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# Center Frequency Shift and Reduction of Feedback in Directly Modulated External Cavity Lasers

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**Abstract**—We show experimentally and theoretically that a center frequency shift occurs when an external cavity laser is directly modulated. The shift may be observed even when the frequency deviation is small compared to the roundtrip frequency of the external cavity and can qualitatively be explained by a reduction in the effective feedback level due to modulation. The frequency shift has been measured as a function of modulation frequency and current, and frequency shifts up to 350 MHz were observed.

## INTRODUCTION

IT IS well known that semiconductor lasers with external feedback can meet the requirement for low linewidth in coherent optical communication systems. Unfortunately, external feedback reduces the overall level of FM response and introduces additional resonance peaks [1], [2]. In this letter, we show that direct frequency modulation of an external cavity laser also results in a reduced effective feedback level, leading to a center frequency shift compared to the unmodulated laser. To our knowledge, this unwanted effect has not previously been reported. The phenomenon can be understood in simple terms. An AR-coated Fabry-Perot laser with optical feedback will usually oscillate in the external cavity mode with lowest carrier density. The reduction in carrier density leads to an increase in refractive index and hence a reduction in oscillation frequency. By modulating the laser, the level of coherent feedback is reduced which results in a smaller reduction of the oscillation frequency. Thus, modulation leads to a positive frequency pulling. We have modeled the effect by use of an optical transmission line theory described in [3].

## EXPERIMENTAL RESULTS

The spectrum of a modulated external cavity laser was observed using a scanning Fabry-Perot interferometer setup (see Fig. 1). The setup includes two optical isolators with a total isolation of approximately 50 dB. The external cavity configuration consists of a 1.3  $\mu\text{m}$  Fabry-Perot laser with one facet cleaved and the other facet AR-coated to a reflectivity of approximately 1 percent and a 6 cm long external cavity with a 600 line/mm grating. The laser has a threshold of 44 mA at a feedback power ratio of approximately 20 percent. In the experiment, the laser was biased at 60 mA. The FM response

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can be determined from the relative height of the modulation sidebands [4]. It was observed that the carrier frequency shifted towards higher frequencies as the modulation was turned on. The shift is denoted by  $\delta f$  in the following.

The frequency shift shows a strongly resonant character when measured as a function of modulation frequency, and a nonlinear behavior when measured as a function of modulation current. Fig. 2 shows the frequency shift as a function of modulation frequency in the range from dc to 1 GHz. The amplitude  $I_m$  of the modulation current was held constant at 2 mA. Fig. 3 shows the frequency shift as a function of modulation current at a modulation frequency of 280 MHz. It should be noted that the amount of frequency shift depends critically on the adjustment of the external cavity. Figs. 2 and 3 are therefore not directly comparable. Both larger and smaller values could be obtained, but in all cases the resonant character and nonlinear behavior were observed. The setup was carefully checked for parasitic optical and electrical resonators.

## THEORY

The observed behavior can qualitatively be explained by the optical transmission line model presented in [3]. The rate equation for the photon number  $I(t)$  and the phase  $\varphi(t)$  is given by (cf. [3, eq. (22)])

$$\begin{aligned} \frac{dI}{dt} + j2I(t) \frac{d\varphi}{dt} - (1 + j\alpha)G_N\Delta N(t)I(t) \\ = 2f_D\{\sigma r_L A^-(t)[A^+(t)]^* - I(t)\} \quad (1) \end{aligned}$$

where  $A^+(t)$  is the envelope function of the right-going field at a reference plane just inside the AR-coated facet. The left-going field at the reference plane is  $A^-(t) = \rho(t) \otimes A^+(t)$  where  $\rho(t)$  is the impulse response of the external cavity and  $\otimes$  denotes convolution.  $\Delta N$  is the change in carrier density compared to the unmodulated laser,  $\alpha$  is the linewidth enhancement factor,  $G_N$  is a gain constant,  $f_D$  is the roundtrip frequency of the diode cavity,  $\sigma$  is a proportionality constant, and  $r_L$  is the effective reflectivity of the Fabry-Perot laser section seen towards the left from the reference plane. Spontaneous emission and phase noise are neglected in the following.

In the case with sinusoidal modulation, we have [4]

$$A^+(t) = A\sqrt{1 + m \sin(\omega_m t)} e^{j[\delta\omega t + \beta \cos(\omega_m t + \theta)]} \quad (2)$$

where  $A$  is a constant,  $m$  is the intensity modulation index,  $\omega_m$

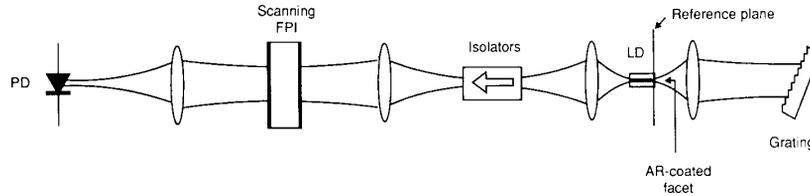


Fig. 1. Measurement setup for measuring the FM response. Fabry-Pérot parameters: FSR = 300 MHz,  $F \approx 100$ .

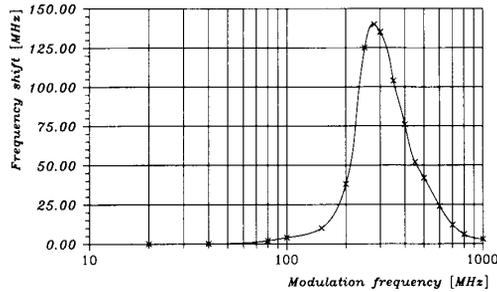


Fig. 2. Measured frequency shift  $\delta f$  versus modulation frequency  $f_m$  at  $I_m = 2$  mA.

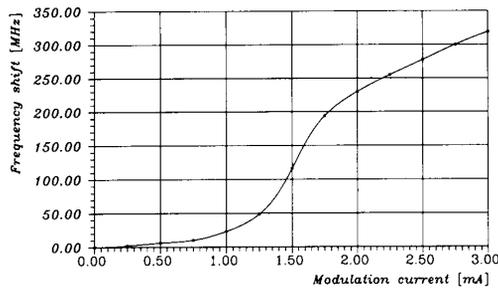


Fig. 3. Measured frequency shift  $\delta f$  versus modulation current  $I_m$  at the modulation frequency  $f_m = 280$  MHz.

is the angular modulation frequency ( $= 2\pi f_m$ ),  $\beta$  is the FM index,  $\theta$  is the phase delay between IM and FM, and  $\delta\omega = 2\pi\delta f$ .

In order to determine the average frequency shift due to modulation, we insert (2) in (1) and take the time average over one modulation period. After some mathematics we obtain

$$\delta\omega = -f_D \left[ \alpha \ln \left| \frac{r'_R(\omega_s + \delta\omega)}{r_R(\omega_s)} \right| - \text{Arg} \{r'_R(\omega_s + \delta\omega)\} + \text{Arg} \{r_R(\omega_s)\} \right] \quad (3)$$

where  $\omega_s$  is the oscillation frequency without modulation and  $r_R$  is the effective reflectivity of the external cavity seen from the reference plane *without modulation*. The relation between  $r_R(\omega)$  and the previously introduced impulse response  $\rho(t)$  is given by

$$\rho(t) = \sum_{n=0}^{\infty} \rho_n e^{-jn\omega_s\tau} \delta(t - n\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} r_R(\omega) e^{j(\omega - \omega_s)t} d\omega \quad (4)$$

where  $\rho_n$  is the strength of the  $n$ th reflection.

The corresponding effective reflectivity *with modulation* is

defined by

$$r'_R(\omega_s + \delta\omega) = \left\langle \frac{\rho(t) \otimes A^+(t)}{A^+(t)} \right\rangle \quad (5)$$

where  $\langle \dots \rangle$  denotes time average over one modulation period. In the case of pure sinusoidal frequency modulation, (5) can be written as

$$r'_R(\omega_s + \delta\omega) = \sum_{n=0}^{\infty} \rho_n J_0 \left( 2\pi n \Delta f \tau \frac{\sin(\pi n f_m \tau)}{\pi n f_m \tau} \right) e^{-jn(\omega_s + \delta\omega)\tau} \quad (6)$$

where  $J_0(x)$  is the Bessel function of order zero, and  $\Delta f = \beta f_m$  is the peak frequency deviation. In practice, only the first few terms in the summation are significant.

A comparison of (6) to (4) shows that in the case of modulation the  $n$ th term in the summation is weighted by a factor less than one. The feedback level will thereby be reduced compared to the unmodulated case leading to a frequency shift towards the laser frequency without external feedback. From (6) it can also be seen that the frequency shift will occur even for short cavity lasers such as monolithically integrated devices, if these are used in high bit rate FSK systems. In this case, the decrease in  $\tau$  can be compensated by the larger frequency deviation which is required in order to have a sufficiently large FM index.

## RESULTS AND DISCUSSION

In order to compare the measured data in Fig. 2 with theory, it would be desirable to have a model for the FM response of the external cavity laser, which takes into account the variation of  $r'_R$ . However, this model has not yet been developed, and we have instead evaluated (3) as a function of modulation frequency  $f_m$  and frequency deviation  $\Delta f$ . We have used the following parameters:  $m = 0.1$ ,  $\theta = 0$ ,  $r_R(\omega_s) = 0.62$ ,  $\alpha = 6.6$ . Fig. 4 shows the result of this calculation together with measured frequency shift versus modulation frequency, from Fig. 2, projected onto the surface. From this projection, we can read off the corresponding frequency deviation versus modulation frequency. The resulting FM response is shown in Fig. 5, and the shape compares well with observations in the laboratory. The coupling between the frequency shift and the FM response can be explained physically by their common dependency on  $r'_R(\omega)$ . Because  $|r'_R(\omega)|$  is decreasing with increasing  $\Delta f$ , and  $\Delta f$  is increasing with decreasing  $|r'_R(\omega)|$ , the system forms a positive feedback loop that causes the resonance seen in Fig. 2. An attempt to verify the theory by measuring the frequency shift as a function of  $f_m$  with constant

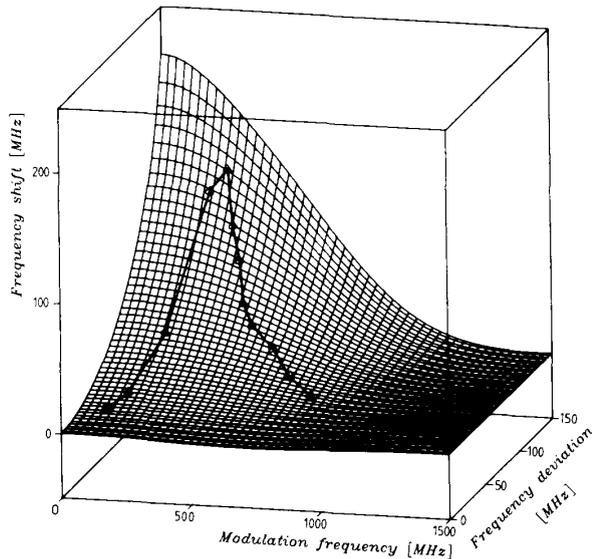


Fig. 4. Calculated frequency shift  $\delta f$  versus modulation frequency  $f_m$  and frequency deviation  $\Delta f$ . The solid line indicates the measured curve from Fig. 2.

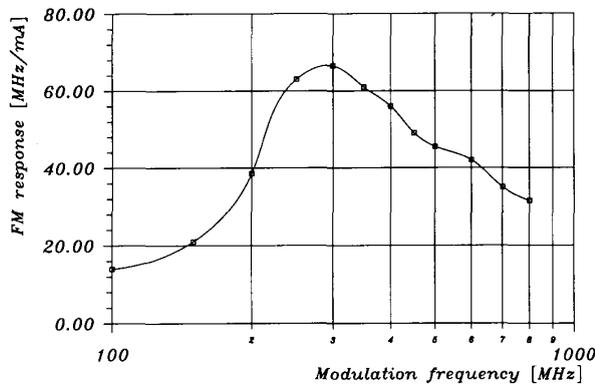


Fig. 5. FM response  $\Delta f/I_m$  obtained from Fig. 4.

$\Delta f$ , thus testing the theory without the coupling to the FM response, failed due to modulation-induced mode hopping.

The positive feedback mechanism complicates the use of the external cavity laser as transmitter in coherent systems, because FM response becomes very sensitive to small changes in the external cavity laser parameters. Another problem is the frequency shift itself, which will introduce a slowly time varying carrier frequency when the laser is modulated with a random bit stream. One might therefore expect a pattern dependent bit error rate.

#### CONCLUSION

Our measurements show that a center frequency shift occurs when an external cavity laser is frequency modulated. This might lead to pattern effects if the laser is used as transmitter in a digital coherent optical communication system.

A model based on a transmission line description of the laser has been developed. Theoretical predictions of the frequency shift of a frequency modulated external cavity laser agree qualitatively with measured results. The model shows that monolithically integrated external cavity lasers will show similar behavior when used in high bit rate FSK-systems.

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