A stabilized integrated ring laser for high resolution fibre based sensing

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We present an implementation of the Pound-Drever-Hall locking technique on a monolithically integrated single frequency tuneable ring laser fabricated using InP active-passive integration technology. The laser which is based on three cascaded asymmetric Mach-Zehnder interferometers is locked to a fibre Fabry-Perot interferometer with 1 MHz full-width at half-maximum. The electric feedback signal is fed to a separate intracavity electro-refractive modulator which controls the wavelength of the lasing mode. We demonstrate the laser wavelength stabilization on long time scales. We intend to use such an integrated stabilised laser in a fibre based sensing system.

Introduction

For lasers in applications including tele- and data-communication, sensing and metrology, there are strict requirements on their spectral purity as optical oscillators. To quantify their spectral purity parameters such as linewidth, wavelength stability, phase noise and Relative Intensity Noise (RIN) are used. The fundamental linewidth limit of a laser is a result of spontaneous emission. Specifically for semiconductor lasers, it is described by the modified Schawlow-Townes linewidth [1] and the linewidth enhancement factor which describes the coupling between intensity and noise fluctuations [2]. However, lasers usually exhibit much wider linewidth and wavelength drift due to technical noise associated with the operating environment e.g. temperature fluctuations, mechanical vibrations, current source quality etc..

A number of different strategies can be followed for the wavelength stabilisation and/or linewidth reduction depending on the application and its requirements. Main techniques are the use of extended laser cavities, optical or electrical feedback to the laser and feed-forward techniques. In this paper, we deploy the standard Pound-Drever-Hall (PDH) [3] stabilisation technique for applying feedback to the laser. The wavelength of a single mode monolithically integrated ring laser is stabilised by locking it to an external cavity and realising an electrical feedback loop which corrects for any of the laser's wavelength excursions by changing its cavity length. When applied to semiconductor lasers, in the PDH technique the feedback is commonly applied through a) a change in the injected current to the optical amplifier which generates excess RIN or b) a change in temperature of the cavity by neighbouring heaters which are fairly slow. In this work presented, a monolithically integrated tuneable 1.5µm semiconductor laser is stabilised by applying the feedback to an intracavity electro-refractive modulator (ERM).

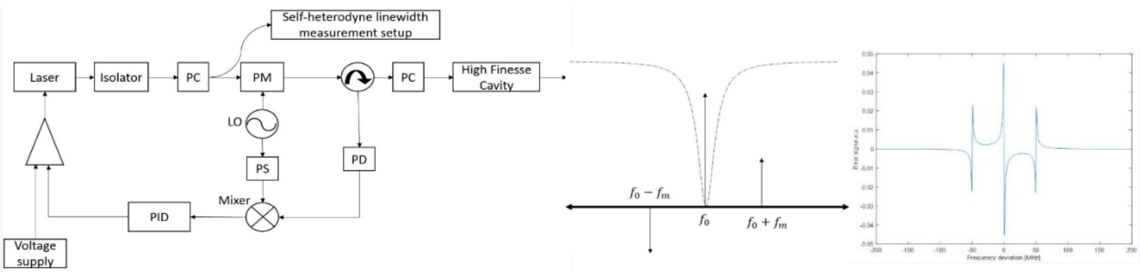

Figure 1. (a)Pound-Drever-Hall schematic (b) Phase modulation Principle (c) Error signal

This ERM directly controls the wavelength of the lasing cavity mode without affecting the output power of the laser as it would do with feedback on the amplifier. This integrated stabilised laser system is intended to be used for fibre based sensing. For this application the ultimate goal is to have a linewidth of the laser of a couple of kHz and at the same time keep the wavelength absolutely stable to the same order of magnitude.

The Pound-Drever-Hall technique

In Pound-Drever-Hall technique a laser is locked to a resonance of an external cavity or an atomic resonance which serves as an absolute reference for the laser's central wavelength. A schematic for PDH is illustrated in Fig.1a. The technique relies on the phase modulation (PM) of the laser output which falls onto the cavity as it is illustrated in Fig.1b where the dash line is the resonance reflection. If the central wavelength is exactly in the middle of the reflection dip then the carrier is not reflected at all and the sidebands are perfectly out of phase so they cancel out. Slight deviations of the central wavelength from this regime or any phase noise create means that the sidebands are not perfectly out of phase anymore which creates a signal at the output of the photodetector (PD). Effectively this is a phase sensitive frequency discriminator and its resolution depends in the resonance full width half maximum (FWHM). Using the PDH technique, it is reported that a laser can be locked down to 1/1000 of the FWHM of the reference cavity resonance [6]. The output signal of the PD is exactly at the phase modulation frequency and it is down-converted to the baseband with the appropriate phase for maximizing its amplitude. This is the error signal which is fed to a PID controller and corrects any laser drifts. It is apparent that such a scheme can be used for the wavelength stabilisation of the laser but it is also possible to realise a feedback loop which is fast enough in order to correct any phase noise and effectively reduce the laser's linewidth.

Laser structure and characterisation

The laser [4] shown in Fig.2a is a CW single frequency ring laser monolithically integrated using InP active-passive integration technology [5]. The frequency selective components of the laser are three cascaded asymmetric Mach-Zehnder interferometers (AMZI) and in every arm there is an ERM for tuning these filters. Additionally, there is an in-line ERM for tuning the cavity modes of the laser independently. Unidirectionality is enforced by a Multimode Interference Reflector (MIR). Right after the laser output there is an amplifier which boosts the output.

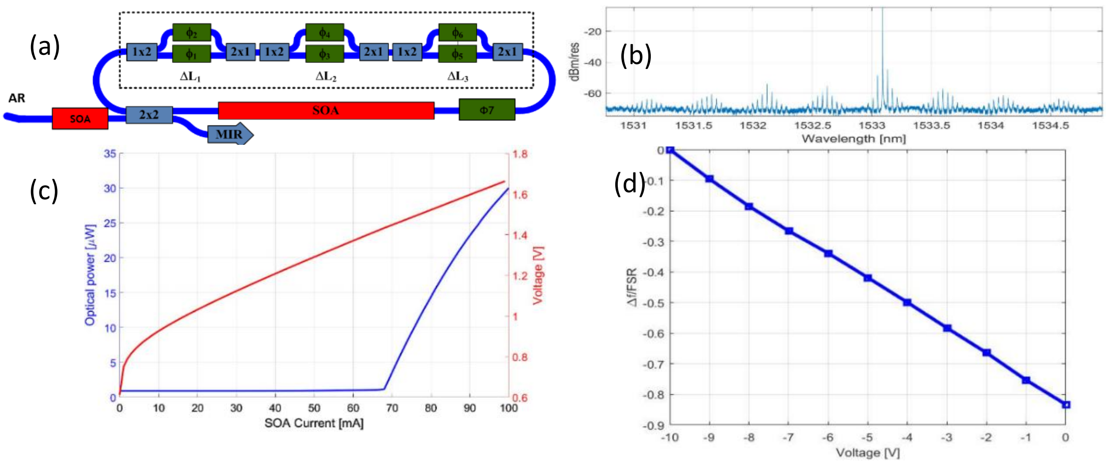

Figure 2. (a) Tuneable ring laser based on three cascaded AMZI, (b) Typical laser spectrum with SMSR>40 dB, (c) LI and VI curves of the laser, $J_{threshold}$ = 3.4 kA/cm2, (d) Frequency shift of a cavity mode versus the reverse bias voltage. The frequency shift is in units of the laser cavity FSR (5 GHz).

A disadvantage of this amplifier is that it at the same time injects more spontaneous emission to the cavity. The output facet is angled and AR coated for avoiding back-reflections. The chip is also packaged and wired bonded. First we characterised the laser which was fabricated in a multi-project wafer (MPW) run by Smart Photonics. The LI and VI curve are shown in Fig.2 (c) where the threshold current is shown to be 68 mA and the laser was tuned to 1535 nm. This threshold current corresponds to a specific alignment of the intracavity filters since different alignments yield different gains for every longitudinal mode. Typical spectrum is shown in Fig.2 (b) with an SMSR>40dB. The threshold current density in the 1 mm long SOA is 3.4 kA/cm^2 with a slope resistance of 8 Ω. The cavity losses are approximately 20 dB including passive components and output coupling. The tuning efficiency of the in-line ERM which is used for the cavity modes fine tuning was also measured. In below threshold operation, the cavity modes spectra of the amplified spontaneous emission were recorded by a high resolution (20MHz) optical spectrum analyser for voltages from -10 V to 0 V. In Fig.2 (d) the frequency shift normalised by the FSR (5 GHz) is shown as a function of the reverse bias. The ERM section is 1.4 mm long thus yielding an efficiency of 21.5 °/Vmm and gives the ability to tune over almost a whole FSR. This actually shows that the range of the stabilisation system is not constrained by the range of the ERM but rather the range at which the laser can be kept single mode while the AMZI-filters are fixed.

Experimental results and discussion

The experimental setup is shown in Fig.1(a). A polarisation controller (PC) which is right before the external phase modulator (PM) is used to align the polarisation of the light with the lithium niobate phase modulator axis for efficient modulation. The second PC is used because the high finesse fibre coupled Fabry-Perot interferometer (FFPI) cavity is polarisation sensitive. The FFPI has a FWHM of 1 MHz and an FSR of 500MHz corresponding to a finesse of 500. The FFPI is sensitive to temperature changes and in order to prevent large drifts it is also placed on a TEC. The PD with transimpedance amplifier has a bandwidth of 200 MHz. The electronics in the dashed box (Fig.1(a)) is realised in one single instrument using a Digilock110 from Toptica GmbH. The output resolution of this unit is 2-3 mV. A step of 2 mV applied to the in-line ERM corresponds to ~1 MHz change in frequency of the laser output. This is more than the linewidth measured in [4] according to the ERM efficiency. This implies that no real linewidth reduction is actually expected in this structure and the ERM length must be decreased accordingly. The phase modulation frequency used was 12.5 MHz which is an order of magnitude larger that the FFPI FWHM.

When we apply a low frequency (30 Hz) saw tooth voltage signal to the in-line intracavity ERM of the laser, the lasing mode moves along a resonance of the FFPI thus creating an ordinary PDH error signal which is depicted in Fig.3 (a). In Fig.3 (b) the PD output which illustrates the reflected from the FFPI light is shown as a function of offset frequency. From this signal it is evident that the initial linewidth of the laser is comparable to the etalon's FWHM since the reflected power does not have the exact shape of the FFPI reflectance. Indeed, in self-heterodyne measurements the linewidth was found to be close to 1.2 MHz. We believe that the wide linewidth is a consequence of back reflections in combination with the amplification and electromagnetic interference due to the laser cabling since for devices without output amplifier linewidths down to 363 kHz were reported [4].To evaluate the quality of the locking mechanism, we analyse the drift of the central wavelength of the laser. This is done using a wavemeter with an absolute wavelength accuracy of 0.3 pm (40 MHz). The wavelength is observed in the free running

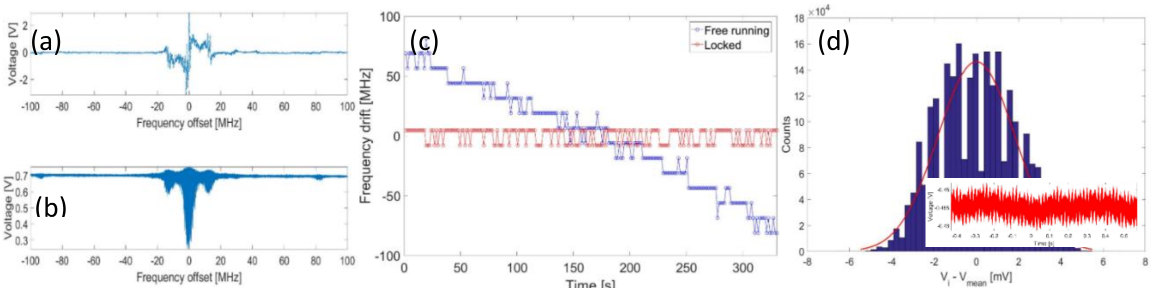

Figure 3. (a) PDH error signal, (b) PDH reflection signal, (c) Wavelength versus time, (d) Feedback signal histogram shows Gaussian like distribution with a FWHM 4.3 mV. The inset is the feedback signal voltage as a function of time

and locked regimes and it is presented as a function of time in Fig.3(c). We observe that for a period of over 5 minutes the free running laser shifts about 150 MHz while in the locked regime the measurement points fall within two consecutive discretisation levels of the wavemeter which differ by 10 MHz which is less than the 40 MHz accuracy of the wavemeter. This shows that wavelength drift can be stabilised. To further examine the locking quality, the next test is to look at the feedback signal Fig.3 (d). This signal can be linked with the drift of the central laser wavelength from the etalon resonance wavelength. The peak to peak fluctuations in a period of 1 second is roughly 10 mV. The feedback signal samples show a Gaussian distribution with a FWHM of ~4mV which corresponds to less than 2 MHz of wavelength drift. This is consistent with the wavelength observations made earlier and not detectable using the wavemeter due to its accuracy. To characterise the lock quality on shorter time-scales the linewidth of the laser has to be quantified. From these linewidth measurements no reduction was observed as expected.
To further improve on the lock quality and subsequently reduce the laser's linewidth we need to identify the noise sources and ensure that their spectral content falls within the bandwidth of the feedback loop bandwidth. The latter is limited by the round-trip delay time which is at least 200 ns thus yield a bandwidth of almost 1 MHz. At the moment, some external factors impact the stabilisation scheme and the linewidth of our laser. These factors are associated with electromagnetic interference and the cabling that is used to inject current to the SOA and tune the intracavity filters of the laser. Moreover, the length of the in-line ERM should be optimised by taking into account its efficiency and the resolution of the electronics in order to be able to finely tune the central wavelength.

Conclusions

We present some early results on the stabilisation of a monolithically integrated CW ring laser using the PDH locking technique. The concept of using an in-line intracavity ERM as a wavelength tuning mean is realised and it is demonstrated by stabilizing the wavelength drift of the tuneable laser. For linewidth narrowing, the control system needs to be optimised.

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