Low phase noise fully integrated millimeter-wave photonic source using cross injection locking

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***Abstract*— We report the stabilization of a 90 GHz mmW signal generated from a fully integrated photonic source. The chip consists of two distributed feedback (DFB) single mode lasers which optical signals are combined on a fast photodiode to generate a largely tunable heterodyne beat note. By generating an optical comb from each laser, thanks to an external synthesizer, and by optically self-injecting the resulting signal, we mutually correlate the phase noise of each DFB and we stabilize the RF beating on the external reference. The performances achieved beating linewidth below 30 Hz.**

***Keywords*— Lasers, distributed-feedback, Heterodyne detector, Integrated optics, Radio frequency photonics**

I. Introduction

Millimeter-wave frequency range is of great interest for broadband wireless communications mainly because of the available bandwidth and the good directivity of the signal [1]. Optical solutions for the generation and the modulation of mmW frequency signals are an attractive way particularly in term of tunability and compactness. Thus, it is possible to generate a heterodyne beat note in the mmW range by combining two single frequency lasers optical signals on a fast photodiode. In a previous work [2], we have demonstrated the generation of a signal tunable from 5 to 110 GHz with a fully integrated chip containing two DFB lasers, a high speed photodetector and electro-absorption modulator. The later allows us to modulate data on the carrier by electro-optical modulation of the optical power. However, a main issue is related to the large beat note linewidth which can impact the quality of the transmission when the photonic source is used in high data-rate wireless communications. To solve this problem, we have achieved the first cross injection locking of a 90 GHz RF signal from a fully integrated mmW photonic and largely tunable source. Some solutions based on phase-locking techniques have been investigated.

- Phase-lock of the generated signal onto a reference oscillator (LO) [3] thanks to a feedback loop to transfer the spectral purity of the LO to the beatnote frequency. This requires the optical linewidth of each of the two optical tones to be narrow enough and the feedback electronics to be fast enough, with a short time delay.
- Optical injection of an optical reference such as an optical frequency comb. This was successfully demonstrated on devices very similar to those presented here [6].
- Self-optical injection locking of the dual wavelength laser to its own signal after electro-optical modulation with a stable electronic oscillator. This solution avoids the use of an additional optical source and was already demonstrated with solid-state and dual-frequency lasers [4], [5].

In this paper we present the first cross injection locking of a 90 GHz mmW signal issued by a fully integrated and largely tunable mmW photonic source.

II. Description of the device

The photonic integrated circuit (PIC) under consideration is shown in Figure 1. It includes two single mode optical sources (DFB1 and DFB2) working at a wavelength of about 1555 nm. Their beams are combined with a multimode interference (MMI) coupler. Semiconductor amplifiers (SOA) are placed at different positions of the circuit to amplify and adjust the signals levels. At last, the optical beat signal is sent onto a UTC photodiode where it is converted into a mmW signal. If we call λ1 and λ2 (resp. ν1 and ν2) the wavelengths (resp. frequencies) of the two DFB lasers, the mmW frequency is:

$$f = \frac{c(\lambda 2 - \lambda 1)}{\lambda 2 \lambda 1} \quad (1)$$

An integrated electro-optical modulator is inserted before the UTC photodiode in order to modulate the beatnote which is used as a carrier frequency . The photodiode output can then be directly connected to a mmW antenna for free space data transmission. An optical access to the DFB lasers is still possible on the other side of the chip (left-hand side in Fig. 1) enabling monitoring of the optical signals as well as optical feedback as shown in the following. All these functions are realized in a single 4.4mm x 0.7mm device.

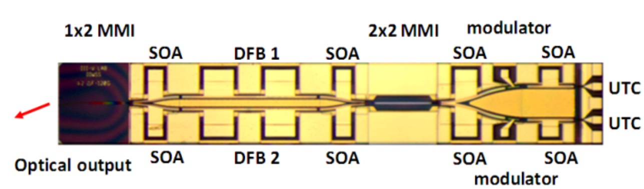

Fig. 1. Microscope view of the integrated photonic mmW source.

To adjust the tuning of the beatnote, we benefit from the simple and easy tuning of the DFBs wavelengths by adjusting the driving current. Indeed, the current induces heating and results in a change of the refractive index and, by means of consequence, in an increase of the wavelength. So by controlling both DFB bias currents independently we can tune the beatnote frequency as described by equation (1). Hence, we were able to demonstrate a continuous tuning from 5 GHz up to 110 GHz [2]. This validated possible continuous tunability of the beatnote as well as the high frequency response of the integrated UTC photodiode.

Moreover, as already shown in [8] the electro-optical modulator integrated in the chip enables high data rate transmissions: back-to-back transmission up to 4 Gbit/s was demonstrated. Nevertheless, we observed that the data rate is in practice limited to 200 Mbit/s for a full wireless transmission due to the high phase noise level of the mmW carrier. Indeed, in addition to the intrinsic optical phase noise associated to the natural linewidth of each of the DFB lasers, additive phase noise appears because of parasitic reflections in the photonic integrated circuit and on the back of the photodetectors that are modulated by the data stream applied to the electro-optical modulator. Consequently, these effects have to be reduced and the mmW carrier phase noise improved in order to make this PIC fully compatible with wireless transmissions.

III. Cross Injection Locking

The proposed solution involves optical injection locking (OIL). It is well known that injecting a slave laser (SL) with a low-phase-noise master laser (ML) forces the SL to operate at the same wavelength and to have a phase noise similar to the ML [11], provided that the wavelength of the two lasers are sufficiently close and that the injected optical power is optimized. If the ML is not single frequency but is a comb of optical tones, the SL can lock to the nearest tone as it has been successfully tested on one of our PIC [7]. Nevertheless, such a solution is not versatile and is quite heavy in terms of implementation since it requires an additional stable laser to generate the comb. To overcome this limitation, we propose a new approach which consists in generating a frequency comb around each DFB line and optically re-inject this dual-comb into the PIC. The principle is illustrated in Figure 2.

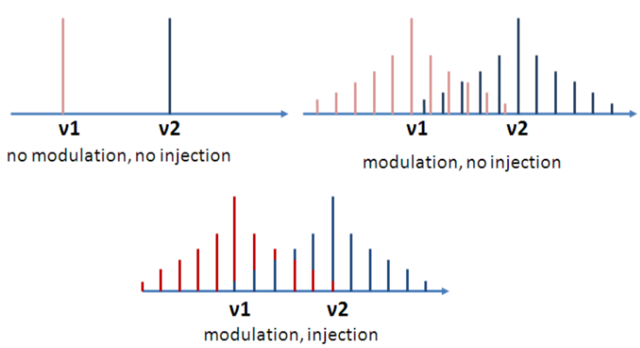

Fig. 2. Optical spectrum : illustration of the cross self-injection phase locking.

The free spectral range of the combs are adjusted so that mutual optical injection occurs for a given tone of each comb. By this way, the scheme leads to spectral narrowing for each DFB line thanks to optical self injection after a delay in the fiber loop. Moreover, the loop can ensure cross-stabilization. Indeed, one comb line generated with ν1 can inject ν2 and, simultaneously, one comb line generated with ν2 can inject ν1. By properly choosing the modulation frequency f_{RF}, it is possible to match a given harmonic issued from the first laser with the frequency of the second laser and vice-versa. In this case, $\nu 2 = \nu 1 + N.f_{RF}$, where N is the harmonic number of the injected tone. Both DFBs are optically self-injected as well as mutually cross-injected.

The experimental setup is shown in Figure 3. Thanks to the optical output port of the PIC, the dual frequency signal is coupled in a lensed fiber and sent into an optical circulator. Following the light direction, a 10 GHz bandwidth phase modulator (MΦ) is used to generate the optical frequency comb around each DFB laser line. It is driven with a 33 dBm signal provided by a synthesizer (AGILENT E8257D) followed by an RF amplifier allowing efficient harmonics generation which is useful for locking the two lasers in a large range of frequencies. Due to the weakness of the optical signal in this proof of concept experiment, an Erbium Doped Fiber Amplifier (EDFA) is included in the loop for optical amplification. Moreover, an optical filter with 0.7 nm bandwidth is introduced after the EDFA to filter out the amplified spontaneous emission ensuring a relatively clean optical reinjection. After a cycle, the signal is injected back into the PIC through the lensed fiber. Two polarization controllers are used: the first one to adjust the beam polarization at the entrance of the phase modulator and the second one to control the polarization matching of the PIC output and re-injected signal. The electrical beat note and the optical spectrum are simultaneously monitored using an electrical spectrum analyzer and an optical spectral analyzer.

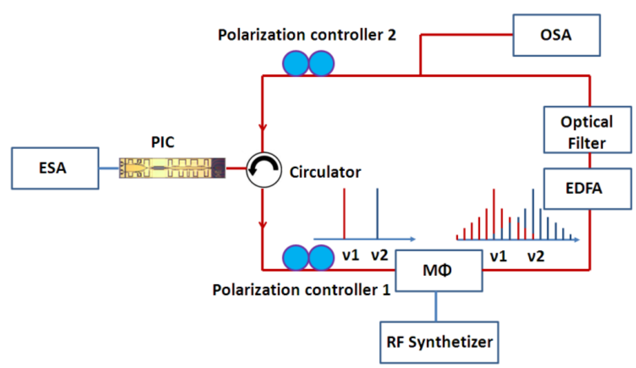

Fig. 3. Schematic representation of the self injection setup.

IV. Results

For the experiment, the beatnote frequency delivered by the PIC is tuned at 90 GHz and the temperature is maintained at 20° to improve the long-time stability of the system. The signal delivered by the monolithically integrated high speed photodiode is then electrically down-converted with an external mixer prior analysis with an electrical spectrum analyzer. Figure 4 shows the comparison between the electrical spectra of the original free running beatnote and the successfully phase locked beatnote. On the latter, we can observe the 5 MHz free spectral range of the filtering effect of the optical loop which acts in these conditions as a simple external cavity coupled to the two DFB lasers.

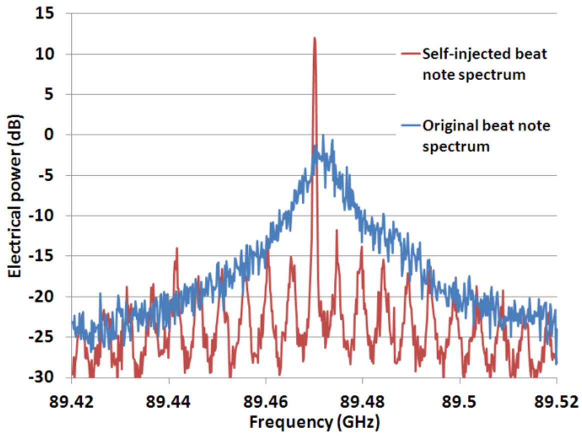

Fig. 4. Comparison between the original and the self-injected beatnote spectrum (RBW=300 kHz, Span=100 MHz).

To achieve proper injection locking, the phase modulator is driven at 18 GHz so that the fifth harmonic of each optical comb matches the line of the other laser. By finely adjusting the modulation frequency, one reaches periodically the situation where one harmonic of the RF signal lies in the vicinity of the original free running beatnote and where it matches one of the feedback loop longitudinal modes. By this way, a narrow linewidth beatnote strongly emerges and we observe a consequent reduction of the power of the non-injected modes, illustrating a nice example of energy transfer. We can notice the strong emerging power of the selected mode, i.e., close to 15 dB increase as compared to the free running regime. These results clearly prove that the spectral narrowing is not related to a simple feedback loop but to efficient optical cross-injection which leads to the huge reduction of the beatnote linewidth and the concentration of energy on one mode. In the cross-injected operating mode, the beatnote linewidth at half maximum drops below 30 Hz (limited by the resolution of our spectrum analyzer). This excellent result is in the same order of magnitude as dual-frequency solid-state lasers [10] but in a monolithically integrated semiconductor laser.

The corresponding phase noise power spectral density of the self-injected beatnote was measured experimentally, as shown in Fig.5, using the phase noise setting of the ESA.

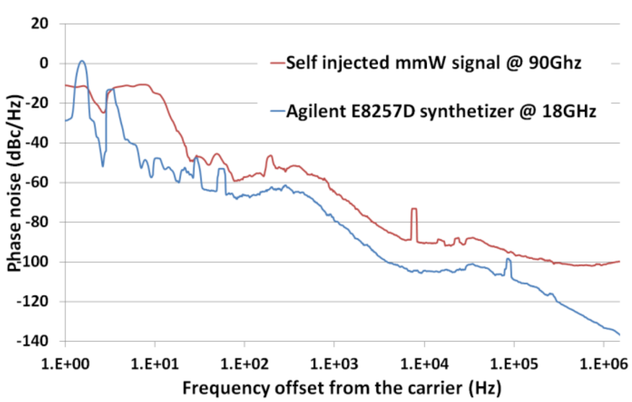

Fig. 5. Comparison between the synthetizer and the self-injected beatnote phase noise

The phase noise level of the self injected beatnote is below −90 dBc/Hz for frequency offsets from the carrier of 10 kHz or more attesting the high purity of the signal. The phase noise spectral density of the synthesizer is shown for comparison. The additive noise is evaluated about to 14dB for frequencies between 100 Hz and 10 kHz corresponding to the additive phase noise level to reach the fifth harmonic of the synthesizer frequency following the equation:

$$L(f_n) = L(f_0) + 20Log(n)$$

With $L(f_n)$ the phase noise of the nth harmonic and $L(f_0)$ the phase noise of the original synthesizer note.

V. Summary

The phase locking of a monolithically integrated photonic mmW source has been successfully demonstrated using a high order optoelectronic cross injection technique. The proposed technique benefits from the combination of optical self and mutual cross-injection leading to a robust and high spectral purity mmW signal without any master laser external reference. The linewidth of the beat note at 90 GHz was reduced below 30 Hz and the phase noise level below−90 dBc/Hz for frequency offsets from the carrier of 1 kHz or more which is the state of the art for this kind of monolithically integrated semiconductor device. The power spectral density of the mmW carrier is significantly improved. These results support the promising prospects of monolithically integrated photonic mmW sources in future communication networks.

Acknowledgment

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