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Efficient generation of two coherent spectral lines using two mutually injection locked DFB lasers

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Abstract. This work proposes a new energy efficient method for generating two mutually coherent laser lines. This method combines mutual optical injection locking with external modulation, which can be implemented with an electro-absorption modulator (EAM). Numerical simulations demonstrate that the proposed method is feasible within a narrow locking range. In addition, it is demonstrated that suppressing the optical carrier of the modulated signal extends the locking range by a factor of 3.

1 Introduction

Microwave photonics (MP) intertwines radio-frequency technology with photonics to generate and process RF signals in the optical domain. This field takes advantage of the fact that converting RF signals to the optical domain reduces the wavelength by three orders of magnitude, thereby enabling a decrease in the size, weight, and power consumption (SWaP) [1]. One of the most important basic functionality that a MP circuit may provide is an RF signal generator [2]. In fact, there are many different techniques for building such a circuit.

Generating a single tone RF signal can be accomplished by beating two laser lines in a photodiode. However, beating two incoherent spectral lines generates an RF signal with wandering RF frequency and strong phase noise. External modulation [3] enables producing two mutually frequency- and phase-locked spectral lines. However, the power of the generated spectral lines is low due to low modulation efficiency. As a result, optical frequency combs [4] and mode locking lasers [5] have been proposed since they are able to generate several spectral lines with high efficiency. However, these methods end up being inefficient given that only two spectral lines are selected, resulting in a significant amount of energy being wasted on unused lines. Optical injection locking (OIL) can be combined with external modulation to overcome the aforementioned shortcomings [3]. However, OIL requires optical isolation of the master laser, which cannot be achieved at least directly in photonic integrated circuits (PICs). In short, a method to efficiently generate two and only two coherent spectral lines with high power efficiency is still missing.

This work proposes a new energy-efficient methodology for the generation of two mutually coherent spectral lines, which combines mutual optical injection locking (MOIL) with external modulation produced by an electro-absorption modulator (EAM).

This paper is structured to first introduce the theoretical background of MOIL, followed by the presentation of the proposed concept, numerical results, and finally, the conclusion and future work.

2 Theoretical background

2.1 Optical Injection locking

In OIL, the electric field of a master laser is injected in the cavity of a slave laser, as illustrated in Figure 1. As result, the electric field of the slave laser will operate at the frequency of the master laser and with a constant phase difference. Therefore, in the end the two lasers are coherent.

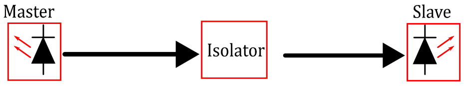

Figure **1**. Optical Injection Locking scheme.

The influence of the injected field can be expressed by a differential equation [6,7]:

$$\frac{dE_s(t)}{dt} = \frac{1}{2}(1+i\alpha)g(N(t)-N_{th})E_s(t)+\kappa E_m(t)e^{i\Delta\omega t}, \quad \textbf{(1)}$$

where $E_s(t)$ is the electric field of the slave laser and $E_m(t)$ is the electric field of the master laser. α is the linewidth enhancement factor, g is the coefficient gain and N_{th} is the threshold carrier. κ is proportional to the injection ratio, r_{in}, which it is defined as the power that is injected into the slave laser: $\kappa = 1/\tau_{in}(1-r_0^2)r_{in}/r_0$. The other terms are constant and detailed in [7]. The first term of the previous equation is related to the normal functioning of the laser without injection locking. Nonetheless, the second term governs the participation of the master laser in the slave laser cavity.

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The authors of [6,7] derived the expression for the locking range in OIL. The locking range can be defined as the frequency difference between the lasers within which injection locking is achievable. The locking range is usually determined as function of the injection ratio.

2.2 Mutual optical injection locking

In MOIL both lasers are slave and masters. In others words the electric field of both lasers have influence in each other as it is represented in Figure 2.

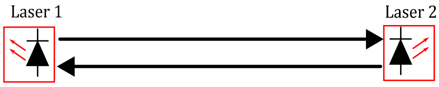

Figure **2**. Mutual optical injection locking scheme.

The main advantage of MOIL is the possibility to synchronize the lasers without the use of optical isolators. However, the set of equations that describe MOIL are more complex. They can be expressed as (based on [7,8]):

$$\frac{dE_1(t)}{dt} = \frac{1}{2}(1+i\alpha)g(N_1(t)-N_{th})E_1(t) + \kappa E_2(t-\tau)e^{+i(\omega_2\tau+\Delta\omega t)}, \quad \textbf{(2)}$$

$$\frac{dE_2(t)}{dt} = \frac{1}{2}(1+i\alpha)g(N_2(t)-N_{th})E_2(t) + \kappa E_1(t-\tau)e^{+i(\omega_1\tau-\Delta\omega t)}, \quad \textbf{(3)}$$

$$\frac{dN_1(t)}{dt} = J_1 - \gamma_N N_1(t) - [\gamma_p + g(N_1(t)-N_{th})]A_1(t)^2, \quad \textbf{(4)}$$

$$\frac{dN_2(t)}{dt} = J_2 - \gamma_N N_2(t) - [\gamma_p + g(N_2(t)-N_{th})]A_2(t)^2 \quad \textbf{(5)}$$

$E_1(t)$ and $E_2(t)$ are the electric field of the laser 1 and 2. $N_1(t)$ and $N_2(t)$ denote the carriers of the laser 1 and 2, respectively. $J_1(t)$ and $J_2(t)$ are the current for both lasers. τ is the time of flight between the two lasers. The other constants are described in [7]: $\alpha = 3.5$ is the linewidth-enhancement factor, $g = 7.0 \times 10^{-6}\, ns^{-1}$ is the linear gain coefficient, $N_{th} = 2.214 \times 10^8$ is the threshold carrier number, $\gamma_p = 500\, ns^{-1}$ is the photon decay rate, $\gamma_N = 0.5\, ns^{-1}$ is the carrier decay rate and $\tau_{in} = 7\, ps$ is the round-trip time in the cavity.

The interaction between both lasers creates the potential for several phenomena to occur: free run, chaos, or MOIL. Consequently, it is essential to identify the conditions under which MOIL occurs. Employing a similar approach to that used by the authors of [6,7] for OIL, we derived an expression for the locking range for MOIL:

$$-2\kappa\sqrt{1+\alpha^2}\,cos(\omega_R\tau+\psi) < \Delta\omega < 2\kappa\sqrt{1+\alpha^2}\,cos(\omega_R\tau+\psi)\,, \quad \textbf{(6)}$$

where ω_R is the resonance frequency and $\psi = \arctan(\alpha)$.

The numerical results will be compared to this expression, to check that the simulations are produced correctly. It should be noted, that a similar expression was obtained by the authors of [9], who used slightly different set of equations to describe MOIL.

3 Proposed concept

The main goal of this paper is to demonstrate a method for energy efficient photonic generation of mm wave signals within a PIC. The setup includes an electro-absorption modulator (EAM) between two lasers, as it is illustrated in Figure 3.

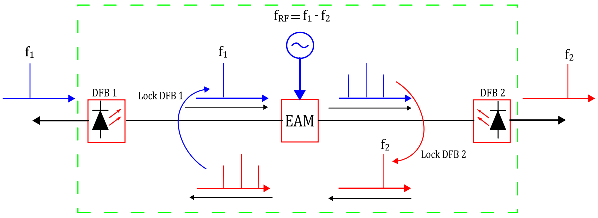

Figure **3**. Proposed 2-tone generator.

Given that the RF frequency is identical to the frequency spacing between distributed feedback (DFB) lasers, i.e., $f_{RF} = f_1 - f_2$, DFB1 and DFB2 can be mutually optical injection locked through the generated RF sidetones. Consequently, two mutually coherent tones are produced and the phase noise is reduced. The main advantage of the proposed approach is that it does not require optical isolators, thus being implementable in a PIC.

In this paper, we investigate the viability of the proposed concept using analytical and numerical assessment. To simulate the proposed concept, a new set of equations which include the modulation of the EAM are considered:

$$\frac{dE_1(t)}{dt} = \frac{1}{2}(1+i\alpha)g(N_1(t)-N_{th})E_1(t) + \kappa\mathbf{EAM}(t-\frac{\tau}{2})E_2(t-\tau)e^{+i(\omega_2\tau+\Delta\omega t)}, \quad \textbf{(7)}$$

$$\frac{dE_2(t)}{dt} = \frac{1}{2}(1+i\alpha)g(N_2(t)-N_{th})E_2(t) + \kappa\mathbf{EAM}(t-\frac{\tau}{2})E_1(t-\tau)e^{+i(\omega_1\tau-\Delta\omega t)}, \quad \textbf{(8)}$$

$$\frac{dN_1(t)}{dt} = J_1 - \gamma_N N_1(t) - [\gamma_p + g(N_1(t)-N_{th})]A_1(t)^2, \quad \textbf{(9)}$$

$$\frac{dN_2(t)}{dt} = J_2 - \gamma_N N_2(t) - [\gamma_p + g(N_2(t)-N_{th})]A_2(t)^2, \quad \textbf{(10)}$$

However, the simulations can only be realized, if an analytical model for the EAM is considered. For now, let us assume that the EAM operates as an amplitude modulator. Hence, the EAM can be described as:

$$\mathrm{EAM}(t) = a_0 + a_1 \sin\omega_{RF}t. \quad \textbf{(11)}$$

The modulation produced by the EAM generates three laser lines. Consequently, several types of interactions can occur between the laser lines of both lasers. It can occur interaction between the main tones of laser 1 and 2, the side tones of laser 1 and 2 and finally, between the main tone of laser 1 and side tone of laser 2, and vice-versa.

Thus, MOIL should only occur between the main tone of laser 1 and the side tone of laser 2, and vice versa. This implies that interactions between the main tones of both lasers should result in free-running lasers, as should interactions between the side tones. Nevertheless, the interaction between the side tones of both lasers can be disregard, since the modulation efficiency of EAM is low.

In short, two conditions must be fulfilled:

1. The interaction between the main tones of laser 1 and 2 should result in free-run lasers. On other words, the main tones should not interact between them.
2. MOIL should only occur between the main tone of laser 1 and side tone of laser 2, and vice-versa.

4 Methodology

In the methodology of this paper, the requirements in terms of injection ratio and detuning needed to meet the previously established conditions are assessed. The work flow realized is the following:

1. MOIL, where the lasers remain unmodulated, $a_1 = 0$. The goal of this stage is to validate simulations with the derived curve and determine the locking range diagram. In particular, this stage is important for understanding the conditions under which interference between the main tones leads to the generation of free-running lasers.
2. MOIL with two tones modulation. Each laser is modulated by single sinusoidal tone: $a_0 = 0$, $\mathrm{EAM}(t) = a_1 \sin \omega_{RF} t$. This type of modulation can be assumed as a double side band modulation with suppression carrier (DSB-SC). The goal of this stage is to determine by simulation the locking range between the main tone and side tone.
3. MOIL with three tones. Each laser is amplitude modulated. The equation that describes the EAM is (11). The goal of this stage is to determine the feasibility of our concept.

Stages 1 and 2 are implemented with the same injection ratio for comparison purposes. For now, the delay between lasers were set to 0. The threshold current for both lasers was 35 mA, and they were both supplied with 50 mA. The RF frequency was constant for the three stages, $f_{RF} = 20\ GHz$. The set of equations were solved using the dde23 routine from Matlab.

5 Results

5.1 MOIL with unmodulated lasers

Figure **4a)** represent the locking range diagram for unmodulated lasers. It is illustrated three different regions: free run, chaos and MOIL. Free-running lasers are achieved when two incoherent main laser lines are present. Chaos occurs when the output becomes unstable, resulting in several unstable laser lines in the spectrum. In MOIL, however, only a single laser line is produced.

As expected, MOIL occurs within the region defined in (6). Moreover, with the increase in injection ratio, the locking range also increases. Free-running lasing is achieved with lower injection ratios but higher detunings. For the proposed modulation frequency, free-run lasers are obtained for injection ratios lower than 0.2%.

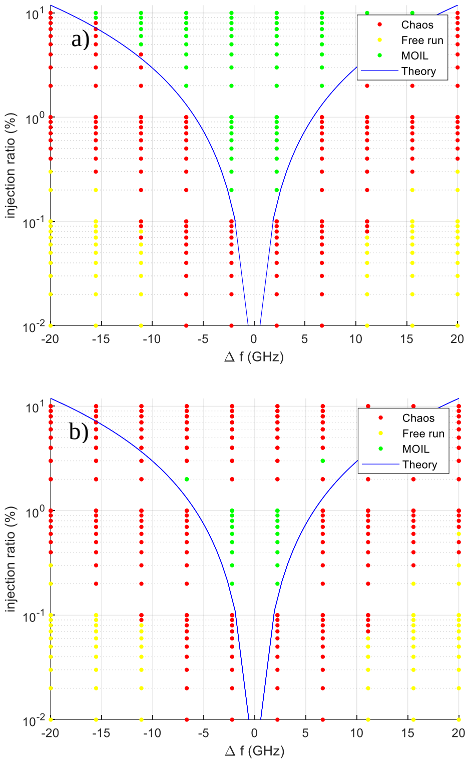

Figure **4.** Locking range diagram for a) unmodulated lasers b) MOIL with DSB-SC modulation.

5.2 MOIL with two tones

The goal of this section is to measure the locking range between the main tone and side tone. In this way, the detuning between the two lasers was defined as $\Delta f' = 20GHz + \Delta f$. Therefore, Δf is the difference between the main tone and the side tone, allowing the utilization of the derived curves for the locking range.

Figure **4b)** represents the locking range diagram for the double side modulation with suppression carrier. It is illustrated that the locking range occurs between derived curves.

Furthermore, it can be observed that for effective injection ratios exceeding 1%, only chaos is observed. Thus, the optimal injection ratio is 1%, as it corresponds to the widest locking range (~ 5.8 GHz). In addition, it is possible to conclude that higher the injection ratio greater is the locking range.

5.3 MOIL with three ones

Through the section 5.1 and 5.2 is possible to achieve some remarks:

1. From section 5.1, it is possible to obtain free-running lasers for lower injection ratio and higher detuning between the carriers, which means that a_0 should be lower. For the simulations conditions previously mentioned, free-running lasers is obtained for injection ratios lower than 0.2 %.

2. From section 5.2, it was shown that to achieve larger locking range, the effective injection ratio for the main tone-side tone should be large, which means that a_1 should be high. The maximum locking range possible is 1 % and the corresponding locking range is 5.8 GHz.

From these results, some remarks can be drawn for the three tones modulation. Realistically, in the modulation produced by the EAM, $a_0 > a_1$, indicating that, injection ratios higher than 0.2 % can be excluded, as interactions between the main tones lead to chaos (Figure **4a**). Consequently, the maximum locking range at 1 % of injection ratio (Figure **4b**) is unattainable, as demonstrated in Figure **5**.

However, the strength of both interferences depends on the amplitudes of the modulation produced by the EAM:

$$\mathrm{EAM}(t) = a_0 + a_1 \sin \omega_{RF} t = a_0 + \frac{1}{2i} a_1 e^{j\omega_{RF}t} - \frac{1}{2i} a_1 e^{-j\omega_{RF}t}. \quad \textbf{(12)}$$

As a result, the power of the generated spectral lines is related to parameters a_0 and a_1. Therefore, the injection ratio can be defined as a function of these parameters for the analyzed use cases. In use case 5.1 (MOIL unmodulated), the injection ratios can be expressed as $r_{m-m} = r_{in} a_0^2$. For use case 5.2 (MOIL with two tones), the injection ratio can be described as $r_{m-s} = \frac{r_{in} a_1^2}{4}$.

In this way, if ideal modulation is assumed, $a_0 = a_1 = 1$, the power of the side tones is one quarter of the main tone. In other words, $r_{m-s} = \frac{1}{4} r_{m-m}$. This implies that, $r_{m-m} = 0.2$ % and $r_{m-s} = 0.05$ %. Consequently, the maximum locking possible, assuming ideal modulation, is 1.7 GHz.

Figure **5** represent the scheme behind the derivation of the maximum locking range possible.

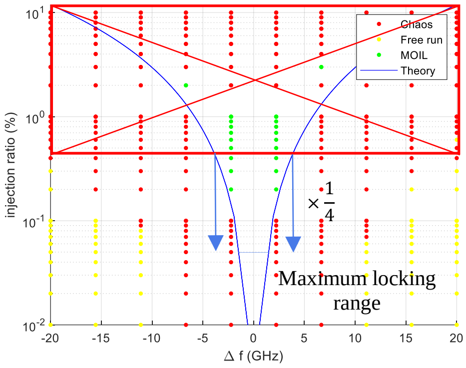

Figure **5**. Derivation of the maximum locking range for three tones modulation.

6 Conclusion

This paper proposes a novel method for generating two mutually coherent laser lines, based on MOIL. Some remarks should be highlighted.

The derived curves are good base to understand the locking range mechanisms, even assuming modulation between the lasers. The locking range determined for MOIL and MOIL with two tones modulation was similar until 1% of injection ratio.

MOIL with two-tone modulation (DSB-SC) offers the widest locking range of 5.8 GHz. However, the practical implementation of this modulation is complex and power-inefficient, as a setup with just one EAM is not viable.

MOIL with three tones modulation (DSB) produces two coherent laser lines, in a narrow locking range (1.7 GHz). However, such a narrow locking range requires a precise monitoring and control system. Nevertheless, this limitation can be reduced by raising the RF frequency at which the EAM is modulated, as a greater spacing between the lasers, free-run lasers is easily achieved.

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References

1. Marpaung, D., Roeloffzen, C., Heideman, R., Leinse, A., Sales, S., & Capmany, J. (2013). Integrated microwave photonics. Laser & Photonics Reviews, 7(4), 506-538.
2. Seeds, A. J., & Williams, K. J. (2006). Microwave photonics. Journal of lightwave technology, 24(12), 4628-4641.
3. Yao, J. (2009). Microwave photonics. Journal of lightwave technology, 27(3), 314-335.
4. Wang, W. T., Liu, J. G., Sun, W. H., Chen, W., & Zhu, N. H. (2015). Multi-band local microwave signal generation based on an optical frequency comb generator. Optics Communications, 338, 90-94.
5. Carpintero, G., Guzmán, R. C., Gordón, C., Kervella, G., Chitoui, M., & Van Dijk, F. (2015). Photonic integrated circuits for radio-frequency signal generation. Journal of Lightwave Technology, 34(2), 508-515.
6. J. Ohtsubo, Semiconductor Lasers: Stability, Instability and Chaos (Springer, 2006).
7. A. Murakami, K. Kawashima and K. Atsuki, "Cavity resonance shift and bandwidth enhancement in semiconductor lasers with strong light injection," in IEEE Journal of Quantum Electronics, vol. 39, no. 10, pp. 1196-1204, Oct. 2003, DOI: 10.1109/JQE.2003.817583.
8. C. Sun *et al*., "Modulation Characteristics Enhancement of Monolithically Integrated Laser Diodes Under Mutual Injection Locking," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 21, no. 6, pp. 628-635, Nov.-Dec. 2015, Art no. 1802008, doi: 10.1109/JSTQE.2015.2478817.
9. Li, Y., Yang, N., Xie, Y., Chu, W., Zhang, W., Duan, S., & Wang, J. (2019). Basic phase-locking, noise, and modulation properties of optically mutual-injected terahertz quantum cascade lasers. Optics Express, 27(3), 3146-3160.