Fully Integrated Photonic Millimeter-Wave Tracking Generators on the Heterogeneous III–V/Si Platform

Rui-Lin Chao, Linjun Liang, Jin-Wei Shi, Tin Komljenovic, Jared Hulme, M. J. Kennedy, and J. E. Bowers

***Abstract*— Fully integrated photonic microwave/millimeter-wave (MMW) tracking generators, which include wavelength-tunable lasers, distributed feedback lasers, phase modulators, and high-speed photodiodes (PDs), are demonstrated on the heterogeneous integrated III–V-on-Si photonic platform. Two on-chip lasers are locked by an external optical phase-locked loop (OPLL), and the two-tone radio-frequency (RF) signals from the on-chip fast PDs can be photonically generated through the heterodyne-beating process between the wavelength-tunable laser and the OPLL output. Furthermore, the frequency spacing between such two-tone RF signals can be tracked by the oscillation frequency in the OPLL with a wide tunability (near dc to 10 GHz). Fast and truly continuous scanning of photo-generated MMW signals thus becomes feasible by simultaneously tuning the OPLL and the central wavelength of the tunable laser in the demonstrated photonic integrated circuit.**

***Index Terms*— Silicon photonics, photonic integrated circuits.**

I. Introduction

THE PHOTONIC millimeter-wave (MMW)/THz generation technique has advantages over the traditional all-electronic-based approach [1]. Combining fast photodiodes (PDs) with such techniques, one can generate in a single sweep frequencies from near dc to sub-THz (hundreds of GHz) [1]–[3], and different metallic waveguide-based MMW frequency multipliers are no longer necessary to cover such wide electrical bandwidth. Recently, combing injection-locking with comb-line generation techniques, researchers have successfully demonstrated high-quality photo-generated radio-frequency (RF) signals with a tunability spanning over seven octaves [4]. However, the frequency spacing between adjacent optical comb-lines limits the truly continuous tuning in the frequency of the generated MMW signals and the size of the whole system is bulky.

Photonic integrated circuits (PICs) are an effective solution to minimize the size of photonic MMW/THz generators. Recently, both monolithic and heterogeneous PICs have been demonstrated for photonic MMW signal generation from near dc to 110 GHz [5], [6]. However, the continuous tuning of the generated MMW signal is limited by the thermal cross-talk and mode-hopping in distributed-feedback (DFB) lasers and wavelength-tunable lasers, respectively [5], [6].

Optical phase-locked loop (OPLL) techniques [7]–[9] have been applied to PICs [8], [9] to realize truly continuous scanning in the frequency of hetero-dyne beating signals and greatly reduce their phase noise. The servo current source, which can be used to build an OPLL with the offset locking frequency range of exceeding 10 GHz is commercially available[1]. Nevertheless, to date, the maximum offset locking frequency in an OPLL is usually less than 20 GHz [8], [9] and limited by the bandwidth of an electrical feedback loop, which remains a challenge to reach the MMW frequency regime.

In this work, we demonstrate a fully integrated photonic microwave/MMW tracking generator, which can have conjugate (two-tone) signal generation with the continuous tuning bandwidth from near dc to the MMW regime. Such a PIC, which includes a wavelength-tunable laser (ring-bus-ring (RBR) or coupled-ring-resonator (CRR) [10], [11]), DFB lasers [12], phase modulators (PMs) [13], and high-speed PDs [6], is demonstrated on the heterogeneous III-V/Si photonic platform. During operation, the two on-chip DFBs are locked by an external OPLL, and the two-tone RF signals from the on-chip fast PDs can be photonically generated through the heterodyne-beating process between the tunable laser and the OPLL outputs. Due to the additional tunable laser in the heterodyne-beating process, the generated frequencies of two-tone RF/MMW signals are limited by the bandwidth of the ultrafast on-chip PD instead of the loop bandwidth in our OPLL. In addition, the frequency separation between the two-tone signals can have a large tunability (from near dc to 10 GHz), which is tracked by the offset locking frequency in our OPLL. Furthermore, fast and truly continuous scanning of photo-generated MMW signals thus becomes feasible by simultaneously tuning the locking frequency in the OPLL and the central wavelength of the tunable laser in the demonstrated PIC. As compared to our previous work [14], the offset locking bandwidth in our tracking signal has been greatly increased from 6 to 10 GHz by improving the loop bandwidth in our OPLL.

II. PIC Structures

Figures 1(a) and (b) show the conceptual block diagram and the picture of the demonstrated PIC chip, respectively. There are three major parts in this chip: the first part is the

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[1]D2-135 offset phase lock servo; Vescent Photonics, Inc. 14998 W 6th Avenue, Suite 700, Golden, CO, 80401

laser source, which is composed of two DFB lasers [12], one CRR tunable laser, and one RBR tunable laser [10], [11]. During operation, we turn on just one of these two tunable lasers and change the resonant frequencies of these rings using integrated heaters. The central wavelengths of the lasers can thus be tuned by Vernier effect [10], [11]. These lasers exhibit excellent performance in terms of a narrow linewidth (∼200 kHz) and a moderate output power (∼10mW) across the entire wide-tuning ranges (∼40 nm) with a high side-mode suppression ratio (>40 dB). The detail on these tunable lasers and their comparison have been published previously [10], [11]. Here, we choose the CRR tunable laser as our light source in our tracking generator. Compared with the DFB laser on the same chip, our CRR tunable laser exhibits a much narrower linewidth (0.2 vs. 2 MHz), which can greatly reduce the phase noise of photo-generated electrical signals during the beating process. The second part is the optical PM for generating modulated signals. By using the combination of quantum-confined Stark effect (QCSE) and plasma dispersion effect in the n-type-doped multiple quantum wells (MQWs) of such a PM [13], we achieve low-driving voltage (V: 4.5 V) and high-speed performance (3 GHz) [13]. The purpose of this integrated optical PM is for generating multi-tone signals for applications to fiber dispersion analysis measurements [15] or advanced modulation formats of a frequency-hopping spread spectrum (FHSS) communications system [16]. The last part of the PIC is a high-speed PD for optical heterodyne-beating signal generation [6]. The PD has an evanescently coupled waveguide structure, which couples the guided optical signal from the buried silicon-on-insulator (SOI) waveguide to the top III-V active absorber, for high-speed, high-efficiency, and high-saturation-power performance. A performance with a nearly 70 GHz 3-dB optical-to-electrical (O-E) bandwidth and a 0.5-A/W responsivity, which covers the range of wavelengths from 1510 to 1610 nm, and with a high saturation current of up to 9 mA has been successfully demonstrated [6].

During the PIC fabrication, three different kinds of III-V-material-based epi-wafers with three different bandgaps of active layers were bonded for the laser, the PM, and the PD, respectively [6]. Figure 2 shows the conceptual cross-sectional view of PIC. The detail about our design of waveguide tapers for the power coupling between the III-V active layers and the SOI waveguide can be referred to our previous work [17].

Tracking generators, which are composed of two (or more) synchronized local oscillators at RF or MMW frequencies, find applications in electrical scalar network analyzers [18] and phase-locked loops in MMW wireless communications systems [19]. Figure 3 shows the conceptual optical and electrical spectra, which are used to illustrate the working principle of the demonstrated tracking generator here. As shown in the optical spectrum, we can lock the lasing wavelengths of two on-chip DFB lasers by use of an external (off-chip) OPLL, which is built by a commercially available servo current source[2]. In the locking process, as shown in Fig. 1 (a), the beat-note (heterodyne beating) signal from our two DFB lasers is fed back to the current source to align with the targeted locking frequency (Δf) setting in our loop.

[2]D2-135 offset phase lock servo; Vescent Photonics, Inc. 14998 W 6th Avenue, Suite 700, Golden, CO, 80401

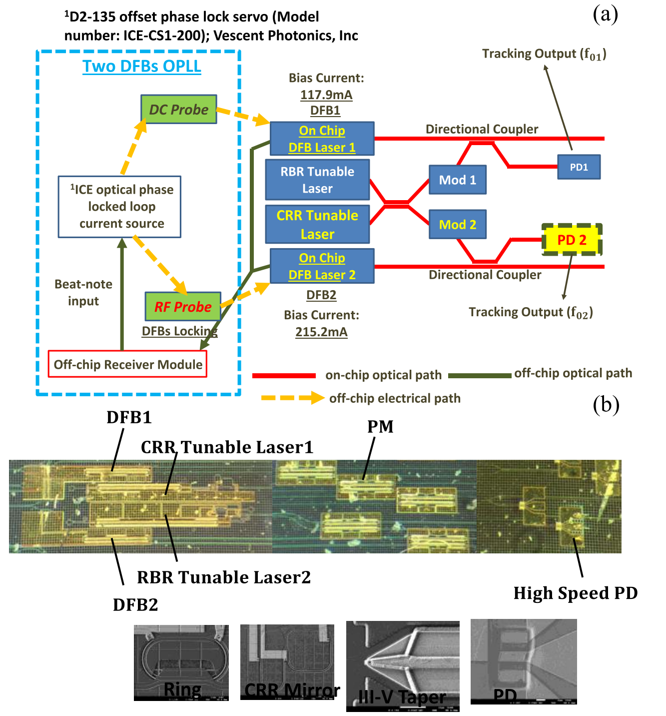

Fig. 1. (a) Functional block diagram of the demonstrated photonic integrated circuit (PIC). (b) Top-view of fabricated photonic micro/millimeter wave tracking generator PIC and Scanning Electron Microscope (SEM) pictures of key parts inside it. CRR: coupled-ring-resonator. RBR: ring-bus-ring. Mod: modulator. PD: photodiode. ICE: D2-135 offset phase lock servo (Model number: ICE-CS1-200); Vescent Photonics, Inc.

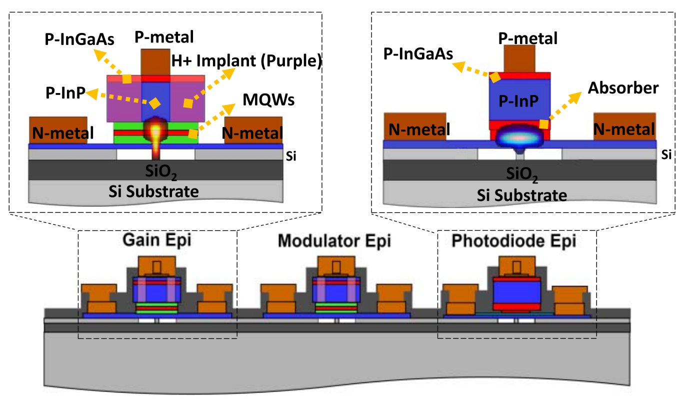

Fig. 2. The conceptual cross-sectional view of demonstrated PIC.

However, there is an intrinsic difference between the lasing wavelengths of such two DFB lasers, which usually corresponds to a beat-note frequency far beyond the loop bandwidth (10 GHz) in our OPLL, and we must feed them different bias currents (215.2 vs. 117.9 mA), as given in Figure 1 (a). This leads to different degrees of thermal-induced wavelength shifts and results in their lasing wavelengths merging together on the optical spectrum. In addition, one port in our current source is for the dc current output, which provides a fixed dc current (117.9 mA) for DFB 1 in our PIC. The other one is the servo port, which feeds DFB 2 in our PIC, as shown in Figure 1 (a), and has the ac+dc current output. Such a time-varying signal output can slightly change the lasing wavelength in DFB 2 and is used to trace the difference in frequencies between the beat-note signal and Δf in our OPLL. With the aid of this servo loop, stable locking can be

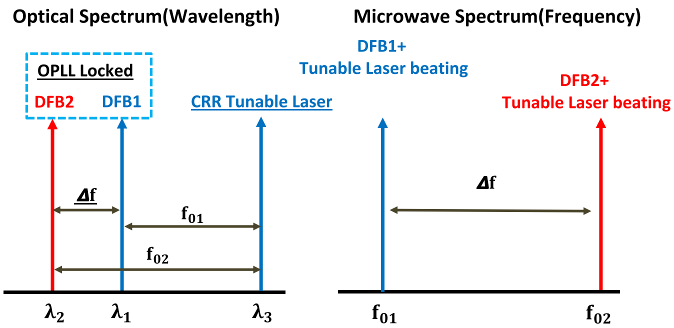

Fig. 3. Conceptual optical and electrical spectra of proposed tracking generator under operation.

sustained [7]. When the locking process is stabilized, we can tune the separation between the optical wavelengths of these two DFBs within the range of 0.3 to 10 GHz, which is limited by the available bandwidth in our current servo source. The two locked optical wavelengths are further combined with the output from the CRR tunable laser and then fed into the on-chip high-speed PD. As shown in the microwave spectrum, we can thus generate a two-tone microwave/MMW signal from PDs through the heterodyne-beating process with these three optical wavelengths.

In addition, as shown in Figure 1 (a), based on our layout of the optical path, the photo-generated two-tone signals (f_{o1} and f_{o2}) could be separately generated from PD 1 or 2, respectively and the difference between these two-tone RF signals ($\Delta f = f_{o2} - f_{o1}$) can be tracked by the OPLL based on the two on-chip DFBs. Here, the values of f_{o1} and f_{o2} shown here are limited by the bandwidth of electrical spectrum analyzer (ESA) used in our experiment, which has a 40 GHz bandwidth (Rhode and Schwartz FSMR43 Electronic Spectrum Analyzer). According to our previous results, which were measured by use of the CRR tunable lasers and free-running DFB lasers on the same chip, higher values of f_{o1} and f_{o2} up to MMW regime (110 GHz) can be generated [6].

III. Measurement Results

Figure 4 (a) shows the measured heterodyne-beating (beat note) RF spectra generated from an off-chip high-speed photoreceiver module (Agilent 11982 A) in our OPLL under different settings of the offset frequency (Δf), which represents the separations of wavelengths of the two-locked on-chip DFB lasers. As can be seen, by controlling the setting values of Δf (0.8-10 GHz), we can sweep the wavelength separations of these two locked on-chip DFB lasers. Compared with the results reported in our previous work [14], here, we have further optimized our OPLL and increased its servo loop bandwidth from around 6 to 10 GHz. Figure 4 (b) shows the measured heterodyne-beating RF spectra of DFB lasers where one is locked to the other. We can clearly see that after locking, there is a narrowing in the measured instantaneous RF linewidth, as expected [7]–[9].

During the tracking generator experiment, we set the optical wavelength separation between the OPLL output and the CRR tunable lasers at around 30 GHz, which is in the range of bandwidth of our ESA (dc to 40 GHz). Figure 5 (a) shows the measured RF spectra of PD 2 under the sweeping of Δf in OPLL from 0.8 to 9.6 GHz. Apparently,

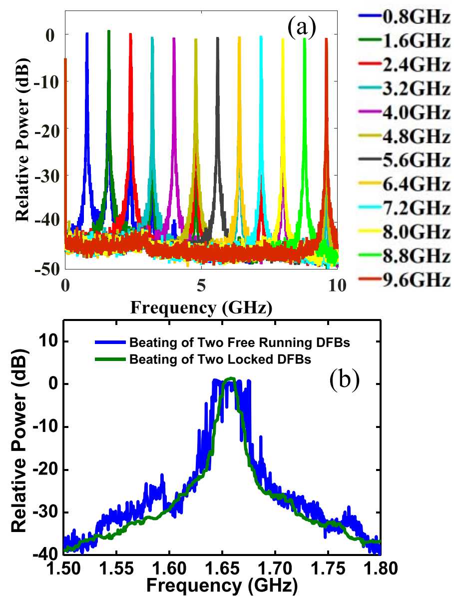

Fig. 4. (a) The measured RF spectrum of beat-note in OPLL of two locked on-chip DFBs at different offset locking frequency (Δf). (b) The measured RF spectrum of beat-note signal before and after OPLL locking.

the beating frequency f_{o2} can be remotely controlled (tracked) by the offset frequency Δf in our two-DFB-locked OPLL. On the other hand, the output from PD 1 (f_{o1}) has a fixed frequency at around 30 GHz under such a Δf sweeping due to that DFB 1 is connected with the dc output port of current source in our OPLL as discussed in Fig. 1 (a). Compared with the heterodyne-beating process using only free-running DFB and CRR lasers, which is difficult to have a mode-hop-free wavelength tuning, the demonstrated tracking generator here has superior performance in terms of a continuous MMW frequency scanning. With the aid of OPLL in our tracking generator, we can choose the desired center MMW frequency by setting the optical wavelengths in our CRR laser and the continuous scanning of MMW frequency becomes feasible by tuning the offset locking frequency in OPLL. In addition, the output photocurrent from our on-chip fast PD 1 or 2 can reach 1∼2 mA during measurements, which corresponds to over −16 dBm output MMW power for the case of 100 % optical modulation depth and under a 50 Ω load. However, the measured power shown on the ESA is far below this level (∼ −40 dBm). This is because that in order to allow the optical wavelengths of three on-chip lasers (two DFBs and one CRR) merge together, we must apply different bias currents on them to have different degrees of thermal-induced wavelength drifts, as discussed in Figure 1. It results in the unbalance of output optical power from each laser and seriously degrades the optical modulation depths. Incorporating the optical amplifiers in the optical paths of our PICs [17] is one possible solution to balance the optical power and enhance both the optical modulation depth with the photo-generated MMW power. Figure 5 (b) shows the comparison of measured output RF spectra from PD 2 with/without tracking operation. For the case of non-tracking operation, we disable the external OPLL and measure the heterodyne-beating signal from the CRR tunable laser and the free-running DFB laser. Although the optical linewidth of

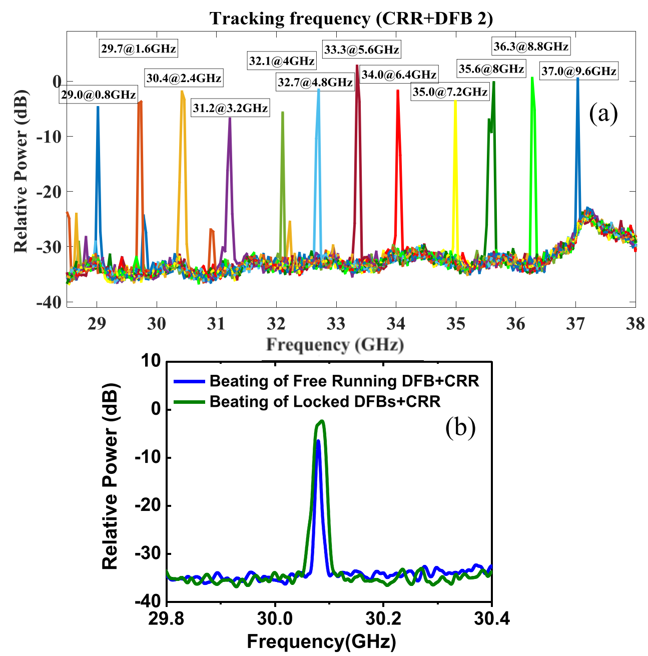

Fig. 5. (a) The measured RF spectrum of tracking generator from PD 2 under sweeping of Δf in OPLL. The central frequency and its corresponding Δf of each RF comb lines are specified. (b) The measured RF spectrum of heterodyne-beating signal from PD 2 with free running DFB and CRR laser and one of the locked DFBs and CRR laser.

CRR tunable laser is as narrow as 200 kHz as discussed [11], the measured instantaneous RF linewidths of both cases are far above this value. In addition, the RF linewidth for the case of non-tracking operation is slightly better than that of the tracking one. These can be attributed to the fact that two on-chip DFBs must be simultaneously turned on for tracking operation and it will lead to a significant thermal-induced optical linewidth broadening on the CRR tunable laser and also its heterodyne-beating microwave signals with the DFB lasers. During the measurement of optical linewidth of the CRR tunable laser, we just need to turn on a single laser and the problem of thermal cross-talk among different on-chip lasers can thus be eliminated. Etching to remove most of the Si layer between the lasers is needed to minimize the thermal cross-talk in the PIC [20]. In addition, integrating our PIC with an on-chip wavelength meter and an external control circuit is one attractive approach to further reduce the phase noise of photo-generated MMW signal [21].

IV. Conclusion

A fully integrated photonic microwave/MMW tracking generator is demonstrated. A two-tone RF signal with the central frequency at around 30 GHz and a wide tunability in its difference frequency that can be tracked by an OPLL is driven by two on-chip DFBs. The generated conjugated/two-tone RF signal from such a PIC chip can find applications for tunable microwave generators, for fiber dispersion analysis and other applications. Furthermore, by tuning the offset locking frequency in OPLL, the mode-hopping problem in tunable lasers during wavelength sweeping can be eliminated and the continuous and fast frequency scanning of the photo-generated MMW signals become feasible.

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