

**INSTABILITIES IN THE POWER SPECTRUM OF MODE-LOCKED SEMICONDUCTOR LASERS**

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Abstract: Sideband instabilities in the intensity spectrum of synchronously mode-locked external cavity semiconductor lasers are investigated as a function of the cavity length and frequency detuning. A sideband spectrum with distinct narrow lines is observed in the optical power spectrum for modulation frequencies smaller than the inverse photon round trip time and is attributed to frequency and phase modulation of the modelocked pulse train.

1.INTRODUCTION: Mode-locking of semiconductor lasers has been widely used for the generation of coherent short light pulses on the picosecond and subpicosecond timescale applying either active, passive or hybrid mode-locking techniques. With purely active mode-locking coherent pulses with 5ps duration have been obtained [1]. Apart from its use as a source for very short light pulses the mode-locked laser may serve as a model system for the investigations on nonlinear dynamics and instabilities.

We have performed systematic studies of the power spectrum of an actively mode-locked semiconductor laser as a function of the detuning between the modulation frequency  $f_{\text{mod}}$  and the inverse photon round trip time  $f_{\text{res}}$ .

2.EXPERIMENTAL: We use an external cavity configuration (cavity length 1.87m) with an one facet antireflection coated GaAs / (GaAl)As CSP laser (Hitachi HLP1400) in the experiments. The residual reflectivity of the coated facet is smaller than  $10^{-4}$ .

An intracavity etalon (bandwidth 10nm) is employed for spectral bandwidth con-

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trol and tuning. The cw threshold in the external cavity configuration is about the same as for the solitary laser ( $I_{th} = 54.5\text{mA}$ ) without antireflection coating.

Mode-locking is achieved by modulating the prebiased diode ( $I_{DC} < I_{th}$ ) with the current pulses from a comb generator (HP33002A), which have a duration of 130ps and an amplitude of typically 15V at an impedance of 50 Ohms. The optical output was analyzed by a fast photodiode (risetime 100ps) and an electrical spectrum analyzer (DC-2GHz).

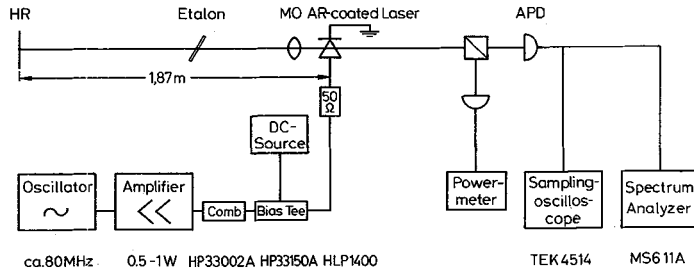


Fig.1: Experimental setup.

**3. RESULTS:** Under optimum mode-locking conditions,  $f_{mod} = f_{res} = 80\text{MHz}$ , the power spectrum consists of a series of equally spaced narrow lines of width 150kHz and signal to noise ratio 50dB at multiples of the modulation frequency  $f_{mod}$ , indicating proper mode-locking. The power spectrum shows an unstructured noise band of width 13MHz for positive detuning ( $f_{mod} - f_{res} > 0$ ). This broad noise band is symmetric with respect to the inverse resonator round trip time  $f_{res}$ , independent on detuning. Its height and width are a measure for the amplitude and phase fluctuations in qualitative agreement with the results of mode-locked dye lasers [2]. Opposite, the power spectrum shows a characteristic structure of narrow sidebands (Fig.2), if the laser is detuned a few 10kHz to the negative side. This sideband structure is symmetric with respect to the modulation frequency  $f_{mod}$ .

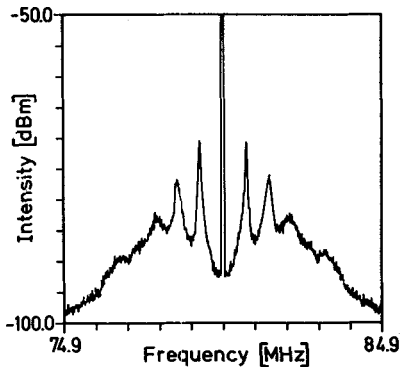


Fig.2: Power spectrum of the laser output at a detuning of -71kHz.

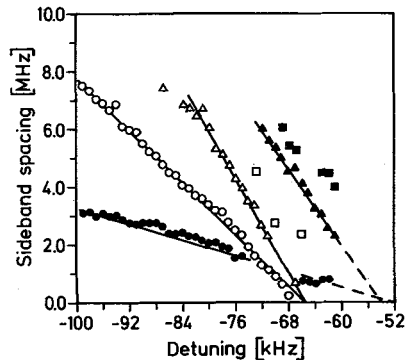


Fig.3: Frequency spacing of the sidebands as a function of detuning.

All these observations are exactly reproduced when the modulation frequency

is kept fixed and the length of the cavity is changed instead. Negative frequency detuning corresponds to a too short cavity.

The sideband spacing shows a linear variation with detuning and at a critical detuning the sidebands merge together with the modulation frequency peak. However, according to the value of this critical detuning, two classes of sidebands can be distinguished (see Fig.3).

The sidebands of the first class (open symbols in Fig.3) are narrow (halfwidth typically 150kHz) and vanish at a detuning of approximately -66kHz. The sidebands of the second class (closed symbols in Fig.3) are appreciably broader and they vanish at a detuning of nearly -54kHz, which, however, is still far away from the optimum mode-locking frequency.

We further have investigated the dependence of the sideband spacing on the optical power. The optical power is varied by changing the bias current or the pulsed current. In both cases the sidebands of the first class do not show a power dependence. However, the spacing of the sidebands of the second class increases weakly with increasing optical power.

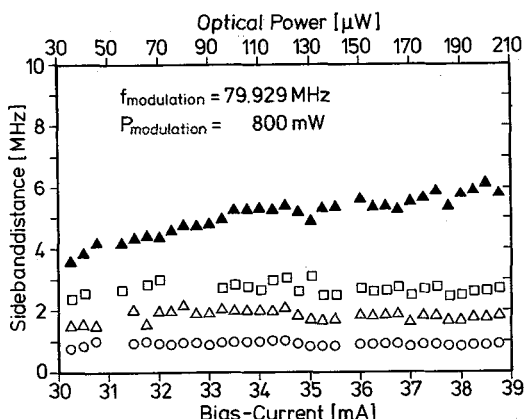


Fig.4:Dependence of sideband spacing on optical power by change of bias current.

4.DISCUSSION: We first can exclude that the narrow sidebands appearing for negative detuning are due to beat frequencies between the modulation frequency and the eigenfrequencies of the external resonator configuration, because the spacing of the sidebands is of the order of 1MHz while the detuning is smaller than 100kHz.

We further can exclude relaxation oscillations as the origin of the sidebands. In an external resonator configuration the relaxation frequency

$$f = 1/2\pi * \sqrt{A P_o / \tau_{photon}} \text{ should scale according to:}$$

$$\frac{f_{ext\ cavity}}{f_{diode\ laser}} = \sqrt{\frac{\tau_{diode\ laser}}{\tau_{ext\ cavity}}} = \sqrt{\frac{n * L_{diode\ laser}}{L_{ext\ cavity}}}$$

With  $f_{diode\ laser} = 5\text{GHz} / 3$  we estimate  $f_{ext\ cavity} = 100\text{MHz}$ , which is much larger

than the observed spacing of about 1MHz. In addition a square root power dependence is expected for the relaxation oscillation frequency, which is not seen in our experiments.

To get an idea of the physical origin of the sidebands we have performed simulation experiments by external amplitude (AM), frequency (FM) and phase (PM) modulation of the driving current of the comb generator at zero detuning. Because of experimental restrictions a modulation frequency of up to 120kHz could only be employed in these simulation experiments. The results for FM and PM are shown in Fig.5a) and 5b) respectively. The spectra consist of narrow lines corresponding to the the modulation sidebands of the FM or PM frequency and a broad background signal, which corresponds qualitatively to the result of Fig.2. FM or PM with 1MHz instead of 80kHz is thus expected to simulate the spectra properly.

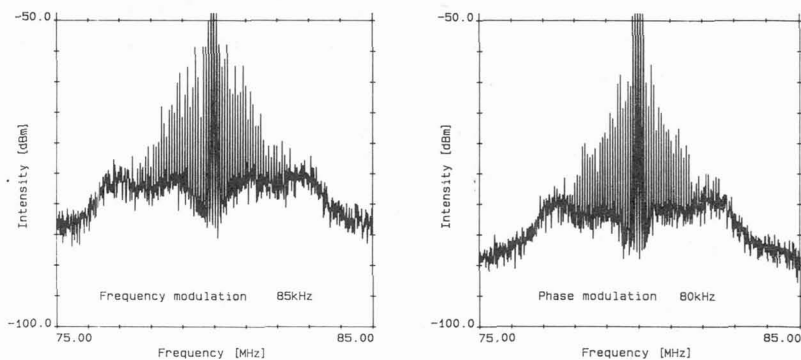


Fig.5a) Simulated spectrum of the undetuned laser obtained by FM, b) same with PM.

In conclusion, we find that the simulations with FM as well as with PM modulated current pulses qualitatively reproduce the power spectrum of Fig.2, opposite to the simulations with AM modulated current pulses. We consequently conclude, that the optical instabilities introduced in a mode-locked semiconductor laser for negative detuning basically arise from frequency and phase fluctuations, which can be coupled to each other by the nonlinear refractive index of the active region. However, further experiments are required to obtain a complete understanding of the interrelations between the nonlinearities of the semiconductor laser and the optical instabilities under incomplete mode-locking conditions.

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References:

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