Comparison of plasma-effect in different InP-based VCSELs

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Abstract: The FM amplitude/phase responses of InP-based VCSELs at 1.5µm, 1.8µm and 2.3µm are presented and compared. The plasma effect is clearly observed although at 2.3µm it is significantly lower. This interesting result is discussed.

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1. Introduction

Wavelength tuning is basically caused by two effects in semiconductor lasers: thermal tuning and electronic tuning, i.e. the plasma effect. Thermal tuning introduces a red shift with increasing current, whereas the plasma effect acts inversely but is much weaker at frequencies below 1 MHz. Furthermore, thermal tuning is governed by the inert process of heat conduction with cutoff frequencies in the 10 kHz to 100 kHz range for vertical-cavity surface-emitting lasers (VCSELs). The plasma effect has similar dynamic as shown by the AM response of lasers, i.e. the cutoff frequency is at several GHz. Recently, the plasma effect was observed in a direct FM response measurement of VCSELs [1]. At DC frequency the strength of the plasma effect is around 10% of overall tuning. Compared to edge emitters the plasma effect is higher for VCSELs i.e. several GHz/mA instead of several 100 MHz/mA, which is also known as "adiabatic chirp" in high speed communications [2]. In this paper, FM response measurements of single-mode continuous-wave InP-based VCSELs are presented, whereas a significantly lower plasma effect is observed at 2.3 µm. This surprising result is analyzed and compared with theory.

2. FM response measurements and theory of the plasma effect

In Fig. 1 and Fig. 2 the measured FM amplitude and phase response for VCSELs emitting at 1.5 µm, 1.8 µm and 2.3 µm ([3, 4]) is shown. The sinusoidal current modulation with amplitude Δi was chosen to be small compared to the bias current I_0, the resulting wavelength modulation amplitude is denoted as $\Delta\nu = \Delta\nu(f)$ (unit: Hz).

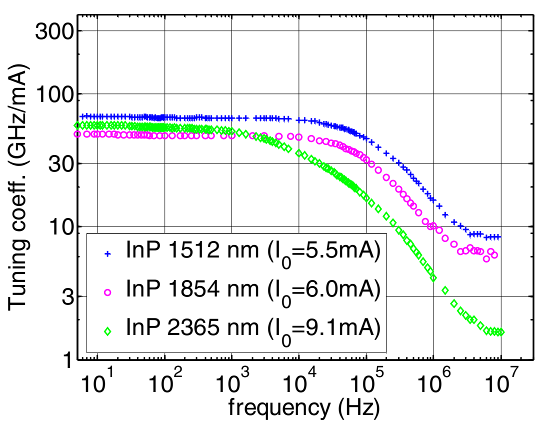

Fig. 1: The absolute value of the measured tuning coefficient Δν/Δi. At several MHz a transition from thermal to electronic tuning takes place, whereas the plasma is visible as constant behavior. The measurement at 1.5 µm and 1.8 µm is taken from [1]

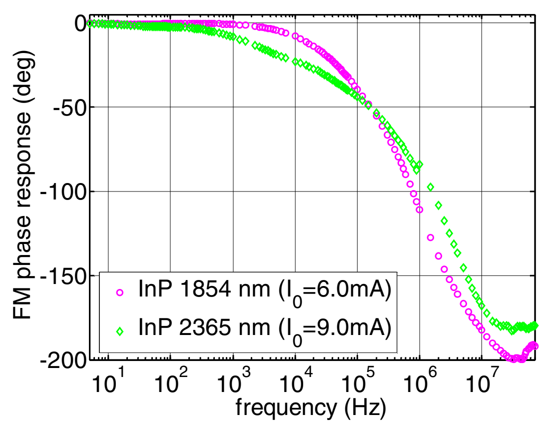

Fig. 2: The measured FM phase shift. The plasma effect is clearly observed at f > 10 MHz, because -180° is reached.

To explain the observed behavior, the FM response $\Delta\nu(f)/\Delta i = H(f)$ can be written as

$$H(f) = H_{therm}(f) - H_{plasma}(f),$$

with thermal tuning $H_{\text{therm}}(f)$ and plasma effect contribution $H_{\text{plasma}}(f)$. For thermal tuning, an analytical theory with closed form expression for $H_{\text{therm}}(f)$ is available [5], which is preferred over the traditional first order lowpass model. To understand the plasma effect, recall that a change of carrier density Δn introduces a frequency shift $\Delta\nu$ of the laser: A change in carrier density changes the gain coefficient g (unit: 1/m) (due to stimulated emission) and thus the imaginary part κ of the effective refractive index of the laser resonator. Due to the Kramers-Kronig relation, this also changes the real part μ of the effective refractive index μ–iκ, which determines the cavity resonance and laser emission frequency. The frequency change is given as (see [6]):

$$\Delta\nu = -\frac{\alpha_H}{4\pi}\frac{1}{\tau_S}\frac{\partial G}{\partial n}\Delta n\,.$$

with α factor α_H as differential ratio of real and imaginary part of the effective refractive index when the carrier density changes $\alpha_H = \partial\mu/\partial\kappa$ (unit: 1) [7], the mean photon lifetime τ_S (unit: *s*) as a measure for losses, and the normalized gain $G = \Gamma\, g/\alpha_{tot}$ (unit: 1), with α_{tot} being the absorption coefficient including out coupling losses (unit: 1/m) and the overlap between light mode and gain medium Γ. Above threshold, *G* is slightly below 1. The α_H factor depends on the material of the active region and the geometry of the laser resonator. The factor of $4\pi\tau_S$ is due to the definition of the α factor in terms of refractive index and not in terms of gain/absorption coefficient.

When the laser modulated below relaxation frequency, i.e. $f < 100$ MHz, a current change Δi causes a change in carrier density according to the steady state laser rate equations [6]. When neglecting spontaneous emission and assuming $\tau_S\, \partial G/\partial S \ll \tau_d V\, \partial G/\partial n$ (V: volume of active region, τ_d: mean differential carrier lifetime), we get

$$\Delta n = -\tau_S\frac{\partial G/\partial S}{e\,\partial G/\partial n}\Delta i\,, \qquad f < 100\text{ MHz}$$

yielding,

$$H_{plasma}(0) = -\frac{\alpha_H}{4\pi e}\frac{\partial G}{\partial S} = \frac{\alpha_H}{4\pi e}\frac{G}{V/\Gamma}\varepsilon\,,$$

with $1/(4\pi e) \approx 49.67$ THz/mA, $\partial G/\partial S$ being the derivate of the normalized gain *G* with respect to the number of photons *S* in the resonator, V/Γ the mode volume in the laser resonator and ε: the gain compression factor. $\partial G/\partial S$ is typically negative and a measure for the nonlinearity of the gain with respect to light intensity. The plasma effect is thus mainly influenced by the alpha factor and the nonlinearity of the gain. Reading from measurement data, for $\alpha_H\cdot\partial G/\partial S$ the following values are obtained: $-1.7\cdot10^{-5}$ (1.5 µm), $-1.3\cdot10^{-5}$ (1.8 µm) and $-3.2\cdot10^{-6}$ (2.3 µm). Here the α_H factor is unknown, but linewidth measurements with similar lasers typically show $\alpha_H \approx 3$–4 [8]. Usually, $\partial G/\partial S$ is described with the material constant ε, which is a phenomenological parameter caused by a number of possible effects. For edge emitters, spatial and spectral hole burning is among these effects [9]. This is essentially a non uniform gain characteristic with respect to spectrum or lateral extend in the laser, that changes with absolute light intensity. The measurement result indicates that the lasers could have different behavior with respect to one of these effects. Note that above threshold G≈1 and the mode volume is more likely to be higher with higher wavelength, thus ε is definitely lower at 2.3 µm.

3. Conclusion

Measurements of the FM response of three different InP-based VCSELs are presented and the strength of the plasma-effect is quantitatively determined for the first time. Since the thermal tuning is negligible at several MHz, the plasma effect becomes the dominant tuning effect for $f > 10$ MHz. Its observation in the FM amplitude response as flat behavior is confirmed in the phase shift, as this clearly reaches -180° which is expected from theory. The strength of the plasma effect at 2.3µm is nearly a factor of 4 lower than for the lasers at 1.4 µm and 1.8 µm, which is analyzed according to rate equation theory. The behavior can only be explained with a reduced alpha factor or a lower saturation nonlinearity of the gain, given by the gain compression factor ε.

Further work includes a linewidth measurement, to determine whether the alpha factor (also linewidth enhancement factor) or -more likely- the gain nonlinearity is lower at 2.3 µm. In any case this would provide indications for possible improvements of the VCSELs either in linewidth or with respect to strength of the plasma effect. This latter is important for high-speed communications, as "chirp" typically either limits the maximum distance or bandwidth.

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