InP-Si_3N_4 Hybrid Integrated Optical Source for High-purity Mm-wave Communications

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Abstract: We present the optical injection locking to a comb of a hybrid InP-Si_3N_4 dual laser source for high-purity mm-wave generation. Key performance parameters such as adjacent-comb-line side mode suppression ratio and locking range are reported.

1. Introduction

Hybrid photonic integration is gaining more and more momentum as it allows the use of the best substrate material for each functional building block in a Photonic Integrated Circuit (PIC). The hybrid integration of InP and Si_3N_4 combines the efficient optical gain of the former platform with the ultra-low loss waveguides of the latter, enabling the development of small form factor, low cost, and high volume transceivers. In the past few years, this platform has produced outstanding results in the development of ultra-narrow linewidth lasers [1] and microwave photonic trasmitters [2]. A microwave photonics application that has been recently explored in this platform is mm-wave heterodyne generation [3]. Recent works integrating two InP-Si_3N_4 lasers on the same chip have shown that, while the two lasers can have very low intrinsic linewidth, the RF beatnote still exhibits a long-term drift due to thermal instabilities [3]. This drift can hinder the use of such a solution on any telecom system due to failing to comply with current regulations on frequency stability [4]. This drift, however, can be eliminated by optical injection locking (OIL) of the two lasers to an optical frequency comb. In this case, the dual-laser PIC acts as a comb demultiplexer (demux) filter, a functionality that has been extensively explored in the InP technology [5–11] but remains unexplored in this hybrid platform. A key characteristic that makes the InP-Si_3N_4 lasers interesting for this functionality is the high Q-factor they exhibit, which directly affects the two most important parameters for comb demux: the side mode suppression ratio (SMSR) of adjacent comb lines and the locking range. In this paper we present experimental results on the OIL of an InP-Si_3N_4 dual-laser PIC for high-purity optical-heterodyne mm-wave generation. We show, for the first time, the SMSR characteristics of such lasers when locked to an optical frequency comb as well as their locking range. Ultra-stable mm-wave generation at 90 GHz is demonstrated by locking the dual-laser PIC to an external modulation-based comb generator.

2. Injection locking results

The hybrid laser characterized in this section is one of the lasers forming the module described in [3]. It integrates an InP quantum-well (QW) gain chip and a TriPleX Si_3N_4 microring-based mirror to form a high-Q laser cavity. For the injection locking characterization, a setup consisting on an optical frequency comb generator (OFCG), a circulator, and a high resolution optical spectrum analyzer (OSA) and/or electrical spectrum analyzer (ESA) was used. The frequency comb was generated with a phase modulator and an external cavity laser (ECL). Depending on the measurement, the hybrid laser was locked to either the 0^{th}- (SMSR measurements) or $+1^{st}$-order (locking range measurement) sidebands of the comb. When an offset was required between comb and laser, this was achieved by tuning either the RF synthesizer driving the comb (locking range measurement) or the laser via the microrings (SMSR vs. offset measurement). All the results in this section were obtained for a gain current of 180 mA and no (or very small) bias voltages applied to the laser heater-based phase actuators. With these settings, the hybrid laser emitted at 1550.88 nm with an output power of 12.5 dBm and exhibited a Lorentzian linewidth of 2.9 KHz. It is important to note that, as the linewidth of the ECL used for comb modulation was higher than that of the hybrid laser, the optical linewidth of the latter was disimproved upon OIL. This is not a problem, however, for optical heterodyne RF generation since the two OIL-filtered comb lines remain coherent and a very stable mm-wave signal can be generated regardless of the optical linewidths. Fig. 1 (a) shows the SMSR of the filtered comb line as a function of comb-line frequency separation for different levels of comb power injected into the hybrid laser. Other reported SMSR values from OIL-based comb filters are plotted as well. Above a frequency of around 5GHz, the hybrid laser exhibits SMSR values in excess of values previously reported in the literature. As the SMSR depends on the level of comb signal reflected from the slave laser, the higher SMSR values reported here are likely associated to the additional filtering that the reflected signal encounters in the hybrid laser (due to its high-Q characteristics) compared to standard DFBs. Fig. 1 (b) shows the full locking range of the hybrid laser. The full locking range is substantially lower than that found in monolithically-integrated InP diode lasers. The higher the Q-factor of the locked laser, the higher the SMSR–but also the narrower the locking range for a certain injected power [12]. A wider locking range enables improved wavelength tracking, which can be important for some applications. This can be achieved by increasing the injected power, albeit by sacrificing SMSR (as shown in fig. 1 (a)). However, for other applications, a narrow locking range is essential to avoid locking instabilities arising from the presence of closely-spaced adjacent lines [13]. In this case, a high-Q Si_3N_4 laser can be advantageous over a an InP laser. Fig. 1 (c), (d), (e), and (f) show the SMSR as a function of the frequency detuning between comb and laser for comb line separations of 3, 6, 9 and 18 GHz respectively and two different input-to-output power ratios: -17 and -32 dB. In most cases, the SMSR stays more or less constant with detuning frequency.

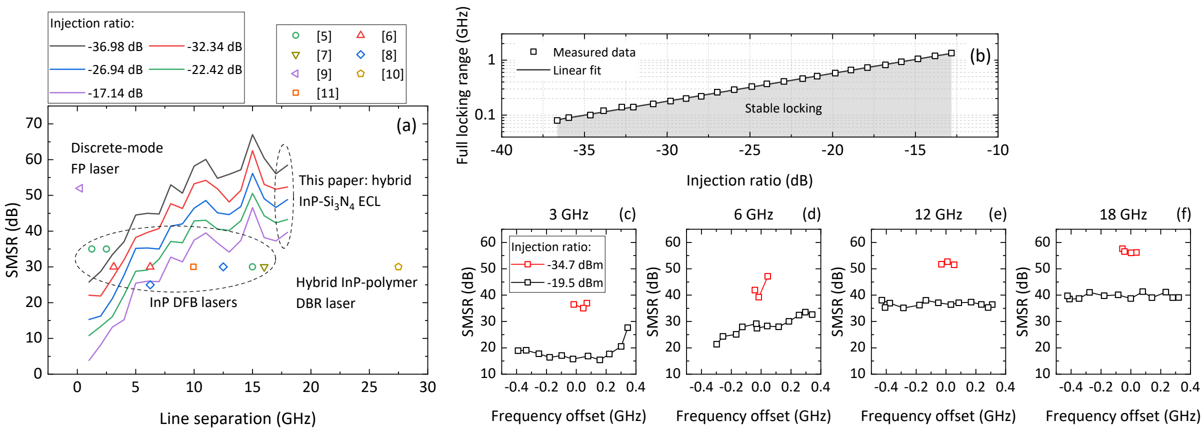

Fig. 1. Injection locking characterization results: (a) SMSR as a function of comb line separation for zero-frequency detuning between locking line and hybrid laser; (b) full-locking range as a function of the injection ratio; and (c), (d), (e), and (f) SMSR as a function of the detuning for comb lines separations of 3, 6, 12, and 18 GHz, respectively. Injection ratio refers to ratio between the power of the comb locking line and that from the hybrid laser in free-running mode.

3. Heterodyne generation

In the previous section, the measurements were taken with no bias applied to the laser heaters. Under this condition, the wavelength of the hybrid laser (whose temperature was controlled with a Peltier) was very stable. This can be seen in Fig. 2 (a), which shows the laser drift measured with a high resolution OSA over a period of 12 hours. As reference, the drift of an off-the-shelf ECL was also measured. There is a notable drift over the first 4 hours of the measurement. However, since a strong correlation between the hybrid laser and ECL curves can be observed over this period, this drift is attributed to external factors. After this period, the maximum accumulated drift of the hybrid laser was less than $\pm$30 MHz. To offset the two hybrid lasers present in the module by 90 GHz and achieve mm-wave generation at this frequency, three microring heater bias configurations (shown in Fig. 2 (b)) were explored. It is important to mention that the large bias voltages required in the three configurations is due to the fact that the initial biasing conditions (i.e. 0 V bias applied to the microrings) give rise to a wavelength offset between the lasers of about 50 nm. The drift associated with each configuration–in this case measured over a period of 1 hour–is shown in Fig. 2 (b). Since a large drift can bring the laser out of locking, minimizing this drift is critical. As Fig. 2 (b) shows a strong dependency between the bias level and the drift, minimizing the latter can be achieved by reducing the amount of bias level, which, in turn, can be achieved by designing the lasers to start lasing at closer wavelengths.

As it exhibited the lowest amount of drift among the three configurations, config. 3 was chosen for the heterodyne generation. The same optical frequency comb as that in the previous section was used as the external reference. The frequency comb separation was set to 15.6 GHz, with the two lasers locking to the $+$ and -3^{rd}-order sidebands, giving a heterodyne frequency of 93.16 GHz. The spectrum of the injected comb, and that of the locking output are shown in Fig. 2 (c). Fig. 2 (d) shows the obtained max.-hold spectrum for the free-running and injection-locked signals over a period of 5 minutes. As one can see, the free-running spectrum stretches over more than 16 MHz. This would already violate current regulations on the stability of mm-wave signals, which specifies

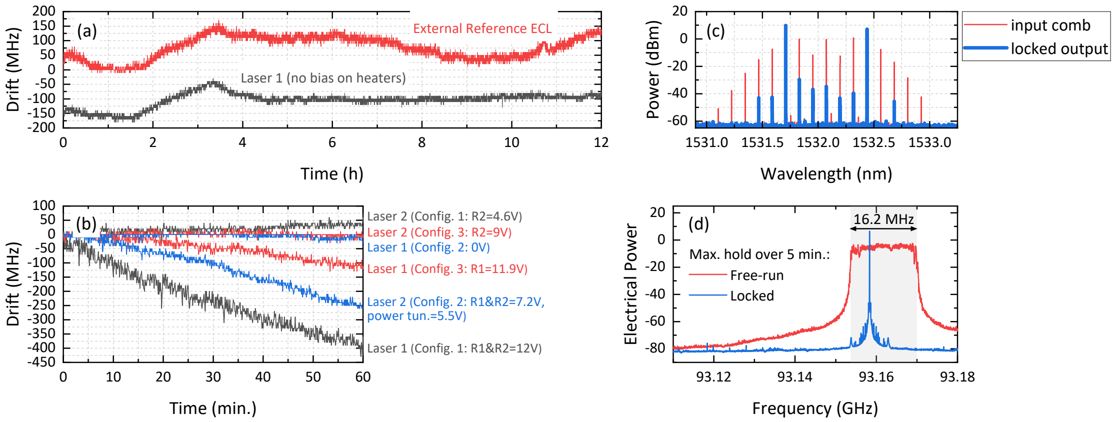

Fig. 2. Long-term drifts measurements using a high-resolution OSA: (a) stability of hybrid Laser 1 with no bias applied and that of a reference ECL over a period of 12 hours and (b) drift of hybrid lasers 1 and 2 for various heater configurations; (c) input comb and locked output spectra; (d) max.-hold power spectrum over 5 minutes of the free-running and locked signals. R1: microring-1 heater; R2: microring-2 heater; power tun.: thermal coupler regulating the reflectivity of the Si_3N_4 mirror (this coupler can also be used to tune the wavelength [3]).

a maximum tolerance of 150 parts per million [4]. This translates into a bandwidth of just 14 MHz at a carrier frequency of 93 GHz. Thus, a locking technique is likely to be required for practical applications even if dealing with ultra-low linewidth lasers.

4. Conclusion

The narrow filtering provided by Si_3N_4 mirrors makes the injection locking of hybrid InP-Si_3N_4 lasers interesting for comb demux applications. The filtering characteristics of a hybrid InP-Si_3N_4 laser when locked to a comb are characterized here in terms of the SMSR of adjacent comb lines, measuring values in excess of previously reported values for comb line separations above 5 GHz. It is also shown that minimizing the bias level applied to the heater-based phase actuators of these lasers is essential to minimize their free-running drift, which is essential to keep a locking state. By locking a module integrating two hybrid lasers to an external comb, ultra-stable RF generation is reported at 93 GHz.

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References

1. Y. Fan, et al., "Hybrid integrated InP-Si 3 N 4 diode laser with a 40-Hz intrinsic linewidth," Opt. Express **28**, 21713 (2020).
2. C. Tsokos, et al., "True Time Delay Optical Beamforming Network Based on Hybrid InP-Silicon Nitride Integration," J. Light. Technol. pp. 1–1 (2021).
3. R. Guzman, et al., "Widely Tunable RF Signal Generation Using an InP/Si3N4 Hybrid Integrated Dual-Wavelength Optical Heterodyne Source," J. Light. Technol. pp. 1–1 (2021).
4. ITU-R SM.1045-1, "Frequency tolerance of transmitters," **1** (1997).
5. P. D. Lakshmijayasimha, et al., "Characterization of a multifunctional active demultiplexer for optical frequency combs," Opt. Laser Technol. **134**, 106637 (2021).
6. Pilot Photonics, "Photonic Integrated Comb Source and Demux PIC Evaluation Platform," .
7. S. T. Ahmad, et al., "Active demultiplexer enabled mmW ARoF transmission of directly modulated 64-QAM UF-OFDM signals," Opt. Lett. **45**, 5246 (2020).
8. R. Zhou, et al., "Injection Locked Wavelength De-Multiplexer for Optical Comb-Based Nyquist WDM System," IEEE Photonics Technol. Lett. **27**, 2595–2598 (2015).
9. D. S. Wu, et al., "Selective amplification of frequency comb modes via optical injection locking of a semiconductor laser: influence of adjacent unlocked comb modes," Integr. Opt. Phys. Simulations **8781**, 87810J (2013).
10. G. Carpintero, et al., "Wireless Data Transmission at Terahertz Carrier Waves Generated from a Hybrid InP-Polymer Dual Tunable DBR Laser Photonic Integrated Circuit," Sci. Reports **8**, 1–7 (2018).
11. M. C. Lo, et al., "Foundry-fabricated dual-DFB PIC injection-locked to optical frequency comb for high-purity THz generation," Opt. InfoBase Conf. Pap. **Part F160-**, 3–5 (2019).
12. K. Shortiss, et al., "Mode suppression in injection locked multi-mode and single-mode lasers for optical demultiplexing," Photonics **6** (2019).
13. A. C. Bordonalli, et al., "Optical injection locking to optical frequency combs for superchannel coherent detection," Opt. Express **23**, 1547 (2015).