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Actively mode-locked diode laser with a mode spacing stability of $\sim 6 \times 10^{-14}$

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Abstract. **We have studied mode spacing stability in an actively mode-locked external-cavity semiconductor laser. It has been shown that, in the case of mode spacing pulling to the frequency of a highly stable external microwave signal produced by a hydrogen standard (stability of 4×10^{-14} over an averaging period $\tau = 10$ s), this configuration ensures a mode spacing stability of 5.92×10^{-14} ($\tau = 10$ s).**

Keywords: *diode laser, active mode locking, beat spectrum, mode spacing stability.*

A number of reports [1–11] addressed the operation of multimode external-cavity semiconductor lasers (ECSLs), which are convenient tools for the study of many physical processes in a laser diode. Zakharyash et al. [8] examined the effect of microwave pump frequency f_{mw} on the intermode beat spectrum (f_{im}) of ECSLs. Pumping at a frequency $f_{mw} \approx 2f_{im}$ was shown to cause a frequency pulling effect. This paper presents results of further experimental work, concerned with the use of this effect for mode spacing stabilisation. A significant improvement of the experimental setup allowed us to measure frequency stability with an accuracy of $\sim 10^{-14}$.

Figure 1 shows a block diagram of the experimental setup. To simplify the configuration, a mode spacing of 150 MHz (cavity length of $\sim$1 m) was chosen in order to pump the ECSL at a frequency $f_{mw} \approx 300$ MHz. As previously [8], microwave modulation at twice the mode spacing frequency was used, which allowed us to avoid the overlap of the microwave frequency f_{mw} with the intermode beat frequency f_{im} and hence to avoid the parasitic effect of f_{mw} on mode spacing measurement results. The external-cavity length was adjusted so that $f_{mw}/2$ lay in the range where the intermode beat spectrum had a minimum width [8]. We used an ILPN-820-100 semiconductor laser, with a front-facet reflectivity of $\sim$3% and lasing threshold of $\sim$40 mA.

A 100-MHz signal from a hydrogen (H) standard (*1*) (stability of 4×10^{-14} over an averaging period $\tau = 10$ s and 1×10^{-14} over $\tau = 100$ s) was multiplied to a frequency of 300 MHz (*2*) and directed through a microwave power amplifier (*5*) to the semiconductor laser (*9*) through capacitive decoupling (we used a standard drive current source, which is

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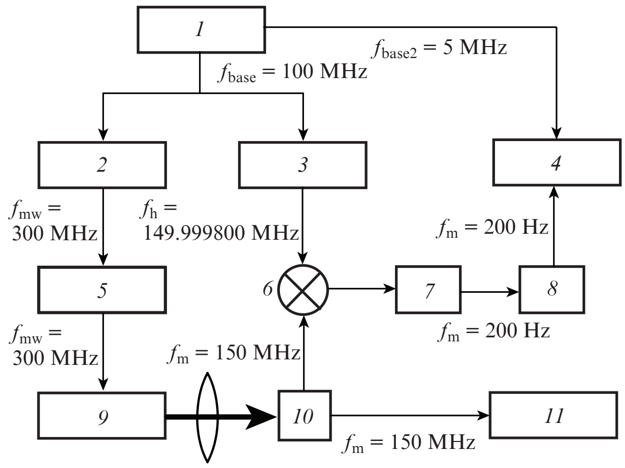

Figure 1. Block diagram of the experimental setup: (*1*) hydrogen frequency standard; (*2*) multiplier; (*3*) frequency synthesiser; (*4*) frequency meter; (*5*) microwave power amplifier; (*6*) mixer; (*7*) LFF; (*8*) limiting amplifier; (*9*) ECSL; (*10*) photodetector; (*11*) spectrum analyser.

omitted in Fig. 1). In addition, the H standard provided a highly stable signal (5 MHz) to a frequency meter (*4*) in order to synchronise its time base with that of the microwave pump signal. The ECSL output was focused onto a photodetector (*10*). The signal was then directed to a spectrum analyser (*11*) and mixer (*6*), where it was mixed with a highly stable signal from a frequency synthesiser (*3*) (f_h = 149999800 Hz). Next, the signal was sent to a low-frequency filter (LFF) (*7*), which separated a signal of frequency f_m = 200 Hz. The low-frequency signal was then directed to a limiting amplifier (*8*) and the frequency meter (*4*).

In our experiments, we measured the signal period (f_m = 200 Hz) at averaging times $\tau = 10$ and 100 s. The number of measurements, N, for these τ values was 100 and 40, respectively. The experimental data are summarised in Table 1. It follows from these data that, at $\tau = 10$ s, the standard deviation (SD) from the average mode spacing is 8.889×10^{-6} Hz. A detailed analysis of the sample ($N = 100$) demonstrates that it consists of alternating measurement regions that have different SDs (Fig. 2). Such sequences consist of several (five to seven) successive measurements with an SD of 8.025×10^{-6} Hz (Table 1). In such intervals, stability reaches 5.355×10^{-14}.

Comparison of frequency stability at $\tau = 10$ and 100 s demonstrates that, with increasing τ, the mode spacing stability degrades, whereas the stability of the master hydrogen standard improves from 4×10^{-14} at $\tau = 10$ s to 10^{-14} at $\tau = 100$ s. One possible cause of this is the small detuning of the external cavity in the frequency pulling range (±2 MHz [8]), which

Table 1. Frequency stability as a function of time.

Average frequency/Hz	SD from the average signal/Hz (at f_m = 200 Hz)	Averaging time/s	Number of measurements	Stability
1.5×10^8	8.889×10^{-6}	10	100	5.928×10^{-14}
1.5×10^8	8.602×10^{-5}	100	40	6.807×10^{-13}
1.5×10^8	8.025×10^{-6}	10	7	5.35×10^{-14}

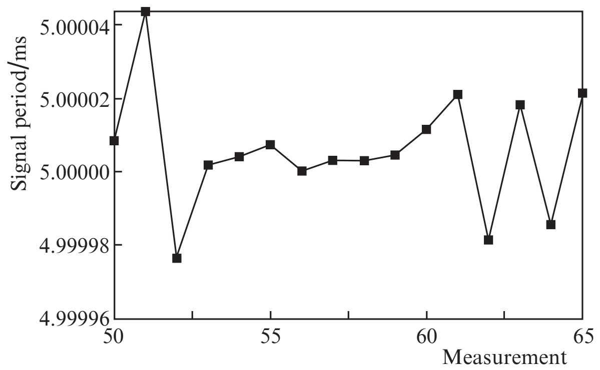

Figure 2. Time scatter of the signal period (200 Hz, τ = 10 s) measured with a frequency meter within measurement regions in an experimental sample.

results in a systematic error and, as a consequence, in degradation of mode locking conditions (variation in amplitude). This conclusion is supported by the asymmetry of the histogram in Fig. 3, which represents the mode spacing distribution about a centre frequency of 150 MHz.

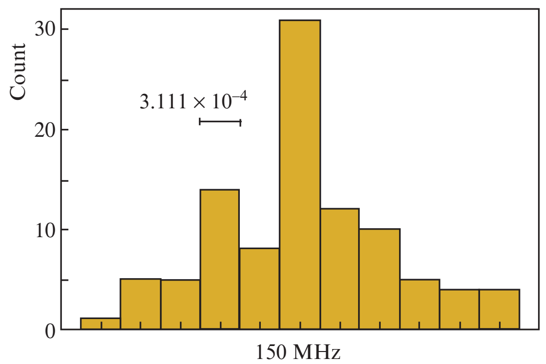

Figure 3. Mode spacing (f_{im}) distribution about a centre frequency of 150 MHz (N = 100, τ = 10 s).

Consider briefly some features of ECSL operation observed in our experiments. Note first of all that, under certain conditions [8], a three-mirror laser system operates in the multimode regime. The considerable nonlinearity in the refractive index of the semiconductor [9] leads to the formation of a dynamic carrier concentration grating in the medium at the mode spacing frequency f_{im}. The interaction of the active medium with the cavity field may lead to multimode operation, depending on the drive current. When an external signal modulating the injection current at a frequency f_{mw} close to the mode spacing frequency f_{im} is applied to a laser with a nonlinear medium, the interaction of wave processes leads to active mode locking. The mode locking process is accompanied by broadening of the optical spectrum (from 1 to 10 nm) and significant narrowing of the observed individual components of the intermode beat spectrum (from ~20 MHz in the case of free-running laser operation to ~1 kHz in the case of mode locking), which was also shown earlier [8]. As the difference between f_{mw} and f_{im} decreases, further interaction between vibrational processes is observed, leading to frequency pulling to the frequency of the stronger external signal.

The pulling effect is so strong that even a relatively slight reduction in external influences (for example, placing the laser in a specially designed container) ensures high intermode beat frequency stability and a sufficiently broad optical spectrum in the phase-locking band.

Thus, mode spacing stability is determined to a significant extent by the microwave oscillator stability, which can be used for making an actively mode-locked semiconductor laser with a highly stable mode spacing. At the same time, the effect of acoustic noise and a number of external-cavity parameters (such as angular detunings of the external mirror and feedback efficiency) on mode spacing stability should be studied in detail in order to ensure reliable actively mode-locked laser operation.

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