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Citation for published version (APA):

Andreou, S., Williams, K., & Bente, E. (2019). Frequency stabilization of an InP-based integrated diode laser deploying electro-optic tuning. *IEEE Photonics Technology Letters*, 31(24), 1983-1986. [8894117].
<https://doi.org/10.1109/LPT.2019.2952243>

DOI:

[10.1109/LPT.2019.2952243](https://doi.org/10.1109/LPT.2019.2952243)

Document status and date:

Published: 15/12/2019

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Frequency stabilization of an InP-based integrated diode laser deploying electro-optic tuning

Stefanos Andreou, Kevin A. Williams, Erwin A. J. M. Bente

Abstract—We present the frequency stabilization of a monolithically integrated extended cavity single mode InP diode laser using the Pound-Drever-Hall (PDH) frequency locking technique. The laser is a multi-section distributed Bragg reflector (DBR) laser with an intra-cavity ring resonator, fabricated using an InP active-passive integration technology. The laser is locked to a 700 kHz wide resonance of a Fabry-Perot etalon. The single electrical feedback is applied on the reverse biased rear DBR section of the laser, used to tune the lasing mode. This is the first time to our knowledge that the feedback is applied on a reverse biased, voltage controlled section of an integrated laser cavity. In our implementation the tuning is based on electro-optic effects avoiding significant thermal effects in the tuning element. We demonstrate a linewidth reduction down to 5 kHz and frequency noise suppression of about 30 dB at 10 Hz offset frequency. The bandwidth of the control loop is about 500 kHz, limited by the phase delay of components in our loop.

Index Terms— Pound-Drever-Hall locking, laser stabilization, InP laser, electro-refractive modulator, linewidth

I. INTRODUCTION

Lasers with good short- and long-term stability are essential in high-resolution sensing, spectroscopy and metrology. The stability of free-running lasers is greatly compromised by environmental disturbances such as temperature and pressure fluctuations, vibrations and flicker noise from electronics. Often, depending on the application, their intrinsic linewidth [1] is not sufficiently low either. In this case stabilization schemes are required to dramatically improve the stability of free-running lasers. Such schemes may deploy electrical or optical feedback, feedforward techniques or even combinations of these.

The most powerful and widely used technique is the PDH frequency locking [2]. In PDH locking, the laser is usually locked to the resonance of a high-finesse optical cavity acting as an absolute reference. If the electrical feedback loop has sufficient bandwidth and correct gain it can not only correct for frequency drifts but also reduce the linewidth of a laser by

suppressing the phase noise resulting from both technical noise and amplified spontaneous emission (ASE) within this bandwidth. The feedback is usually applied on the semiconductor optical amplifier (SOA) section [3] of the laser or current injection phase sections in the cavity [4].

The combination of current-induced thermo-optic tuning in the millisecond time scale and the carrier density variation (plasma effect) in the nanosecond scale causes a non-flat laser tuning phase response, typically above 100-200 kHz [5, 6]. The two effects also result in opposite frequency shifts with increasing current. All of the above many times lead to the use of two feedback loops at different frequency ranges or the design of special feedback loops as proposed in [3] to circumvent the non-flat laser tuning phase response. Further issues, which however are not investigated here, can arise when feedback is applied in the form of current-injection such as excess intensity noise which may limit the frequency noise suppression [3, 5]. Additionally, the laser tuning response is dependent on the SOA current. This means that if the SOA current significantly changes over time due to a large drift, the feedback loop may no longer be optimized for the new conditions [5]. Finally, depending on the use of the stabilized laser, one may want to avoid additional intensity noise. For example as explained in [7] where an extended cavity diode laser in Littman configuration is used, the feedback is preferably applied on an intra-cavity lithium niobate modulator instead of the SOA.

In this work, we investigate and demonstrate the stabilization of an InP-based diode laser using PDH locking by applying the electrical feedback on the reverse biased DBR section of the laser to tune the lasing mode. The reverse bias tuning implementation is based on electro-optic effects and avoids

Fig. 1. (a) Schematic and (b) image of the integrated InP-based DBR laser with an intra-cavity ring resonator. SOA: semiconductor optical amplifier, DBR: distributed Bragg reflector, MMI: multimode interference coupler.

This work was supported by the Netherlands organization for scientific research (NWO) under the project 13930 and the United States Air Force Office of Scientific Research (AFOSR) under the grant FA9550-18-1-0015.

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significant thermal effects contrary to feedback with current injection. The bandwidth of the tuning mechanisms does not limit the control loop bandwidth in our case since the response time is on the nanosecond timescale [8]. In section II the laser cavity is described and the implementation of the PDH locking to a highly-stable Fabry-Perot cavity are given. In section III the stabilization is presented.

II. IMPLEMENTATION OF THE PDH LOCKING WITH AN INP-BASED LASER

A schematic and an image of the InP-based laser fabricated in the framework of a multi-project wafer run using an active-passive integration technology [8] is shown in Fig. 1(a) and (b) respectively. It is a multi-section DBR laser with an intra-cavity ring resonator [9]. The SOA is 500 μm long and the front and rear DBRs are 300 μm and 400 μm long respectively with coupling coefficient of 50 cm^{-1} . The ring resonator has an 80 μm radius and power coupling is implemented using 50:50 2x1 multimode interference couplers (MMI).

The DBR sections have the same cross-section (disregarding the local differences in the grating layer for the weak effective index modulation) as the electro-refractive phase modulators in the same technology. They can be used in reverse or forward bias to change the effective index. The propagating mode is guided in a film of the bulk quaternary material with bandgap at 1.25 μm [6]. Typically reverse bias voltages up to 10 V are applied. As we have shown in [10], the reverse bias tuning does not cause significant losses. Additional losses (<2 dB/cm) are expected only at voltages from -5 to -10 V and slight reduction (0.5 dB/cm) of losses from 0 to -5 V. Therefore maximum additional losses may be roughly 0.08 dB (0.04 $\text{cm} \times 2 \text{ dB/cm}$). These losses are significantly lower than the total intra-cavity loss which is estimated to be 4-5 dB. The laser threshold current is not expected to vary significantly. In reverse bias, the change of the effective index of the guided mode results from primarily electro-optic-effects [10, 11], the Pockels and Kerr effects. Weaker carrier effects are also present, free-carrier plasma and band-filling effects. These are typically an order of magnitude smaller compared to field effects due to low doping levels. Since the current levels flowing through the PIN junction in reverse bias operation are in the order of some μA , thermo-optic tuning is expected to be negligible [12]. This is in contrast with the electric feedback applied on current injection phase sections and/or the laser SOA. In both cases the thermal dissipation is significant. Additionally the thermal tuning has the opposite sign compared to carrier injection tuning therefore two different control signals are typically used.

The integrated laser was fabricated by Smart Photonics [8]. The chip is mounted on an aluminum sub-mount and kept at 18°C. Electrical signals are applied using wire-bonds from a printed circuit board to the on-chip bond-pads. The SOA is driven at ~60 mA using a low-noise battery based laser diode controller (ILX LDX-3620B). Light from the laser is coupled out of the chip using a single-mode lensed fibre. The output waveguides are angled with respect to the chip facet which is coated in order to avoid back-reflections into the laser cavity. A

Fig. 2. Schematic of the Pound-Drever-Hall frequency locking used for the diode laser stabilization.

schematic of the experimental setup used is depicted in Fig. 2. The laser output is phase modulated at 60 MHz using a lithium niobate modulator. The modulated light is fed to the Fabry-Perot cavity through a circulator. The cavity has a full-width at half-maximum (FWHM) of ~700 kHz (StableLasers). Its finesse is $4.5 \cdot 10^3$ and it is made out of ultra-low expansion material. The signal which is reflected from the cavity is directed to a low-noise photodetector (PD, Femto OE-300-IN-01) with a variable transimpedance gain (transimpedance gain: 10^4 V/A , bandwidth: 80 MHz). It is down-converted to base-band and fed to the analogue PID controller with two outputs, high- and low-bandwidth. The 60 MHz oscillator, mixer, phase shifter and analogue PID controller are commercial locking electronics from Toptica (PDD110, FALC110).

Between the PID controller and the integrated laser we place an opto-coupler to electrically isolate the laser and avoid ground loops which leads to spurious signals. The opto-coupler is realized using a visible light emitting diode (LED) and a battery-biased large area PD. A potentiometer with maximum resistance value of 1 k Ω is connected in series with the large-area PD and the voltage drop across the potentiometer is the output voltage of the opto-coupler. We estimate that for the maximum resistance value of the potentiometer the lowest bandwidth is 0.5 MHz. The PID controller has two outputs, a slow output with cut-off frequency of 10 kHz and a fast output with a two stage integrator (cut-off frequencies: 14 kHz and 370 kHz) and a differentiator (cut-off frequency: 420 kHz). The two outputs are summed with a DC voltage using a summing

Fig. 3. (a) The error (blue) and (b) transmission (red) signal through the Fabry-Perot etalon versus the offset frequency from a resonance of the cavity.

amplifier (Stanford Research SIM980) with 1 MHz bandwidth. The summing amplifier output biases the LED of the opto-coupler. The output voltage of the opto-coupler is then applied to the rear DBR section of the laser.

We split the light with a fibre-based splitter and we use 10% of the laser output power to measure its linewidth and frequency noise while the remaining signal is used for the locking. The linewidth is measured using the delayed self-heterodyne (DSH) [13] method with a delay line of 25 km and an electrical spectrum analyzer (ESA – Anritsu MS2830A). The frequency noise is measured using a frequency noise measurement instrument from OEwaves (OE4000). For both measurements, we amplify the optical signal using a low-noise figure (4 dB) erbium doped fibre amplifier (EDFA - Keopsys CEFA-C-HG-SM-50-B130) in order to have sufficient optical power (>5 dBm). At the output of the EDFA a narrow-band bandpass filter (0.5 nm) is placed to filter out the ASE.

III. LOCKING MEASUREMENTS

The open loop error signal as measured at the output of the PID controller is shown in Fig. 3(a) (blue trace) as a function of the detuning frequency of the laser from the resonance transmission maximum. The resulting slope of the error signal around zero frequency offset is 190 $\mu\text{V}/\text{kHz}$. The sensitivity of the laser frequency control can be determined from the same trace in Fig. 3(a). The zero-crossing points left and right are 60 MHz away from the centre. Using this information the sensitivity of the laser frequency control is determined to be 320 kHz/mV. Therefore given the 10 V biasing range, the frequency control range is about 3.2 GHz. The small ripples which are visible in the error signal correspond to the 50 Hz frequency from the equipment power supply. The transmission (red) through the FP cavity is shown in Fig. 3(b). The two smaller peaks correspond to the phase modulation side-bands at 60 MHz.

In Fig. 4(a) the linewidth of both free-running (blue line) and locked laser (orange line) were recorded using an ESA with a resolution bandwidth of 10 kHz and video bandwidth of 1 kHz using the DSH method. The linewidth of the laser is reduced and the peak power density increased. The free-running laser exhibits a Gaussian linewidth, dominated by technical noise. The lineshape of the locked laser shows sub-structure. The peaks that appear at about 800 kHz offset are due to the bandwidth limitation of our feedback loop. At higher frequency offsets the lineshape tails follow the lineshape of the free-running laser. In Fig. 4(b) the electrical spectra are shown with resolution BW of 1 kHz and video BW of 100 Hz. For this span the lineshape is Lorentzian. A single sweep of the ESA recording the linewidth is presented in light orange and an average of twenty sweeps with darker orange. The FWHM of the locked laser is 5 kHz. This is a factor of more than 100 lower than the reference cavity resonance FWHM. The free-running laser (blue line) shows a linewidth of about 300 kHz. Therefore the locking system reduces the linewidth by a factor of about 60.

In Fig. 5 the power spectral density (PSD) of the free-running (blue line) and frequency-locked laser (orange line) frequency

Fig. 4 Electrical spectra from the delayed self-heterodyne setup with 25 km delay line with (a) 10 MHz and (b) 1 MHz span. The linewidth is reduced from ~ 300 kHz for the free-running laser to about 5 kHz.

noise is presented. The free-running laser frequency noise exhibits $1/f^\alpha$ noise, where $0 < \alpha < 2$, with varying slope from 10 Hz to about 1 MHz. Multiple spurious peaks are present with the most prominent line at 50 Hz and its harmonics. Additionally a strong peak at ~ 0.9 kHz is observed. The origin of these peaks is possibly electrical pick-up signals and/or mechanical vibrations of the fibre tip used for coupling light out of the chip.

By comparing the frequency noise for the free-running and locked lasers we observe noise suppression by the control loop of almost 30 dB for the lowest frequencies. The gain reduces gradually until it reaches unity at 500 kHz. In the whole range multiple spurious signals are present. The origin of these spurious signals is not known at the moment. The wide peak which is located at ~ 800 kHz is a result of the phase lag of our feedback loop and corresponds to the same peaks exhibited in the DSH measurements (Fig. 4). At these frequencies the feedback is no longer effective due to the phase lag caused by both the round-trip time delay and the frequency dependent phase delay from components included in the loop. As discussed in section II, the opto-coupler bandwidth is expected to be about ~ 0.5 MHz therefore being the limiting factor for the loop bandwidth.

IV. DISCUSSION

In Fig. 5 the β -separation line expressed by $\beta_{sep}(f) = 8 \ln(2) f / \pi^2$ [14] is plotted which offers a straightforward link between the frequency noise spectrum and linewidth. The part of the frequency noise that contributes to the linewidth as

Fig. 5. Frequency noise power spectral density for the free-running and locked laser. The frequency noise at low frequencies is suppressed by about 30 dB and the control loop bandwidth is about 500 kHz.

measured with the DSH method is the part for which $S_v(f) > \beta_{sep}(f)$, where $S_v(f)$ is the laser frequency noise spectrum. The expression for the laser FWHM is $\Delta\nu = (8 \cdot \ln(2) \cdot A)^{0.5}$ [10] where A is the surface area where $S_v(f) > \beta_{sep}(f)$. This can be calculated from the measured $S_v(f)$ and it depends on the observation time – the frequency range over which $S_v(f)$ is integrated.

From Fig. 5, we find that for the free-running laser, frequency noise below 100 kHz contributes to the linewidth while for the locked laser this frequency decreases to about 10 kHz. Since our control loop bandwidth is about 500 kHz, which is greater than 100 kHz, to further reduce the linewidth we do not need a control loop with higher bandwidth. Further linewidth reduction requires higher gain at frequencies below 10 kHz. An integrator with higher gain at these low frequencies could be deployed to achieve this.

To check the consistency of our DSH measurements with the frequency noise measurements we numerically integrate the surface for which $S_v(f) > \beta_{sep}(f)$. The 25 km delay used in our DSH setup corresponds to a delay/observation time of approximately 120 μ s. For the free-running laser we integrated the frequency noise spectrum from 8 kHz to 100 kHz resulting in a linewidth of 280 kHz. For the locked laser the noise spectrum was integrated from 8 kHz to 10 kHz resulting in an 8 kHz linewidth. These numbers are reasonably close to our observations from the electrical spectra (Fig. 3). The spurious peaks in the frequency noise spectrum slightly contribute to the overestimation of the linewidth calculated for the locked laser.

According to our calculations the stabilization system is not limited by the signal-to-noise ratio (SNR) at the PD. Further suppression of the noise by at least an order of magnitude should be possible based only on the SNR at the PD. We attribute the current gain limitations of our stabilization system to the spurious peaks in the frequency noise spectrum.

V. CONCLUSIONS

We demonstrate the PDH locking of a monolithically integrated extended cavity single frequency laser using a single feedback loop utilizing electro-optic effects. The electrical feedback is applied on the reverse biased rear DBR section of the laser yielding a frequency control range of about 3.2 GHz. The

electro-optic effects deployed for the electrical feedback due to the reverse bias operation all have identical signs and avoid significant heat dissipation. This tuning mechanism avoids non-flat laser tuning phase response and enable the utilization of a single feedback loop without special design compared to feedback using current injection on phase sections or SOAs. The control loop bandwidth is 500 kHz limited by the bandwidth of the opto-coupler used. We measure linewidth reduction of a factor of 60 compared to the free-running laser and about a factor of 140 of the etalon FWHM. The frequency noise measurements show that the control bandwidth is sufficient to suppress high-frequency noise components in order not to contribute to the linewidth. Further linewidth reduction requires higher gain in the lower frequencies. This method is promising for overcoming other shortcomings of current injection feedback such as intensity noise as well.

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