

Optical feedback implementation for polymer based tunable laser

Master's Thesis of

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Karlsruhe, 30.12.2017

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(Tianwen Qian)

Abstract

The optical feedback introduced improvement on laser linewidth and bandwidth has drawn a significant interest for the researchers.

In practice external feedback when coupled into the laser cavity through the output facet, causes a modification of the photon density. This perturbation leads to a fluctuation in the carrier density affecting the optical gain. Since the fluctuations of optical refractive index are directly related to the carrier density [11], the external feedback also introduces phase fluctuations. The interaction of the intensity and phase fluctuations makes the dynamics of the laser system under self-injection very complex leading to system instabilities and even chaos. [Kechaou, Grillot et al 2012]

As high-speed fiber-optic communication becomes increasingly important, so does the need to perform precision measurements on lasers and lightwave systems.

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1. Introduction

The focus of this thesis is the study of the optical feedback effects on polymer-based tunable laser in order to improve its performance in linewidth and bandwidth. The tunable laser is constructed by a hybrid approach combining polymer-based photonic integrated circuits (PIC) and active indium phosphide (InP) components.

The huge possibilities of digital interfaces have an impact on the optical line interfaces of the edge switches and the data-center gateways. Current 100G implementations based on dual-polarization quadrature phase-shift keying are becoming obsolete and we can expect the next migration from 100G to 400G and even further on to 1T based on higher quadrature amplitude modulation (QAM) formats. The aim of the research is to integrate a highly-functional coherent receiver chip, which includes an optical 90° hybrid as the front-end to convert the phase modulated signal into amplitude modulated signal detectable by photodiodes (PDs) [4-6], variable optical attenuators (VOAs) and a wavelength-tunable local oscillator (LO). Everything is done on PolyBoard (polymer-based hybrid platform). This technology allows inserting thin-film elements (TFEs) as polarizations rotators (PR) and polarization beam splitters (PBS). Lasing can be achieved by coupling an InP gain chip (GC) to a polymer Bragg grating. As 90° hybrids 2x4 MMI are used, as VOAs, thermally tunable 1x1 MMIs. This receiver component aims to serve as a potential candidate for 1 Tb/s transceivers for data-centers.

Semiconductor laser diodes with wide direct modulation bandwidth represent a relevant element to fulfill the continuously increasing need for low-cost optical communications systems with high bit-rate.

For the design process a set of three masks is needed, corresponding to the electrode, waveguide and air trench geometry.

The goal of this work is to analyze and improve the characteristics of the laser under feedback condition. Parameters measured by different set-ups for the characterization are presented in Chapter 2.

The samples produced based on this work are then characterized using optical transmission and reflection measurements. The measurements of these lasers, consisting of testing the designs, the application of different tuning principals and tuning experiments, are presented.

2. Theory of Laser Coupled with Passive Cavity

Semiconductor lasers with external cavities exhibit a variety of dynamical phenomena, depending on key parameters, comprising feedback strength, feedback delay, pump current, feedback type, and laser nonlinearity[]. Among all of them the, feedback sensitivity of laser diodes is governed essentially by the feedback parameters C , X and κ_{ext} .

In order to correct consider the feedback effect a three-mirror laser model is considered in Figure 2.1.

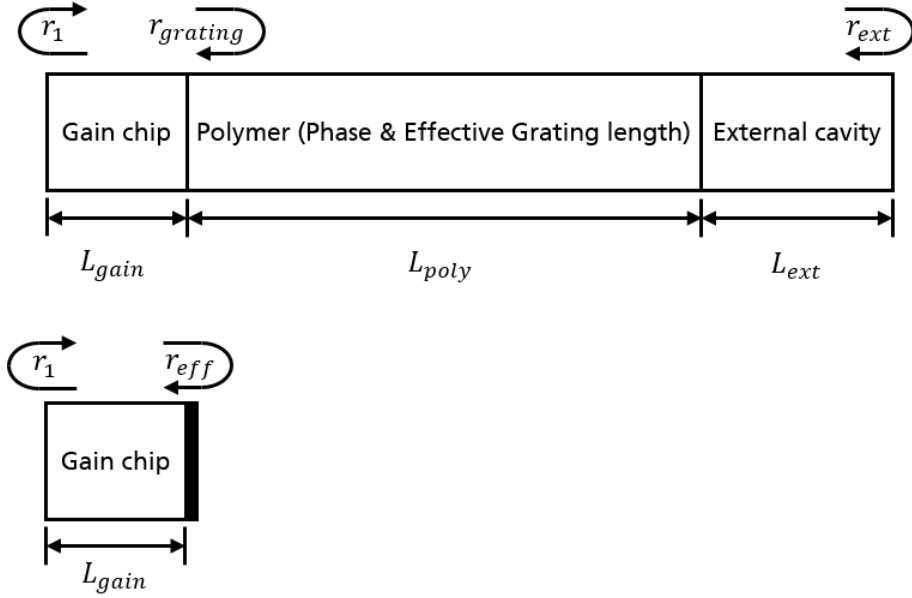


Figure 2.1.: External cavity laser and equivalent cavity with effective mirror to model the external section.

The feedback coefficient, C , characterizes the level of feedback in relation to how it affects the mode structure of the laser, is defined as

$$C = X\sqrt{1 + \alpha^2} \quad (2.1)$$

with

$$X = \frac{\tau_{ext}}{\tau_{gain} + \tau_{poly}} \kappa_{ext} \quad (2.2)$$

$$\kappa_{ext} = \frac{r_{ext}}{r_{grating}} \left(1 - |r_{grating}|^2 \right) \quad (2.3)$$

κ_{ext} is the coupling coefficient from the grating reflector to the external cavity.

The C parameter indicates the laser stability under feedback is affected both by external reflector r_{ext} and external round-time delay τ_{ext} . When $C < 1$, usually for weak feedback and relatively short external cavities, the laser operates in a single mode lasing region and is phase dependent to the external feedback, when $C > 1$, over one stable mode will appear and the laser will undergo a route-to-chaos behavior until it reaches coherence-collapse [] region, which is the region IV for the experimentally identified five distinct regimes of laser performance under feedback [1], if the feedback strength is even higher, the laser will become stable single mode again lasing with the compound cavity mode.

Rate equation models of the field and phase including the time delay of the feedback field reveal unstable solutions and chaotic behavior at these high feedback levels [1]. The collapse begins at the transition to regime IV, where the normally small satellite peaks created by noise-induced relaxation oscillations (depicted in Fig. 5.23) grow larger and larger, eventually becoming comparable to the central peak and broadening the linewidth dramatically [2].

In general, to understand the static lasing behavior under feedback is useful to consider the three-mirror cavity and by the feedback coefficient C , it also relates to the linewidth reduction under weak feedback condition, which will be explained in Section 2.1. However, in order to understand the dynamic lasing behavior we can generally consider the three-mirror cavity as an equivalent two-mirror cavity (shown in Figure 2.1), which replaces the passive section by an effective mirror with reflectivity r_{eff} . The value of r_{eff} is defined as:

$$r_{eff} = \frac{r_{grating} + r_{ext}W}{1 + r_{grating}r_{ext}W} \quad (2.4)$$

$$W = e^{-2\alpha_{poly}L_{ext}} e^{-2i\beta_{poly}L_{ext}} \quad (2.5)$$

The round trip phase within the laser diode cavity must be equal to an integer multiple of 2π yielding the phase condition

$$2\beta L + \phi_r = 2\pi m, m = integer \quad (2.6)$$

The mode spacing in frequency is defined as:

$$dv = \frac{c}{2(n_{ga}L_a + n_{gp}L_{eff})} \quad (2.7)$$

If no reflection exists at the active-passive interface ($r_2 = 0$) and r_3 is positive and real, then $\phi_{eff} = -2\beta_p L_p$, and $L_{eff} = L_p$.

In 1980, Lang and Kobayashi published a rate equation model (the LK model) for a single-mode laser, describing the time evolution of the complex optical field and the carriers. They included the influence of the optical feedback by considering the interference of the laser field with its own coherent delayed field that had propagated once through the external cavity (Lang and Kobayashi, 1980). The model can be written as equations for the excess number of carriers $n(t) = N(t) - N_{th}$ with respect to the solitary threshold level N_{th} , and for the slowly varying complex electrical field amplitude $E(t)$:

$$\frac{dE(t)}{dt} = \frac{1}{2}(1 + i\alpha)\xi n(t)E(t) + \kappa E(t - \tau_f)e^{-i\omega_0\tau_f} \quad (2.8)$$

$$\frac{dn(t)}{dt} = (p - 1)\frac{I_{th}}{e} - \gamma_e n(t) - [\Gamma_0 + \xi n(t)]P(t) \quad (2.9)$$

The optical feedback is taken into account via the feedback term at the end of Equation 2.8, including κ as the feedback rate and τ_f as the delay time. The optical field is normalized such that $P(t) = |E(t)|^2$ is the photon number, ω_0 represents the angular optical frequency of the solitary laser, ξ is the differential gain, $\Gamma_0 = 1/T_p$ is the cavity decay rate, and $\gamma_e = 1/T_e$ is the inverse carrier lifetime. The bias current at the solitary laser threshold is denoted as I_{th} , e is the electron charge, p is the pump parameter, and α is the so-called linewidth enhancement factor discussed in more detail below. The excess phase ϕ_f that the optical field accumulates within the external cavity can be defined as $\phi_f = \omega_0 \tau_f \bmod 2\pi$.

2.1. Linewidth and Chirp Reduction

Linewidth and chirp reduction due to the optical feedback is related to the same factor F , which is given as [3]

$$F = 1 + \frac{1}{\tau_{gain}} \frac{d\phi_{eff}}{d\omega} + \frac{\alpha}{\tau_{gain}} \frac{d \ln r_{eff}}{d\omega} = 1 + A + B \quad (2.10)$$

$$A = \frac{1}{\tau_{gain}} \frac{d \ln r_{eff}}{d\omega} \quad (2.11)$$

$$B = \frac{\alpha}{\tau_{gain}} \frac{d \ln r_{eff}}{d\omega} \quad (2.12)$$

because Equation 2.11 is the frequency-derivative of the r_R phase, it denotes the effective round-trip time in the external cavity divided by τ_{in} []. That is, parameter A represents the ratio of the photon numbers outside to inside the gain medium. It remains nearly constant once the laser cavity is formed. However, parameter B , representing the slope of the spectral reflectivity, is changed if the lasing mode is detuned. Thus, it represents the contribution of the detuned loading effect which will be explained in ??.

If $\Delta\omega_0$ is denoted as the adiabatic chirp in the absence of feedback, then the chirp with external cavity $\Delta\omega$ is obtained as [3]

$$\Delta\omega = \frac{\Delta\omega_0}{F} \quad (2.13)$$

if the spectral linewidth without external feedback is denoted by $\Delta\nu_0$, the spectral linewidth with the external cavity $\Delta\nu$ is simply obtained as []

$$\Delta\nu = \frac{\Delta\nu_0}{F^2} \quad (2.14)$$

Consider the different feedback regions, the reduction factor at weak feedback ($C < 1$) becomes

$$F = 1 + C \cos(\phi_{ext} + \arctan \alpha) \quad (2.15)$$

for strong feedback, which is more interesting and stable for the practical use, the factor F becomes

$$F = 1 + f_{ext} \frac{\tau_{ext}}{\tau_{gain} + \tau_{poly}} \quad (2.16)$$

According to this we can calculate the linewidth reduction factor F^2 versus the external cavity length as shown in Figure 2.2, which will be used for the device design in Section 4.1.

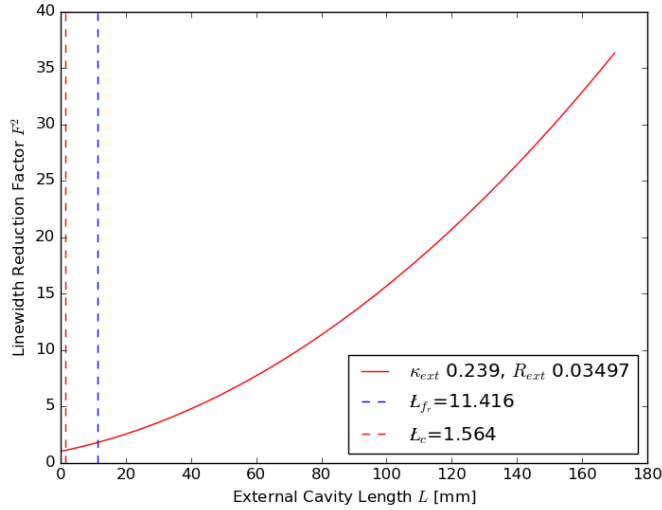


Figure 2.2.: Linewidth reduction factor

2.2. Bandwidth Enhancement

The maximum bit-rate achieved by direct modulated lasers is typically limited by the well known resonance between carriers and photons [2], many solutions have been proposed to overcome this restriction. Three approaches to achieve broader bandwidth are explored in detail.

2.2.1. Detuned Loading Condition

A first mechanism identified to extend the modulation bandwidth of a semiconductor laser is the detuned loading effect that is due the dispersion effect introduced by a coupled cavity^{2,3} or by a distributed mirror (DBR^{4–6} or DFB⁷) when positioning the lasing mode at a slightly higher wavelength respect to the minimum threshold gain condition.

The operation principle for detuned loading condition is to force the lasing mode of a DBR laser to oscillate at the slope of its grating response. It is reported that when the laser is operating at the longer wavelength side, the enhancement of modulation speed, reduction of phase noise (linewidth), and suppression of FM modulation (chirping) can be achieved [4]. The detuned loading of the laser cavity increases the interaction between

the photons and the free carriers in the laser cavity [4] which will both increase the modulation bandwidth and reduce the variation of the carrier density during modulation [5].

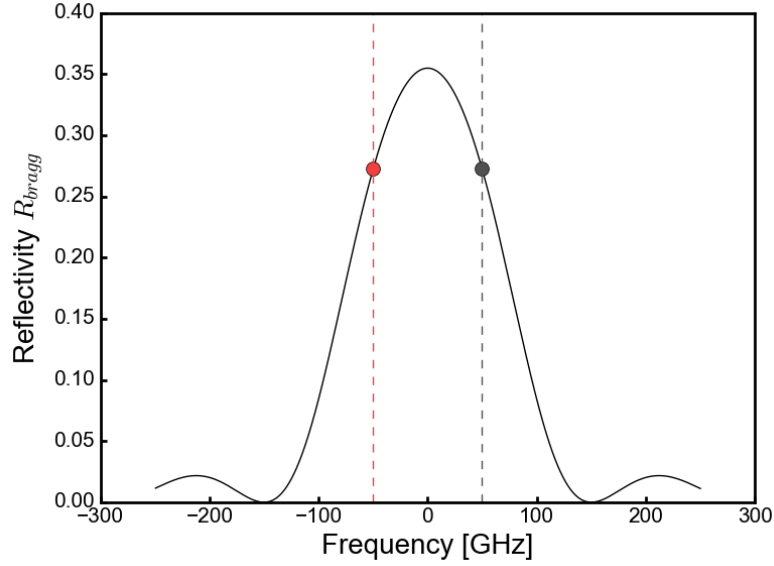


Figure 2.3.: Detuned loading operation principle

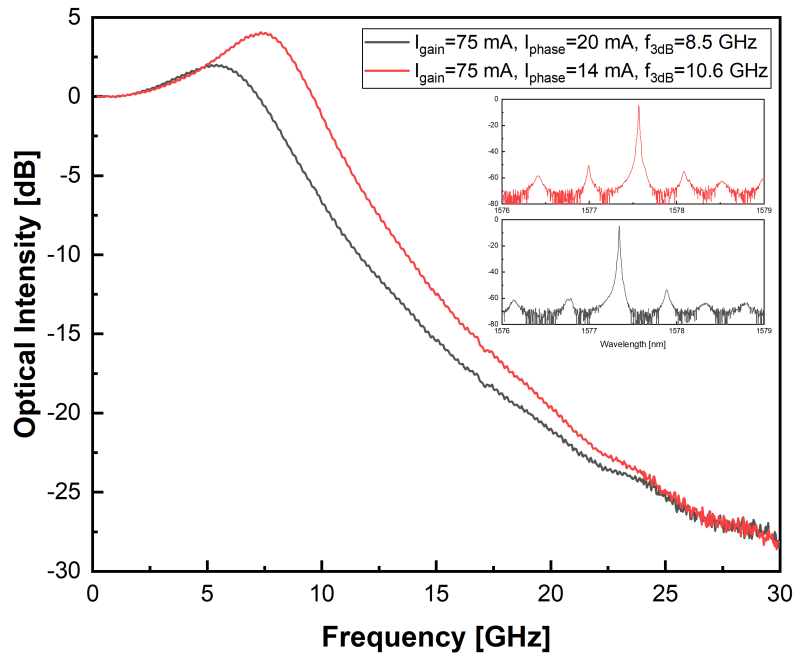


Figure 2.4.: Laser under detuned loading condition

Operating our DBR laser under the detuned loading condition was measured and the result is shown in Figure 2.4. When the laser is lasing on the slope of the grating response, the side modes have a different gain spectrum relative to the peak of the grating response,

which introduces the asymmetric behavior of the side modes. In this case, when the left side mode is higher than the right one, means the lasing mode is operating at the longer wavelength side of the grating response, and vice versa.

2.2.2. Undamped Relaxation Oscillation

Relaxation oscillation in a semiconductor laser occurs because the carrier cannot follow the photon decay rate, it usually smoothly decays out as long as the disturbance (e.g. external feedback) is small enough [6]. However, it can become undamped when the laser exhibits the feedback from the chip facet, which even influences the optical spectra that the undamping peaks are appearing beside the main mode with the mode spacing of relaxation frequency (typically 1~10 GHz). The undamped relaxation oscillation occurs for the appropriate combinations of feedback phase and strength as shown in Figure 2.5. The satellite peaks first appear as Figure 2.6 (b) and then slowly increase their intensity and move towards the main peak, follows with more satellite peaks appearing when the corresponding relaxation oscillation frequency is decreasing. The mode spacing between the main mode and side mode in Figure 2.6 (b) is 11 GHz and decreases to 9 GHz in Figure 2.6 (a).

Since the incoming feedback acts like a perturbation for the normal laser which introduces the amplitude modulation, the undamped RO can be also called as self-modulation or self-pulsation. The mechanism of self-pulsation is analysed and discussed in [7] as "dispersive Q-switching". In order to explain the self-pulsations one usually assumes some kind of a Q-switching process, where the term Q-switching denotes a switching of the quality-factor of the laser cavity. If, due to some reason to be discussed later, an increase of optical power yields a decrease of optical loss (or an increase of optical gain) within the laser, the roundtrip gain G may become larger than unity, yielding an exponential increase of optical power, corresponding to the rising edge of a developing pulse. On the other hand an increased power yields an increasing consumption of carriers so that finally the carrier density is too low to maintain a unity roundtrip gain and therefore the optical power collapses. A recovery time is required in order to increase the carrier density again until the next pulse develops. The repetition frequency for these pulses is of the same order as the relaxation resonance frequency and it varies between several hundred megahertz and several gigahertz [8].

2.2.3. Photon-Photon Resonance

Another approach used to extend the dynamic properties of an integrated laser is similar to detuned loading condition but in addition it takes advantage of the interaction between the lasing mode and an adjacent longitudinal cavity mode, properly separated in frequency in such a way they can interact due to the carrier pulsation introduced by the applied modulation signal at the gain section electrode. This interaction introduces a resonance in the impulse modulation (IM) response at the frequency corresponding to the modes separation. This resonance is frequently called Photon-Photon resonance (PPR), to distinguish this interaction mechanism respect to the Carrier-Photon resonance (CPR) [9]. The appearing of the PP resonance should not be too far away from the relaxation

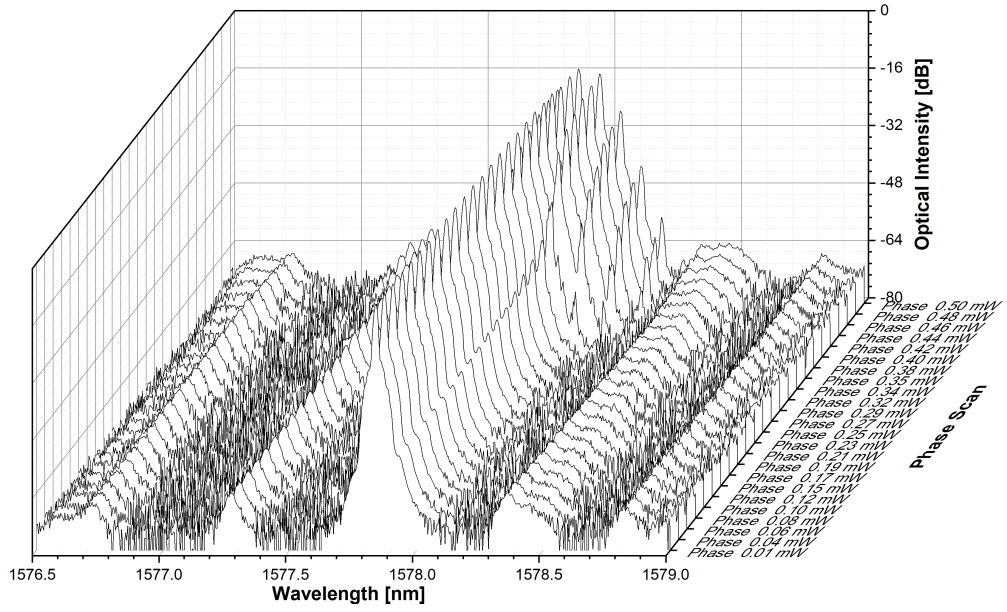


Figure 2.5.: Observation of the undamped relaxation oscillation in OSA

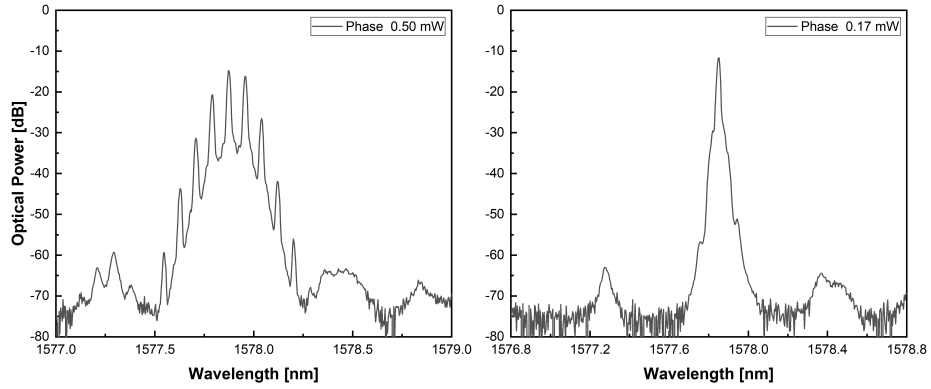


Figure 2.6.: Observation of the undamped relaxation oscillation in OSA

oscillation frequency so that the dip in between two peaks will not be deep enough to reach the -3 dB line in the modulation response as shown in Figure 2.7.

Here we will illustrate the operation principle using the same device parameter provided in [9], which is shown in [].

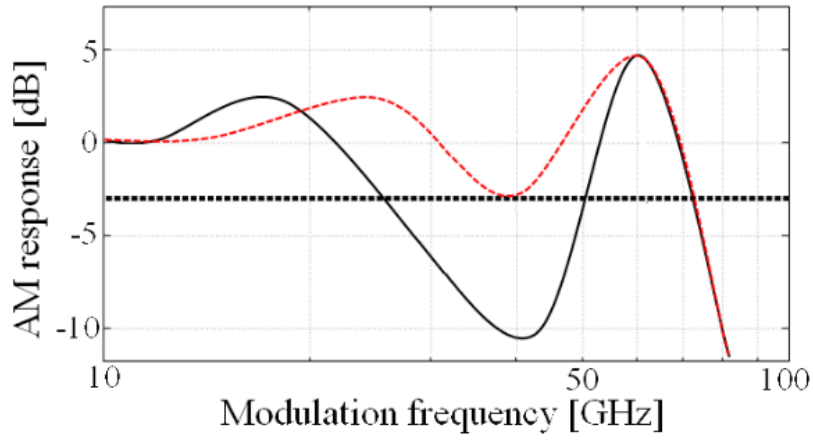


Figure 2.7.: Example of modulation responses obtained in cavity exploiting the PPR effect. The black line indicates a case in which the CP and the Photon–Photon peaks are too much separated whereas in the case indicated by the red line the modulation bandwidth extension is achieved [9].

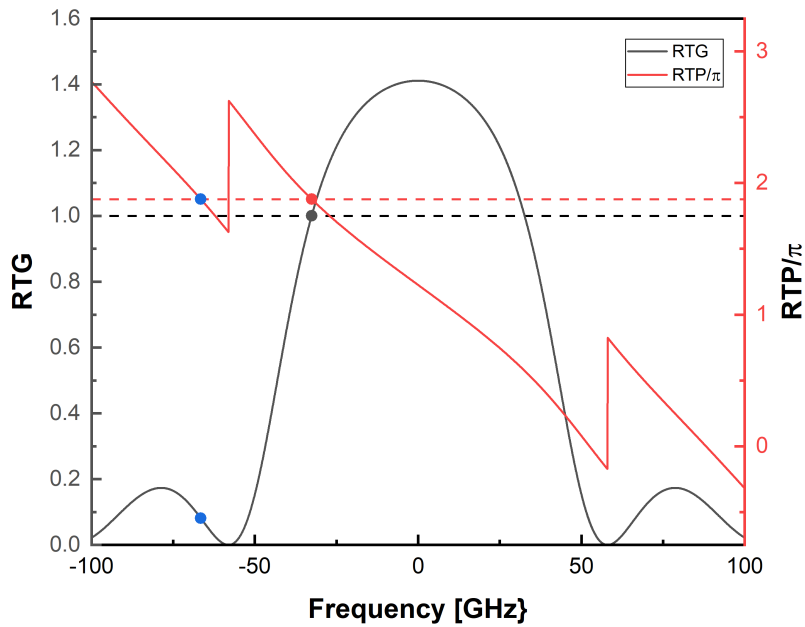


Figure 2.8.: Photon-photon resonance adapt from [9]

3. Tunable Laser with Reflection from Chip Facet

Characterization of the laser linewidth, RIN, bandwidth, α parameter and phase noise are measured with 1) Cleaved fiber with oil and 2) Lensed fiber, which corresponding to the laser without feedback and with feedback conditions. Principle of each measurement will be introduced and the results will be compared in the following sections.

3.1. Linewidth Measurement

Laser linewidth is measured by self-homodyning method in the characterization. Self-homodyning can be described mathematically as a single-delay autocorrelation. The optical spectrum at f_0 autocorrelates with the delayed version of itself to produce a time-fluctuating spectrum, whose detected voltage has a power spectrum centered at zero frequency. For the case of a laser with Lorentzian lineshape, the half-width of the detected spectrum is equal to the linewidth of the laser.

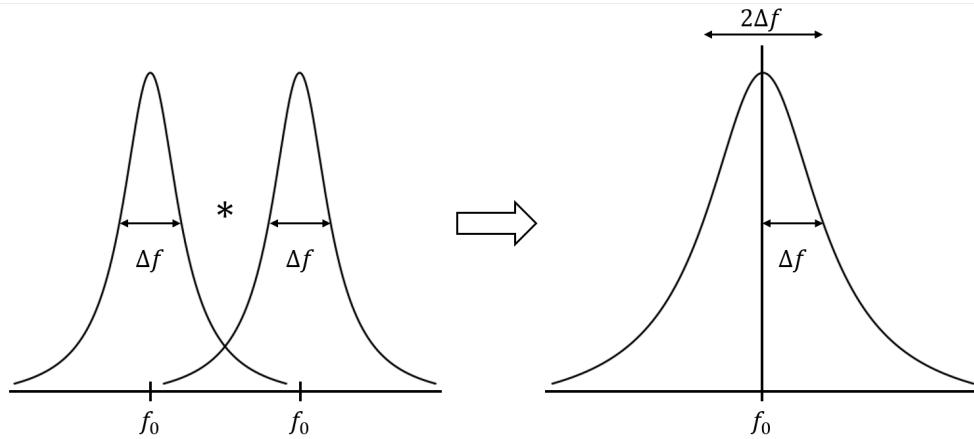


Figure 3.1.: Linewidth of a DBR laser using the self-homodyne technique

The input directional coupler of the interferometer splits the light from the laser into two paths. One path is delayed in order to decorrelate the combining signals, P_1 and P_2 . The output coupler combines the two signals, which are then mixed at the photodetector of the lightwave signal analyzer. The homodyne power spectrum is then observed on the analyzer from which the Lorentzian linewidth is measured by placing a marker at the half power frequency.

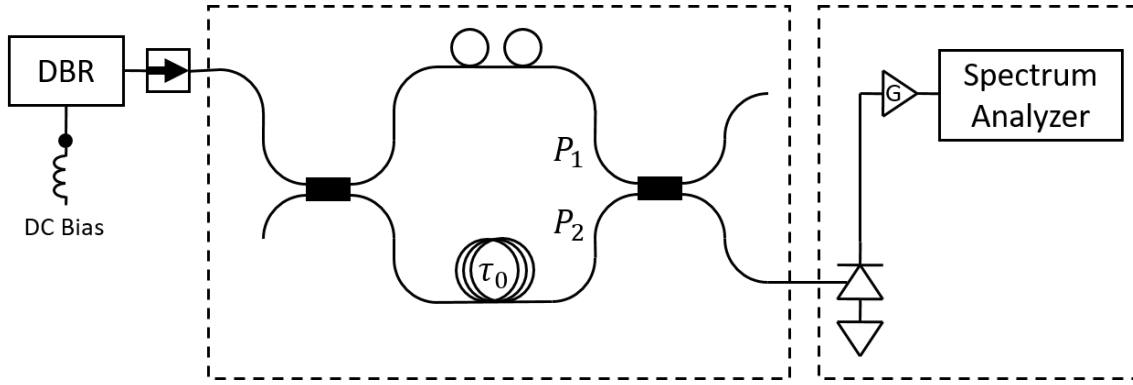


Figure 3.2.: Self-homodyne technique set-up

3.2. Relative Intensity Noise (RIN) Measurement

The measurement of relative intensity noise (*RIN*) describes the laser's maximum available range for signal modulation and serves as a quality indicator of laser devices. *RIN* is defined as the ratio of the mean-square optical intensity noise to the square of the average optical power: [cite]

$$RIN = \frac{\langle \Delta P \rangle^2}{\langle P \rangle^2} \text{dB/Hz} \quad (3.1)$$

where $\langle \Delta P \rangle^2$ is the mean-square optical intensity fluctuations (in a 1-Hz bandwidth) at a specified frequency, and $\langle P \rangle$ is the mean optical power.

In order to measure the *RIN*, the optical power is converted to a current after the receiving photodiode and the ratio of optical powers squared is equivalent to the ratio of the detected electrical powers. Thus, *RIN* can be expressed in terms of detected electrical powers. Equation 3.1 can be rewritten as:

$$RIN = \frac{N_{elec}}{P_{avg}(elec)} \text{dB/Hz} \quad (3.2)$$

where N_{elec} is the power-spectral density of the photocurrent at a specified frequency, and $P_{avg}(elec)$ is the average power of the photocurrent.

The noise at the receiver output results from three fundamental contributions: laser intensity noise primarily due to spontaneous light emissions; thermal noise from the electronics; and photonic shot noise. Since the photonic shot noise and the receiver thermal noise are not included in the definition of N_{elec} , they have to be subtracted from the measured *RIN* results:

$$N_{laser} = N_{elec} - N_{shot} - N_{thermal} \text{ W/Hz} \quad (3.3)$$

By using Equation 3.2 and Equation 3.3, the value of RIN_{laser} can be determined:

$$RIN_{laser} = RIN(measured) - \frac{2e}{I_{avg}} - \frac{N_{thermal}}{P_{avg}(elec)} \quad (3.4)$$

where e is the elementary charge, I_{avg} denotes the detected average photocurrent, $N_{thermal}$ is the measured noise floor of the lightwave signal analyzer in a 1-Hz bandwidth.

3.3. Bandwidth Measurement

3.3.1. Small Signal Modulation

From a practical viewpoint the quantity of interest is the modulation bandwidth ν_B which indicates the frequency range over which the laser responds to the current modulation. It is usually defined as the frequency at which the modulation response has dropped by 3 dB relative to its low-frequency or DC value [10].

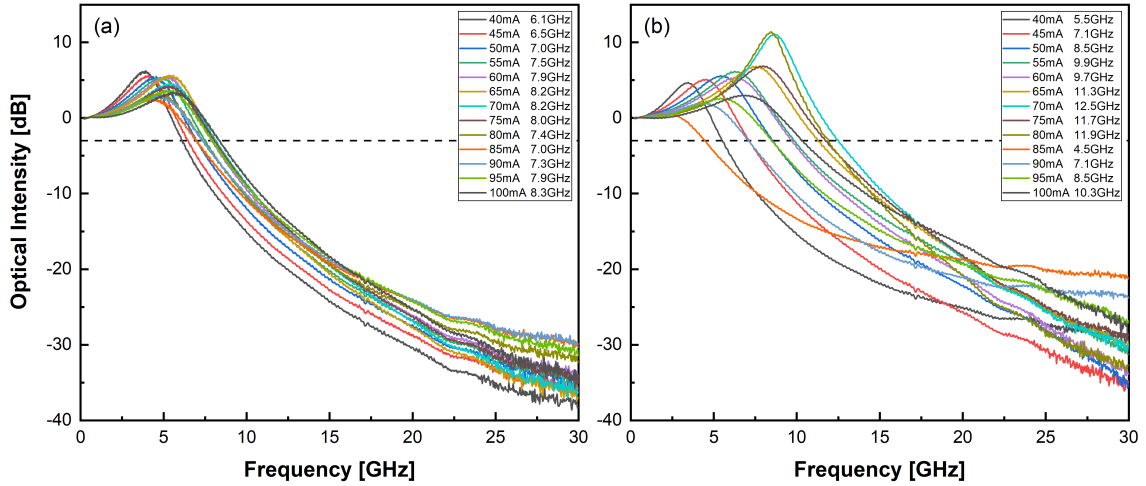


Figure 3.3.: Caption

The frequency response of the laser transmitter under small signal modulation is found by the usual assumption of a harmonic current modulation superimposed on a constant bias above threshold.

$$H(\omega) = \frac{\omega_R^2}{\omega_R^2 - \omega^2 - 2j\omega\gamma} \quad (3.5)$$

in Equation 3.5, ω_R is the relaxation resonance frequency and γ is the damping factor.

The relaxation oscillation frequency is a measure of the maximum modulation ability in semiconductor lasers through the injection current. Above the relaxation oscillation, the modulation efficiency is greatly degraded and intensity modulation through the injection current becomes difficult. [Semiconductor Lasers. Stability, Instability and Chaos.pdf]

The laser seeks a steady-state operation which maximizes feedback. When external feedback is present, the state corresponding to maximum feedback occurs when there is phase alignment between the semiconductor cavity field and the reflected field. A carrier number change n will change the resonance frequency of the semiconductor cavity. This in turn causes a phase change ϕ between the laser field and the reflected field. This acts to decrease the light intensity in proportion to $1 - \cos\phi \approx \frac{\phi^2}{2}$, which decreases the rate of stimulated emission and further increases n . This increase in n again raises the cavity resonance frequency, causing the phase misalignment ϕ to continue to grow. Instability occurs for finite fluctuations of ϕ and n when this effect becomes greater than the restoring forces giving rise to the relaxation oscillations described above.

steady-state operation (phase alignment of the cavity field and reflected field)

In steady-state operation, the laser with reflective feedback can be thought of as phase locked to the reflected field. The phenomenon that we describe is driven by large fluctuations in spontaneous emission that dislodge the laser from this locked state that is stable for small fluctuations. [Henry, Kazarinov 1986]

3.3.2.

Chirp arises because the frequency of the laser mode depends on the carrier number in the active region. Above threshold, the carrier number changes because of two effects: spectral hole burning prohibits the perfect pinning of the carrier number and permits adiabatic chirp, and during transients, there are relaxation oscillations of carrier number, which cause dynamic chirp. [Kazarinov 1987]

Current modulation of the active region results in a modulation of both the photon density and the carrier density. The modulation of the carrier density modulates the gain; however, it also modulates the index of the active region n_a . As a result, the optical length of the cavity is modulated by the current, causing the resonant mode to shift back and forth in frequency. [Larry A. Coldren.pdf]

If we consider the case discussed earlier where the semiconductor cavity is extended by a passive section of length L_1 , with a nonreflective transition between the two sections, the reflection at the semiconductor section constant in magnitude, but has a frequency-dependent phase shift with $d\phi_r/d\omega = 2L_1/v_g$ where $2L/v_g$ is the roundtrip time in the external cavity. Therefore, in this case $B = 0$, the chirp reduction factor is [Kazarinov 1987]

3.4. Chirp Parameter (α -Factor) Measurement

Light chirping is a parasitic property of intensity modulated light. It originates in light emitters that produce a phase shift as the intensity is varied [11]. Semiconductor lasers exhibit a particular nonlinearity in the interaction of the light with the active medium, which distinguishes them from all other lasers. The nonlinearity originates from the physics of the semiconductor band structure, since the photon generation typically occurs due to interband transitions. The gain spectrum of such lasers therefore does not exhibit a symmetric peak, as atomic transitions do, but has a strongly asymmetric shape. This affects the dispersive properties of the lasers as well, since those properties are connected via the Kramers-Kronig relation. As a consequence, the dispersion curve for the refractive index exhibits its zero crossing at higher frequency than the maximum of the gain spectrum. If the gain changes, e.g., by a change of the carrier density, the refractive index changes as well, which would not be the case for atomic transitions. Hence, changes in gain are in semiconductor lasers associated with changes in refractive index and vice versa. Since with a change of refractive index of the medium the optical frequency and thus the optical phase changes, one also speaks of amplitude phase coupling. A small change in the intensity (induced, e.g., by a change in the injection current, by dynamical instabilities, or even a spontaneous emission event) causes an excess perturbation of the phase of the lasing

mode. In the rate equation description, the effect is taken into account via the so-called α parameter, which is also referred to as Henry parameter or linewidth enhancement factor. It is defined as

$$\alpha = -\frac{d\chi_r(n)/dn}{d\chi_i(n)/dn} \quad (3.6)$$

3.4.1. Measurement with LCA

The network analyzer of Figure 3.4 measures the small-signal frequency response of a light emitter, a dispersive medium and a light receiver. The dispersive medium is 81 km of standard, single-mode fiber (zero dispersion at 1.3 μm) from and Er-doped fiber amplifiers pumped at 1.55 μm . Resonance frequencies are observed as sharp peaks in the frequency response. The resonance frequencies f_u of Fig.2 corresponds to the u^{th} -zeros of xx. They

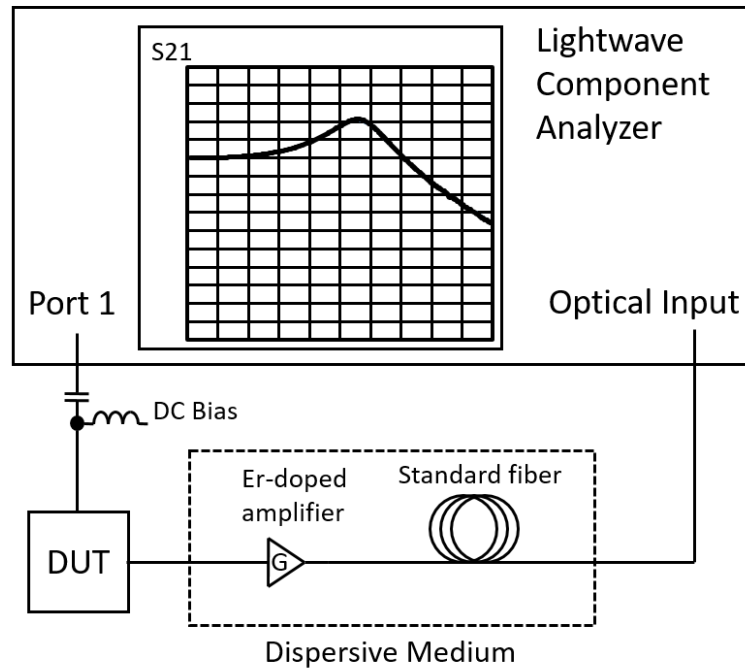


Figure 3.4.: Set-up used to measure the chirp parameter of the laser

follow a very simple law:

$$f_u^2 L = \frac{c}{2D\lambda^2} \left(1 + 2u - \frac{2}{\pi} \arctan(\alpha) \right) \quad (3.7)$$

The equation is the result of two simultaneous interferences between the carrier and the two sidebands. Plotting $f_u^2 L$ versus $2u$ gives a straight line whose slope and position yield the dispersion and the chirp parameter by liner regression.

3.4.2. AM-FM Index Method

The experimental arrangement for measuring the intensity and phase modulation index is shown in Fig. 1. The semiconductor laser is biased above threshold and a small

sinusoidally varying current at frequency Ω is superimposed. The intensity and spectral density of the radiation field are given by

$$\text{Intensity} : E_0^2[1 + m\cos(\Omega t)] \quad (3.8)$$

$$\text{Spectrum} : \text{Center line at } \omega_1 : E_0^2[J_0^2(\beta) + m^2 J_1^2(\beta)] \quad (3.9)$$

$$\text{First sidebands at } \omega_1 \pm \Omega : E_0^2\{J_1^2(\beta) + 1[(m/2)(J_2(\beta) - J_0(\beta))]^2\} \quad (3.10)$$

The phase modulation index β can be found by measuring the relative sideband strength and using Equation 3.9 and Equation 3.10. The factor α_m is then obtained as $\alpha_m = -2(\beta/m)$.

3.5. Phase Noise Measurement

4. Tunable Laser with on Chip Controllable Feedback

4.1. Design

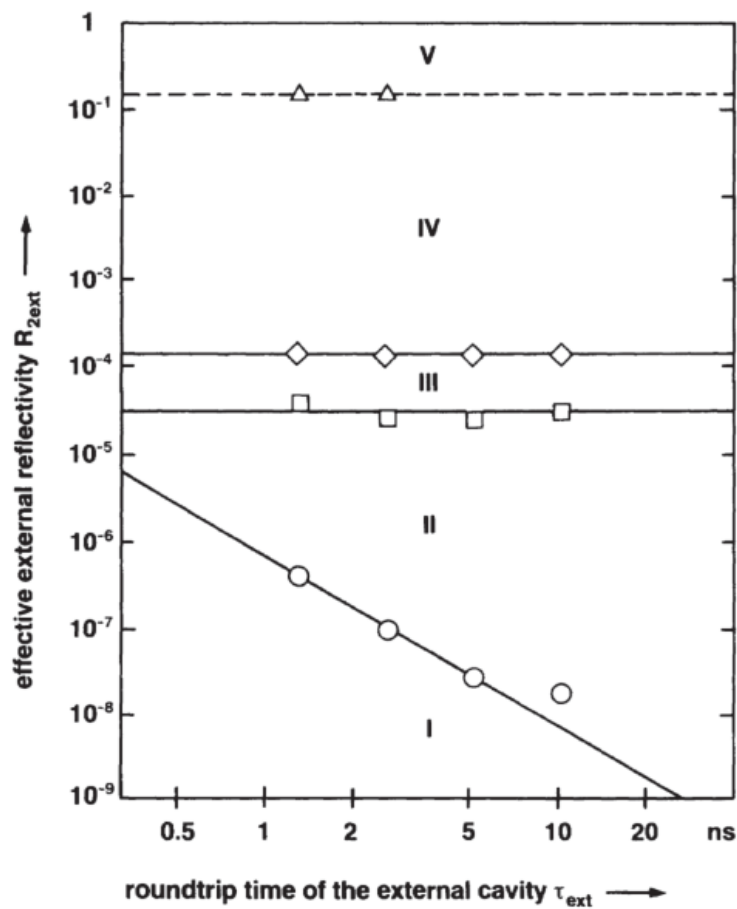


Figure 4.1.: Feedback regimes for a laser diode.

4.1.1. Active and Passive Elements

As a variable optical attenuator (VOA) a 1x1 thermally tunable Multimode interferometer (MMI) is used (Fig.3.4.c). MMI is a multimode waveguide in which the light propagates

in N modes. The various modes interfere with each other and produce an interference pattern in the MMI. This pattern allows at points of constructive interference to place output waveguide and thus to tap multiple outputs, each with a corresponding proportion of the total output power from an input signal. Depending on the design of the structure, the MMI can realize a different power division. On one side along the MMI is placed an electrode that allows using the thermo-optical effect. We distinguish the states ON and OFF. In the OFF state, there is no heating of the electrodes and constructive interference takes place at the point where the output waveguide is. In ON-state, the interference pattern of the MMI is so affected, so that shifts through the partial change of the refractive index of the MMI, the position of constructive interference. Thus, a maximum interference point moves away from the position of the output waveguide and the output signal is tapped at reduced power (Fig.3.4.a and b). In this way a variable optical attenuation is created. An input waveguide with a width and height of $3.2\text{ }\mu\text{m}$ leads light into the interferometer. The height of the MMI (x-axis) also corresponds to $3.2\text{ }\mu\text{m}$, the width is $18\text{ }\mu\text{m}$ and the length is $380\text{ }\mu\text{m}$. The light that is leaving the MMI is received by an output waveguide. Height and width of the output waveguide coincide with the dimensions of the input waveguide. The transition of the input and output waveguide of the MMI is realized with taper sections that reduce the coupling losses. This VOA design was showing the best results compare to the literature [16-18].

4.1.2. Long Feedback Cavity

4.1.3. Short Feedback Cavity

4.2. Characterization

5. Conclusions & Outlook

5.1. Conclusions

5.2. Outlook

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A. Appendix