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Stability of a monolithic integrated filtered-feedback laser

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Abstract: We experimentally and theoretically investigate the stability of a single-mode integrated filtered-feedback laser as a function of the electrically controlled feedback phase. We interpret the measurements in terms of feedback-induced dynamics, compare them with the results from a stability analysis model for conventional feedback, and find good qualitative agreement.

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1. Introduction

Single-wavelength lasers with narrow linewidth are required in many photonic application fields, e.g. in optical communication and sensing. One way to realize such lasers is by utilizing feedback from an external mirror. Although the introduction of delayed optical feedback can be disadvantageous as it may cause instabilities to the laser like the undamping of relaxation oscillations and coherence collapse, under suitable conditions it can improve particular features of the laser, such as enhanced side mode suppression and linewidth narrowing [1].
Many semiconductor external-cavity lasers with different feedback configurations have been reported, where most of them have external cavities outside the chip and the external cavities are much longer than the solitary cavity. Unlike the free-space or fiber-coupled feedback laser systems, the external cavity of an integrated feedback laser is on-chip and with small footprint. Compared to an off-chip cavity, the external cavity is at least two orders of magnitude shorter, implying better stability, better reproducibility from batch to batch and operation on faster time scales.

Here we present the results of a theoretical and experimental investigation of the stability of a monolithically integrated filtered-feedback laser with electrically controlled feedback phase, which is part of a multi-wavelength laser device. A relevant earlier study involving a multi-section laser with phase control is published in [2], but it applies to a coupled-cavity laser in the strong coupling limit, whereas our laser operates in the weak-feedback regime, where external cavity modes are non-existent. In our device, each laser channel operates in single wavelength, which has been achieved by the presence of an arrayed waveguide grating (AWG) filter within the external feedback section. The experimental stability study is obtained by the analysis of the optical and electrical spectra, while the theoretical study is based on a rate equation approach for a single-mode laser with conventional external feedback and leads to results that are in good agreement with experimental findings.

2. Device description

The laser we investigate here is one channel of an integrated filtered-feedback 4-channel multi-wavelength laser (MWL) with channel spacing of 200 GHz and operating in the C-band, as reported by some of us earlier [3]. The operation principle of this MWL can be understood from its schematic representation in Fig. 1(a). The device consists of an array of four Fabry-Pérot (FP) lasers, each of which is formed by a semiconductor optical amplifier (SOA) and two on-chip broadband multi-mode interference reflectors (MIRs) [4] as FP-mirrors. The MIRs provide reflection and transmission to and from the laser cavity. The physical length of each FP-cavity is 820 mm. One side of each FP-laser is connected to one common arrayed-waveguide grating (AWG) filter through a phase shifter, all on a single chip (Fig. 1(b)). Each FP-laser generates a broad spectrum of longitudinal modes, of which the spacing is determined by the FP-cavity length. The AWG multiplexes the light of the FP-laser channels and connects to another on-chip broadband reflector. This reflector will reflect the light and subsequently the AWG will demultiplex and route the reflected signals back to each original FP laser. Only the FP-mode with wavelength within the corresponding AWG pass band will have sufficiently low feedback-reduced loss to suppress all other longitudinal modes through gain competition. Hence, each laser will be operating in a single mode and the wavelength spacing between the lasers is determined by the spacing of the AWG pass bands, 200 GHz in this case. Thus, the AWG together with the external reflector effectively forms an external feedback section for each FP laser, as shown in Fig. 2. The phase shifting section (PHS, see Fig. 1(a)) allows to individually control the feedback phase for each FP-cavity.

Each FP-laser has 49.5 GHz mode spacing, and the two-port MIRs forming the cavity have power reflectivity and transmittivity of R = T = ~0.32. The feedback section is formed by a common 1-port MIR with ~80% reflectivity [4], a single AWG channel and a separate phase shifter for each channel. In the following example we will show recorded spectra for a laser channel that has an external cavity of ~3.0 mm physical length. The AWG is estimated to have 5 dB loss per pass. The forward-biased phase shifter is 0.35 mm long with negligible loss and phase-shift efficiency of 15 degree per mA per pass, which was measured from a test structure with a Mach-Zehnder configuration. Including the waveguide and AWG losses back and forth, the effective strength of the feedback is estimated to be 2% of the light transmitted to the external cavity.
3. Theory and model

The lasers under study are subject to filtered feedback [5]. The filtering is achieved by the presence of the AWG. The main purpose of the AWG is to provide slightly reduced loss for the longitudinal mode that falls within a certain channel, so as to force that laser to operate in one particular mode. As the effective width (3-dB passband) of the AWG pass band filter is ~50 GHz and the laser operates in a single mode, while the feedback-induced frequency change is below ~2 GHz, the feedback can be modelled as conventional feedback [6], which simplifies the treatment and leads to good qualitative agreement with observations.

We will express the optical field inside the laser cavity as $\sqrt{P(t)e^{i\phi(t)}}\cos(\omega_0 t + \phi)\hat{E}(t)$, where the power $P$ and the phase $\phi$ depend slowly on time on the scale of the rapid oscillations implied by the optical frequency $\omega_0$ of the solitary laser. The power is in dimensionless units, such that $P$ is the number of photons in the cavity. The variable characterizing the gain is the slowly time-dependent number of electron-hole pairs $N(t)$, taken with respect to its threshold value for the solitary laser (i.e. without feedback). In terms of the three variables $P$, $\phi$ and $N$, the equations describing the time evolution of the laser in the presence of feedback are

$$\dot{P} = \xi NP + 2\gamma \sqrt{P(t)P(t-\tau)} \cos[\phi(t)-\phi(t-\tau)+\phi_0\tau],$$

$$\dot{\phi} = \frac{1}{2} \alpha \xi N - \gamma \sqrt{\frac{P(t-\tau)}{P(t)}} \sin[\phi(t)-\phi(t-\tau)+\phi_0\tau],$$

$$\dot{N} = -(\frac{1}{\Gamma_0} + \xi P)N - \Gamma_0(P-P_0).$$

where $\xi$ is the linearized gain coefficient at threshold; $\gamma$ is the feedback rate, defined as [6]
\[ \gamma = \frac{r_{\text{ext}}(1-r^2)}{\tau_{\text{in}}r} \]  

with \( r_{\text{ext}} \) the (amplitude) reflectivity of the external mirror, \( r \) the (amplitude) reflectivity of the laser mirror and \( \tau_{\text{in}} \) the internal roundtrip time of the laser cavity. The parameter \( \tau \) is the feedback delay time and \( \alpha \) the linewidth-enhancement factor; \( T_s \) is the effective carrier lifetime for spontaneous recombination at threshold, \( \Gamma_0 \) the cavity decay rate (inverse photon lifetime) and \( P_0 \) the solitary laser power, given by [6]

\[ P_0 = \frac{J - J_{\text{thr}}}{\Gamma_0} \]  

where \( J_{\text{thr}} \) is the solitary threshold current (in units of electrons per second).

This completes the model for the dynamical description of the laser with feedback section. In the next section we will study the steady-state solutions to the rate Eqs. (1)-(3), followed in sec.3.2 by a stability analysis for the corresponding stationary state.

### 3.1 Stationary state

Single-frequency laser operation corresponds to solutions of Eqs. (1), (2) and (3) satisfying

\[ P = P_s; \quad N = N_s; \quad \phi = \Delta \omega t \]  

where \( P_s, N_s \) and \( \Delta \omega_s \) are time independent. This yields

\[ \Delta \omega_s = -\gamma \sqrt{1 + \alpha^2} \sin(\arctan \alpha + \omega_s \tau + \Delta \omega \tau), \]  

\[ N_s = \frac{2\gamma}{\xi} \cos(\omega_s \tau + \Delta \omega \tau), \]  

\[ P_s = \frac{P_0 - N_s}{\Gamma_0 J_0}. \]  

First, the frequency shift \( \Delta \omega_s \) is numerically solved from Eq. (7). It was shown by Ref [7] that, so long the feedback strength satisfies \( C = \gamma \sqrt{1 + \alpha^2} < 1 \), only one single solution to Eq. (7) exists. Substituting this solution in Eq. (8) yields a value for \( N_s \), where after the value for \( P_s \) can be evaluated with Eq. (9). Thus we obtain for each setting of the laser, determined by the value of the feedback phase delay \( \omega_0 \tau \) and the solitary laser power \( P_0 \), a set of values for \( \Delta \omega_s, N_s \) and \( P_s \). It is important to note that the applied phase \( \phi_\text{pr} \) in the phase shifting element will be accounted for in \( \omega_s \tau \) as well (see below, at the end of Sec.3.2).

### 3.2 Stability

Now the issue at stake is that the stationary state defined by Eqs. (7), (8) and (9) is not always stable. It is known that the transition from stable to unstable operation is associated with a so-called Hopf bifurcation, which indicates the birth of an undamped relaxation oscillation (RO) [6,8]. If this happens, there are, among others, the following possible scenarios:
1) A self-sustained harmonic RO has appeared, notable as oscillations in \( P, N \) and \( \phi \), at a frequency approximately given by

\[
\nu = \frac{1}{2\pi} \sqrt{\xi (J - J_{\text{thr}})}
\]  

with typical values ranging from 1 to 10 GHz.

2) The oscillation period may double (frequency halves), often referred to as period-doubling bifurcation [9].

3) As the amplitude of the RO increases, higher harmonics appear.

4) The oscillations turn chaotic; in case the chaos is fully developed this state of operation is also referred to as coherence collapse [10]. The stability of the state characterized by Eqs. (7)-(9) is investigated by considering small deviations, i.e. putting

\[
\phi = \Delta \omega t + \delta \phi; \quad N = N_0 + \delta N; \quad P = P_0 + \delta P.
\]  

After substituting Eq. (11) in Eqs. (1)-(3) and Eqs. (7)-(9) we obtain, in lowest order, three coupled first-order differential delay equations for \( \delta \phi \), \( \delta N \) and \( \delta P \), which are analyzed for solutions with time dependence \( e^{st} \) for complex-valued \( s \). This leads to a system determinant with zeroes in the complex \( s \)-plane. If at least one zero has a positive real part, the corresponding solution Eqs. (7)-(9) is unstable. This has been investigated using the principle of the argument. In this manner, we have obtained a stability diagram for a laser with delayed feedback indicating whether the laser is stable or unstable as functions of the applied feedback phase \( \phi_{\text{fs}} \) (between 0 and \( 2\pi \)) and the applied pump strength \( p \), where the latter is defined as \( p \equiv (J - J_{\text{thr}}) / J_{\text{thr}} \).

The stability diagram is displayed in Fig. 5(b) of Sec.5.2. Here, the total effective feedback phase has been taken as \( \omega_0 t = \phi_{\text{fs}} + \omega' J_{\text{thr}} \tau_0 \), where \( \omega' \) is the (empirical) injection-current-induced frequency shift per mA injection current and \( J_{\text{thr}} \) is the threshold injection current (in mA), i.e. \( J_{\text{thr}} = 10^{-3} q J_{\text{thr}} \), with \( q \) the unit charge. We clearly observe tilted bands of stability and instability, respectively, which connect at \( 2\pi \). The negative slope of the bands is due to the negative current-induced frequency shift of the solitary laser (see the text pertaining to Fig. 5 in Sec.4).

4. Characterization of the device

The measurement setup is depicted in Fig. 3. The device we investigated is one channel of the integrated filtered-feedback multi-wavelength laser with external cavity length ~3.0 mm. The laser chip is mounted on a copper chuck and its temperature is stabilized at 18 °C during the measurements. At this temperature the laser has a threshold current of 16 mA. The electrical currents applied to the SOA and to the phase shifter, respectively, are provided through two probe needles. A lensed fiber mounted on a nano-positioning stage is used to collect the light. An optical isolator is used to avoid the unwanted back reflection into the laser chip. The light
is analyzed using a 50 GHz bandwidth photodetector with an 8 GHz 30 dB gain low noise amplifier connected to a 50 GHz electrical spectrum analyzer [Agilent E4448A]. A fraction of the light is sent to an optical spectrum analyzer [APEX AP2041B] with a high resolution of 0.16 pm.

4.1 Spectral lasing regimes

First, the phase shifter is unbiased, and the SOA injection current is varied until the laser shows a stable single wavelength lasing mode. Then keeping the injection current fixed to that value, the feedback phase shift is slowly swept from 0° to 210° by steps of 15°. The optical signal and the noise intensity signal are recorded only when there is a clear change in the signal appearance, and presented in Fig. 4. Strong dynamics have been observed for certain feedback phase conditions, and the size of this region varies with the injection currents level applied to the SOA.

The results presented in Fig. 4 are obtained by applying a fixed current of 72 mA to the SOA. When there is no extra phase shift applied to the feedback, the laser is very stable emitting single wavelength with narrow linewidth, where the latter could not be resolved by the 0.16 pm resolution of the OSA (<20 MHz). The electrical spectrum (Fig. 4(a)) presents a flat and relatively low response. The relaxation oscillation (RO) frequency is damped below the noise level of the spectrum analyzer. With the feedback phase tuned to 90° (Fig. 4(b)), the laser is not stable anymore. The RO becomes undamped and it is identified as a narrow peak in the electrical spectrum at 6.8 GHz, while in the optical spectrum two series of side peaks appear at distances equal to multiples of the RO-frequency on both sides of the central peak. When the phase is increased (Fig. 4(c)), the laser enters a period-doubling regime, identified by more side peaks in the optical spectrum and a new peak at half the RO frequency in the electrical spectrum. In the next three cases, Figs. 4(c)-4(e), the RO has developed into a more complicated and ultimately irregular oscillation indicating period doubling and higher-harmonic effects, but with the dominant frequency near the RO frequency. Gradually, after entering the instability region, the noise floor increases significantly, as seen in the noise intensity spectra and optical spectra. The last case presented in Fig. 4(e) (ϕ = 210°) shows coherence collapsed operation [10] dominated by relaxation oscillations. The different lasing regimes with different feedback phase are very reproducible.

To get a clearer picture of the overall stability of our filtered-feedback laser, the same phase tuning procedure is repeated for all injection currents above threshold, with a step of 2 mA. The situation as in Fig. 4(a), single wavelength lasing with no relaxation oscillation dynamics, is considered as stable. We have identified such stable regions and made a stability map plotted in Fig. 5(a). The map displays the laser stability as a function of the feedback phase (horizontal) and injection current (vertical), where white indicates stability and black indicates instability, which includes all other unstable regimes. With injection current increase, the laser demonstrates different stable regions. The location of these regions changes with changing feedback phase. Unfortunately, the full 2π phase shift could not be achieved,
because the phase shifter starts to saturate at currents beyond ~7 mA and is fully saturated at 10 mA (Fig. 5(a)), thus limiting the maximum feedback tuning to 210°.

Fig. 4. Intensity noise (dashed lines) and optical spectral (solid lines) from the ESA and OSA, respectively, for different feedback phase tuning 0°, 90°, 150°, 180°, 210°.

4.2 Stability analysis

As was mentioned in Sec.3.2, we have applied a numerical stability analysis to the laser with feedback by investigating the dynamical system determinant. Using the value $\alpha = 2.6$ for the linewidth enhancement factor, as obtained from injection locking measurements (see Appendix A), and the external cavity length and loss estimated as above, we find for the case of injection current of 72 mA (pump strength $p \sim 3$) that over a phase range interval of about 100° the single frequency operation is stable, whereas it is unstable for other values of the applied feedback phase. Apparently, Fig. 4(a) is within this stability interval.
Figure 5(b) is the stability map generated from the theoretical model. The stability situation is recorded as a function of the feedback phase (0-2π; horizontal axis) and pump strength (injection current from threshold up to 80 mA, \( p = 4 \)). The parameter values used for this diagram are given in the caption. It is to be noted that zero phase on the horizontal scale in Fig. 5(b) is arbitrary; it does not necessarily coincide with zero current in Fig. 5(a). Comparing this with the measured map Fig. 5(a), the structures of stable and unstable bands with negative slope show good qualitative agreement between experiment and theory, although theory predicts wider unstable bands. The slope is due to the injection current induced phase shift inside the FP laser cavity.

5. Discussion and conclusion

An integrated laser with a filtered-feedback configuration has been realized. The external cavity is integrated on the chip and the phase of the feedback can be controlled via an integrated phase shifter. We have measured the laser feedback dynamics as a function of the feedback phase and injection current. By changing the feedback phase, the laser can be set to operate in a stable single-frequency state as well as in various unstable states. Comparison of the measurements with the results from a stability model, confirms that the theory is applicable to a laser with short and integrated feedback. We are able to simulate the stability of the device with respect to pump current, feedback phase and delay time. This will allow further optimized designs for integrated filtered-feedback lasers that will show less or no feedback phase sensitivity, thus improving the laser stability and simplicity of the circuit.

Appendix: linewidth-enhancement factor

The linewidth-enhancement factor (\( \alpha \)) is one of the key parameters for semiconductor lasers. This factor is also used in the model discussed in section 3, where it is taken as 2.6. This appendix will describe how the value 2.6 for \( \alpha \) is measured. The determination of the \( \alpha \) is based on measuring the injection-locking range of the laser [11]. The FP-laser in this measurement is a test laser with identical design of the solitary laser in the filtered-feedback multi-wavelength laser, and is fabricated under the same technology.
The measurement setup is shown in Fig. 6. An optical spectrum analyzer (OSA, APEX) is used to measure the optical spectra of the test laser and the master laser. The tunable master laser (Agilent 86100B) and the MIR based FP laser were both temperature stabilized during the measurements. The tunable laser was set to a certain output power, and was attenuated by a variable optical attenuator. After the attenuator, the light was connected to a polarizing beam splitter (PBS) through a polarization controller (PC). The PC tunes the TE output from the PBS to the maximum, and the TE light is injected into the FP laser via a polarization-maintaining (PM) fiber. On the other side of the chip, a lensed fiber is aligned to the output facet of the FP laser to couple out the output light, and the light is sent to an APEX optical spectrum analyzer (OSA) for spectral analysis of the emission.

Fig. 6. Injection locking measurement setup. DUT is the device under test. See the text for other details.

The locking range of this FP laser at 35 mA pump current for a longitudinal mode around 1545 nm is measured. The locked region is determined by both frequency detuning and the external injection light power at a fixed laser pump current. At each injecting power, the wavelength is swept from below and above the frequency of this mode, and the frequencies when the mode loses locking are recorded and plotted in Fig. 7 versus the square root of the injection power. The boundaries of the locking region are fitted by the two lines. Outside this area is the unlocked region, where the injection level is too low or the detuning is too high to reach injection-locking condition. According to [11,12], the linewidth enhancement factor can be obtained as \( \alpha = \sqrt{(\Delta f_{\text{max}} / \Delta f_{\text{min}})^2 - 1} \). The ratio of the two slopes of the boundaries of the locking region is independent of the optical powers. The linewidth enhancement factor of the active material can be estimated to be 2.6.

Fig. 7. Frequency locking range dependence on injected power. FP laser is under injection current of 35 mA at 18 °C.