave modulation.*

Introduction. In studies of semiconductor lasers during the 1980's and 1990's, considerable attention was devoted to the problem of minimizing pulse length in mode synchronization (mode locking) regimes [1, 2]. At the same time, lasers with an external cavity were proposed and studied [1–6], so it was possible to study the frequency characteristics of semiconductor lasers and obtain both single-frequency [1–5] and multimode [6, 7] lasing. Later on, interest in semiconductor lasers has continued because of the improved characteristics of diode lasers and cavity (resonator) structures [7–13]. Semiconductor lasers with an external cavity are of interest from the standpoint of practical applications, e.g., as a basis for synthesizers and spectrometers in the terahertz (THz) range [14], when mode synchronization takes place in an external cavity with the possibility of tuning an intermode frequency.

In this paper, we obtain an active mode synchronization regime by modulating the current of a semiconductor laser at an intermode beat frequency with a photomultiplier that detects the laser optical output. As in experiments with current modulation of semiconductor lasers by an external microwave generator [8], in this new series of experiments effects characteristic of synchronization have been observed (broadening of the optical spectrum, frequency capture and pulling, etc.). Here the modulation technique that is described makes it possible to obtain a stable mode synchronization regime by tuning the length of the external cavity, i.e., tuning the intermode frequency during active mode locking.

Experimental Apparatus. Figure 1 is a block diagram of the experimental apparatus. The output of a semiconductor laser 1 is split by the mirror splitter M_1 into two beams which are fed to photodetectors 3 and 8. The signal from detector 3 is delivered to a microwave amplifier-clipper 4 which ensures stabilization of the power at the input to a regulated power amplifier 5 and proceeds to the power supply circuit 6 for the semiconductor laser. A dc current is fed through a choke to separate it from the microwave, and the microwave is fed through a divider capacitor. For cutting off the negative half wave of the microwave, the power supply circuit is shunted by a Schottky diode (the choke, capacitor, and Schottky diode are not shown). An optical spectrum analyzer 7 and a spectrum analyzer for the intermode frequency 9 are used to record the emission parameters. The analyzer 7 is used to study the broadening process for the optical spectrum and the analyzer 9, to examine the width of the beat spectrum of the optical modes. The arrows indicate that the mirror of the external cavity can be mechanically displaced within a tuning range of ±25 mm ($\Delta f_m = f_m \Delta L/L = \pm 15$ MHz) at the intermode frequency of ~300 MHz.

The gain of the amplifier-clipper is 75 dB at a frequency of ~300 MHz with a bandwidth of ~60 MHz. The output power of the amplifier-clipper is 5 mW. The regulated power amplifier (0.5–2000 mW) includes a directional coupler with a detector and series operational amplifier for stabilization of the power. Temperature stabilization of the amplifier regime is provided by an independent system based on a Peltier unit. The laser is mounted on a damped plate.

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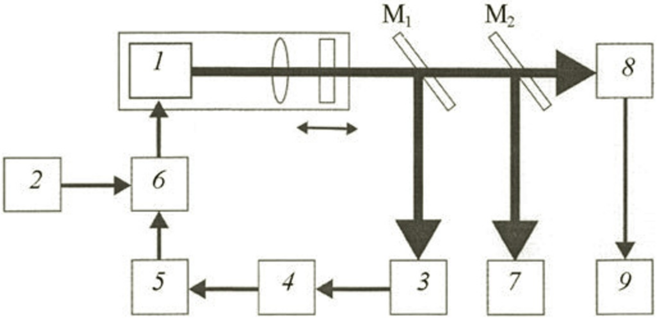

Fig. 1. Block diagram of the experimental apparatus: (1) semiconductor laser; (2) dc current source; (3) photodetector; (4) microwave amplifier-clipper; (5) regulated power amplifier; (6) power supply circuit for semiconductor laser; (7) spectrometer; (8) photodetector; (9) radio-frequency spectrum analyzer/optical spectrum analyzer; (10) damped plate; M_1 and M_2 are splitter-mirrors.

Results and Discussion. In the first stage, the characteristics of a single-mode ILPN-820-100 laser when the laser was modulated by an hf power of <2 W at a constant current close to the threshold were studied. Figure 2 shows the pulse for synchronized modes at an intermode frequency of 400 MHz in the optical emission from the photodetector. When the power of the modulating signal exceeds a certain limit (~150 mW), the integrated power of the synchronized modes increases in proportion to the power of the modulating signal to a first approximation. In our case a power of the synchronized modes of ~60 mW was reached for a modulating power of ~2 W. The duration of the pulse is determined by the cutoff angle of the modulating sinusoidal signal. The pulse can be expanded in the spectrum

$$A(t) = a_0 + a_1 \sin(\omega t + \varphi_1) + a_2 \sin(2\omega t + \varphi_2) + \ldots + a_n \sin(N\omega t + \varphi_n) + \ldots , \quad (1)$$

where ω is the modulation frequency and φ_n is the phase of the mode. The frequencies (1) are a consequence of the modulation of the laser current. An estimate of the width of the pulse spectrum from the duration of the optical pulse ($\Delta\omega = 1/t_{\text{pulse}}$) yields a width of ~2 GHz. Here in the optical spectrum (Fig. 3) there is a broadening to 4–5 nm that is related to nonlinear processes in the semiconductor laser and covers a range of intermode frequencies up to the THz region. This broadening is indicative of so-called frequency "chirping" [15].

In the second stage, the laser current modulation regime was studied with feedback through amplification in the electronics channel at a frequency of ~300 MHz. For free lasing close to the threshold (without modulation of the laser current), the spectrum analyzer 9 at frequencies equal to the intermode frequency (defined by the parameters of the external cavity, ~300 MHz ($c/2L$)) or multiples of it, small intermodal beating signals are observed against the noise background with an amplitude of several decibels and a width of ~50 MHz (Fig. 4a). When the feedback is turned on, there is a qualitative change in the beating spectrum (Fig. 4b). Amplification of the beating signal at a frequency of 300 MHz by choosing the power of the microwave amplifier 5, the constant component of the laser current (using the current source 2), and the length of the external cavity yields an automatically stable frequency synchronization regime with an intermediate frequency of ~300 MHz. A width of ~300 Hz (Fig. 5) for the beating spectrum was obtained without special efforts, beyond those indicated above, to protect the external cavity from external noise during tuning of the intermode frequency of the external cavity in the $\Delta f_m = \pm 15$ MHz range. This means that operation with stable forced synchronization occurs if the external perturbations of the cavity do not exceed the capture and regulation region. In addition, the noise is significantly reduced and broadening of the optical spectrum occurs, so that the difference between the extreme frequencies in the crest (Fig. 3) of the intermode frequencies reaches THz values. This regime is observed for the type ILPN-820-100 laser under the following conditions: threshold diode current 50 mA and output power of the amplifier 5 regulated over an interval of 0.1–2 W. The experiments were done with a coupling coefficient of $T < 0.5$ for the cavities, a reflectivity $R_d \sim 3\%$ from the front face of the diode, and a reflectivity from the external mirror of ~0.7. A stable mode synchronization process is generally observed in the region of the diode threshold current when the power of the modulated signal exceeds a certain limit (~150 mW).

Figure 3 shows the optical spectra of a semiconductor laser without and with feedback. It can be seen that when the feedback is turned on the laser shifts to a mode-synchronized regime and the optical spectrum of the semiconductor laser output is broadened.

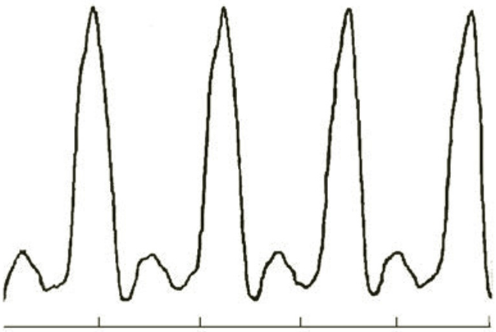

Fig. 2. Intermode signal pulses from the photodetector.

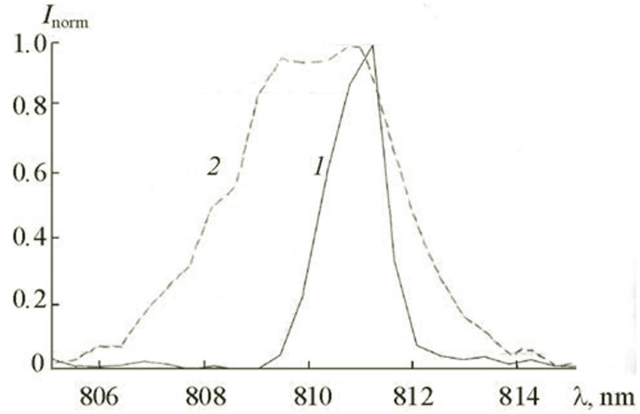

Fig. 3. The optical spectrum under free lasing conditions (1) and with active mode synchronization (2).

Modulation of the current of a semiconductor diode with a frequency close to or equal to multiples of the intermode frequency leads to polarizability of the diode, i.e., to amplitude and frequency modulation [11]. It has been noted [11] that when the current of a semiconductor laser is modulated in a synchronization regime, the nonlinearity of the diode plays a fundamental role. The refractive index takes the form [15]

$$n(I) = n(0) + n_2 I \,, \tag{2}$$

where n_2 is the nonlinearity coefficient and I is the intensity of the optical field. The nonselectivity of the processes described by Eq. (2) has been pointed out [2]. Here a dynamic lattice of the carriers develops in the medium at the frequency Ω_{m} of the intermode beats:

$$\Delta n(r, I) = GI' \exp\left[i(\Omega_{\text{m}} t - \Delta k r)\right] \,, \tag{3}$$

where G is a proportionality coefficient describing the properties of the medium; I' is the intensity of the intermode beating; and $\Omega_{\text{m}} = 2\pi f_{\text{m}}$.

When a current-modulated signal at the frequency f_{m} is fed to the nonlinear element (the diode), the interaction of the wave processes in the cavities leads to active mode synchronization. The synchronization process is accompanied by a broadening of the optical spectrum (to 4 nm) and a significant narrowing of the spectrum of the intermode beating. For a certain difference $\Omega_{\text{m}} \pm \Omega'_{\text{m}}$, because of the detuning of the external cavity, in some frequency band (the phase capture band) there is mode pulling of the outer cavity toward the microwave pump frequency f_{m}. It is so large that for relatively small attenuation of the external perturbations (use of damping) it is possible to obtain stable mode synchronization. Effective mode synchronization usually takes place near the current threshold. As the diode current is raised the phase capture band becomes narrower with a fixed modulation power [4]. The phase capture and frequency pulling process described in [7] and here with

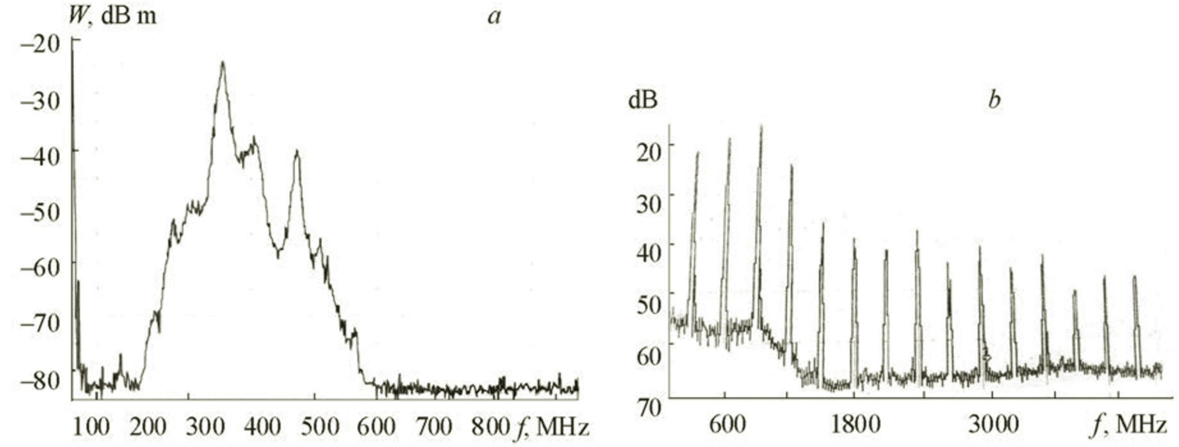

Fig. 4. The noise spectrum without feedback (a) and the spectrum of the synchronized modes with feedback (b).

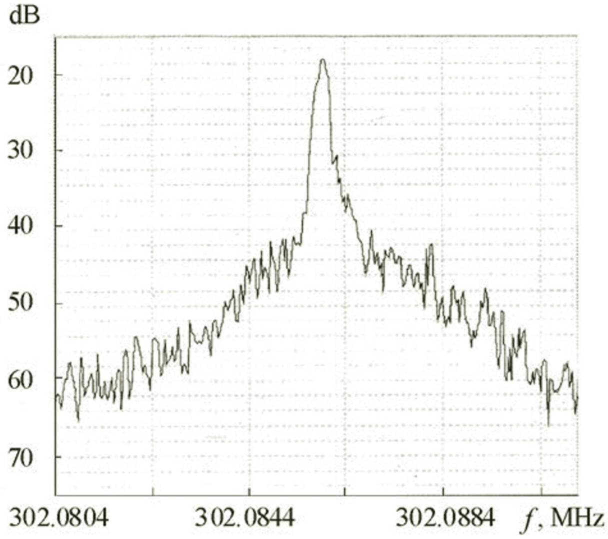

Fig. 5. The spectrum of an individual component of the intermode beating when the feedback is turned on.

[8] and [9], can be characterized as an analog of phase self-adjustment in a six-pole circuit [16, 17] where the role of the input bipolars is played by the modulation signal and the internal coupling of the external cavity with the diode, while the nonlinearity of the diode serves as the phase detector. The confinement band in this case can be represented in the form [4]

$$\Delta\omega \approx \gamma \frac{d\varnothing}{dt}(1\pm T)\rho \,, \tag{4}$$

where γ is the gain in the loop; T is the coupling coefficient of the cavities; $\varnothing = \delta(\Delta\nu)/\delta L_{\mathrm{ext}}$ is the tuning slope; and ρ is the reflection coefficient of the front cleavage. When the conditions for mode synchronization are met, a phase shift takes place owing to the effect of Eq. (2). This leads to a frequency shift

$$d\Phi/dt = n_2 I\Omega_{\mathrm{m}}(dL/cdt) = n_2 I\Omega_{\mathrm{m}}(v_{\mathrm{M}}/c) \,. \tag{5}$$

The frequency shift can be interpreted as the slope of the tuning owing to the ratio v_{M}/c, where v_{M} is the velocity at which the outer mirror moves.

We now estimate the confinement band $\Delta\omega$ based on the parameters of the apparatus: the tuning slope ~2.8 MHz/cm, $T \sim 0.4$, $\rho = 0.7$, and $\chi \sim 1$ cm^{-1}. For these parameters, $\Delta\omega \sim 0.8$ MHz and stable synchronization occurs (the external perturbations of the cavity are ≤1 mm). These results are a basis for creating small-sized synthesizers and spectrometers in the radio-THz ranges with high resolution (10^{-11}–10^{-12}).

Conclusions. Stable mode synchronization at an intermode frequency with feedback for simple tuning of the external cavity frequency, i.e., a tunable intermode frequency with mode synchronization, has been obtained. This device can serve as the basis of frequency synthesizers in the terahertz range with a tunable frequency, as well as of spectrometers in the same spectral range. Effects that occur when an external laser is used are also observed [9]: phase capture, narrowing of the beating spectrum, broadening of the optical spectrum, etc. The significant difference is that in the first case the stability of the intermode beating is determined by the characteristics of an external laser (a hydrogen maser) and in the second, of an external cavity. Thus, the important problem is to create a high-Q cavity that is protected from noise. A synchronization regime is observed, as in [9], near the lasing threshold and is accompanied by a sharp narrowing of the width of the intermode beating spectrum. Because of the increased modulated power the optical spectrum of the laser radiation broadens, and the interval between extreme modes reaches the terahertz range. The nonlinearity of the laser diode, which serves as a phase detector, plays an important role in the mode synchronization process. There is a contradiction between a synchronization phase band of 0.8 MHz and a tuning band of ±15 MHz. The synchronization band, however, follows the tunable frequency, which is determined by the mechanical movement of a third mirror.

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