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On the design and characterization procedure of 300-GHz slotline-coupled oscillators in CMOS

Marta Ferreras
Information Processing and Telecommunications Center
Universidad Politécnica de Madrid
Madrid, Spain
marta.ferreras@upm.es

Jesús Grajal
Information Processing and Telecommunications Center
Universidad Politécnica de Madrid
Madrid, Spain
jesus.grajal@upm.es

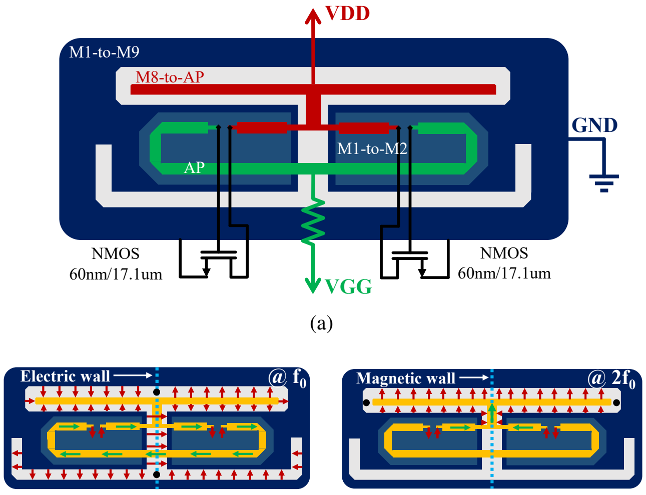
***Abstract*—This contribution reports on a submillimeter-wave source consisting of two mutually coupled harmonic oscillators in CMOS that emit coherent radiation at 300 GHz. The unitary oscillator cell uses a differential self-feeding topology which incorporates an on-chip integrated folded-slot antenna for second-harmonic radiation. To increase the radiated power, two free-running oscillator units are injection-locked by each other through their respective slotline resonators. In this case, a standing wave is sustained across the array with a virtual short circuit at the connection point. Both, the single and the two-coupled oscillator were prototyped in commercial 65-nm CMOS technology. In combination with a silicon lens, the measured samples produced linear-polarized radiation above 290 GHz with frequency tunability exceeding 10 GHz and 6 GHz for the single and the double oscillator designs, respectively.**

***Index Terms*—CMOS, co-simulation, harmonic oscillator, MMIC, standing-wave oscillator (SWO), terahertz, voltage-controlled oscillator (VCO)**

I. INTRODUCTION

The commercial exploitation of terahertz (THz) and submillimeter-wave technology is still hindered by the lack of affordable powerful sources. In this context, the miniaturization of silicon transistors opens the possibility of developing submillimeter-wave sources in cost-effective silicon process technologies like CMOS or BiCMOS. Moreover, since the operation wavelength is smaller than the typical size of the dies, distributed passives and antennas may also be integrated on chip, thus reducing losses and uncertainties [1], [2].

Focusing on self-sustaining sources, the power available from a single CMOS oscillator is still scarce for most THz applications. A promising solution involves the implementation of scalable 2D arrays comprising a large number of synchronous low-power CMOS radiators that combine their power coherently in free space [2]–[4]. Following this idea, this paper first tackles the design of a 300-GHz free-running voltage-controlled oscillator (VCO) emitter based on CMOS. Since the maximum oscillation frequency (f_{max}) of the used technology is below the target frequency, the desired radiation arises from the second harmonic of an oscillation at 150 GHz [5]. To increase the radiated power, a distributed standing-wave oscillator (SWO) source based on mutually coupled self-feeding oscillators is also proposed. In this case, the oscillator units operate synchronously at the fundamental frequency and radiate coherently the second harmonic power at 300 GHz via closely spaced on-chip antennas [6]. Both designs have been prototyped using the 65-nm CMOS technology from TSMC foundry and then experimentally characterized.



(a)

(b)

(c)

Fig. 1. Topology and operation principle of the stand-alone oscillator [5]: (a) layout with details on the transistor connections and the used metal layers (M1 to M9, and AP) of the CMOS stack, (b) electric field (E-field) propagation at the oscillation frequency (f_0), and (c) E-field propagation at the radiation frequency ($2 \cdot f_0$). The black dots indicate the position of stationary nulls of E-field. The layout occupies $362 \times 208\,\mu m^2$.

II. ELECTROMAGNETIC DESIGN

A. Stand-alone Oscillator

Figure 1(a) depicts the proposed CMOS radiative source. It consists of a pair of transistors fed back from the drain to the gate [2], [3], which oscillate differentially at f_0=150 GHz. The NMOS transistors were chosen with 14 fingers each, gate length of 60 nm, and gate width of 1.22 µm/finger. The positive feedback path to achieve close-to-optimum voltage gain at f_0 has a total electrical length of 81° at 150 GHz and it was realized using a 56-Ω grounded coplanar waveguide

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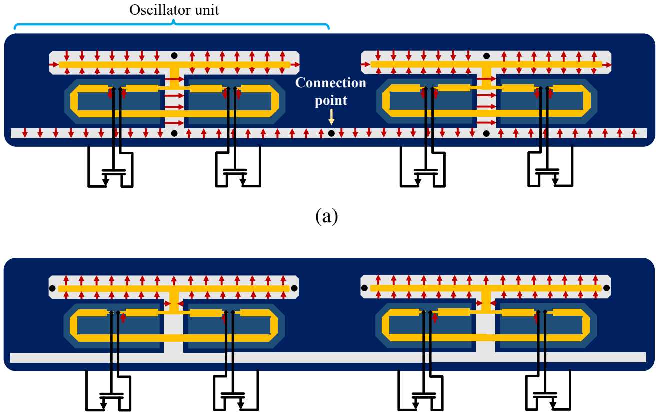


(a)

(b)

Fig. 2. Topology and operation principle of the array of coupled oscillators [6]: (a) electric field (E-field) propagation at the oscillation frequency (f_0), and (b) E-field propagation at the radiation frequency ($2 \cdot f_0$). The black dots indicate the positions of stationary nulls of E-field. The layout occupies $722 \times 208\,\mu m^2$.

(green in Fig. 1(a)). The vertical slotline section ensures that the feedback path only exists if the transistors operate in differential mode (Fig. 1(b)). Hence, the second-harmonic drain signals (at $2 \cdot f_0$) are generated in phase and may only propagate towards the upper slotline resonator (Fig. 1(c)), which was specifically shaped as an antenna with resonance at approximately 300 GHz.

It is noteworthy that the proposed emitters are fully compliant with all design rules of the used CMOS technology. To enforce CMOS metal density rules, most passives are implemented as slots etched into a thick radiofrequency (RF) ground plane formed by all the metal layers of the process shunted together with on-chip vias. To avoid disturbing the oscillation activity, the required DC biasing for the RF transistors is applied through the layout's symmetry plane.

B. Linear Array of Coupled Oscillators

As shown in Fig. 2(a), two identical adjacent oscillator units can be injection-locked by each other by connecting together their (originally) short-terminated slotline resonators [4].

By symmetry, the steady state of the system occurs for either in-phase or out-of-phase coupling of the units [3]. The desired out-of-phase mode in Fig. 2(a) would lead to a virtual short circuit at the connection point. This node ensures that the transistors operate under the same impedance boundary conditions as if they were isolated, with the compound sustaining a distributed standing-wave at 150 GHz. In contrast, the in-phase mode of the array (not shown) cannot sustain an oscillation, as the loop gain of the system falls below unity at all frequencies. Moreover, our simulations suggest that the out-of-phase mode is also the only stable mode able to sustain an oscillation when the number of horizontally coupled units increases. This is because the used oscillator topology presents negative resistance only in a narrow band around the desired oscillation frequency of 150 GHz [4].

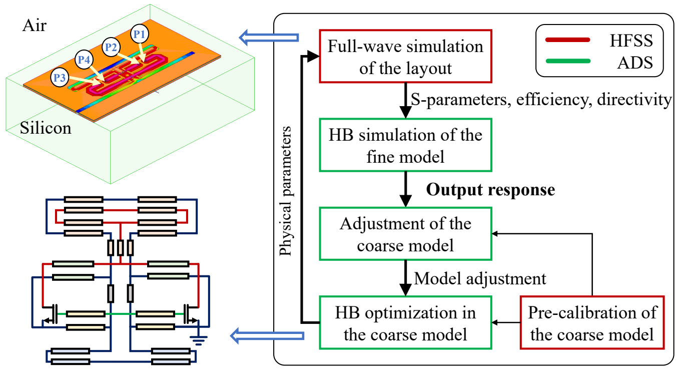


Fig. 3. Scheme of the space-mapping technique used for optimization.

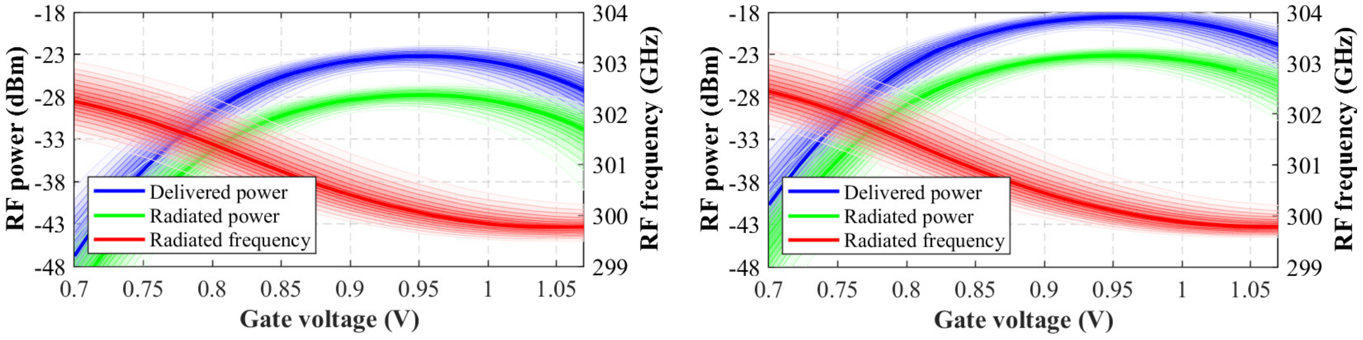
SWOs have the property that even harmonics are generated in phase regardless of the extraction point [4]. Consequently, the second-harmonic drain content generated by each oscillator cell would be delivered in phase to the on-chip slot antennas to be combined constructively in free space (Fig. 2(b)).

C. Simulation and Optimization

The active and passive elements of both oscillator designs were co-simulated and co-optimized together in the Keysight ADS environment through harmonic balance (HB) simulations. In particular, the nonlinear transistor behavior was modeled using the foundry-provided models, while the passive electromagnetic (EM) structures were simulated with the Ansys HFSS 3D EM solver. The on-chip slot antennas in this design radiate primarily towards the silicon substrate side of the die, requiring an additional silicon substrate lens to mitigate substrate-wave propagation [1], [7]. To account for the substrate-wave reduction by this lens, in HFSS, the layout was placed between air–silicon half-spaces terminated by radiation boundaries. The lens impact on the antenna patterns and radiation efficiency was addressed afterwards via the geometric optics solution [7].

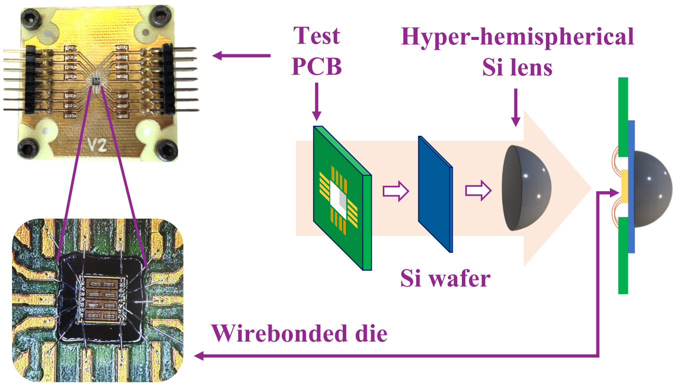
The optimization was carried out in ADS following the conventional double-model strategy employed in space-mapping optimization techniques (Fig. 3). This approach involves the utilization of a fast model ("coarse model") based on pre-calibrated models for the transmission lines and resonators, and a high-precision but computationally expensive model ("fine model") based on full-wave HFSS simulations of the complete layout. The optimization process follows an iterative approach, starting with the optimization of the coarse model to find the physical dimensions of the layout. Then, the layout is solved in HFSS and the solution is imported into ADS to yield the final response of the harmonic oscillator. The iteration process continues with an intermediate step where the coarse model is fine-tuned to locally align the coarse model solution to the specific full-wave response of the previous iteration.

Figure 4 presents the simulated output radiation for both VCO designs as a function of the gate voltage. The power delivered to the on-chip antennas (blue curves) is ~4.5 dB larger than the power actually radiated by the chip+lens as-



(a) (b)

Fig. 4. Simulated second-harmonic radiation of the CMOS emitters: (a) stand-alone oscillator, and (b) two-coupled oscillator. Drain voltage is fixed at 1.2 V. The shaded areas indicate the confidence intervals of a Montecarlo analysis with ×1000 trials, where the transistor parameters were randomly varied according to the default statistics preconfigured in the foundry-provided PDK.



(a) (b)

Fig. 5. Assembly of the source module for testing: (a) photographs of the die and the test PCB, and (b) scheme of the assembling procedure.

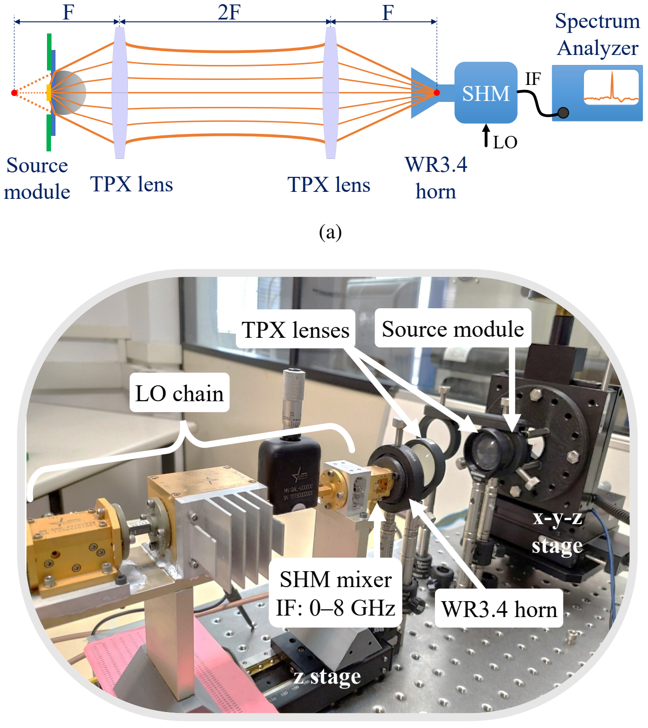
sembly (green curves). This calculation considers the antenna radiation efficiency, the loss in the low-resistivity substrate of the die, and the Fresnel reflection loss at the lens-to-air interface. With an uncoated hyper-hemispherical silicon lens attached to the backside of the chip, the stand-alone and the two-coupled oscillators are expected to radiate approximately −27 dBm and −23 dBm at 300 GHz, respectively.

III. Experimental Characterization

A. *Measurement Setup*

Various oscillator designs were prototyped in a $1 \times 1\,\mathrm{mm}^2$ die and fabricated using the commercial 65-nm CMOS process from TSMC foundry. For testing, first, the die was wirebonded to a custom printed circuit board (PCB) (Fig. 5(a)). Then, the assembly was backed by a hyper-hemispherical silicon lens (Fig. 5(b)) and mounted on an x-y-z translation stage. Before taking any measurement, the lens position was mechanically optimized with respect to the phase center of the active circuit by searching the peak radiation in the broadside direction.

The prototypes were characterized at room temperature using the subharmonic-mixer (SHM) setup depicted in Fig. 6. The TPX lenses collected the emitted RF power, enabling that the generated linear-polarized radiation could be acquired at intermediate frequency (IF) using a spectrum analyzer.



(a)

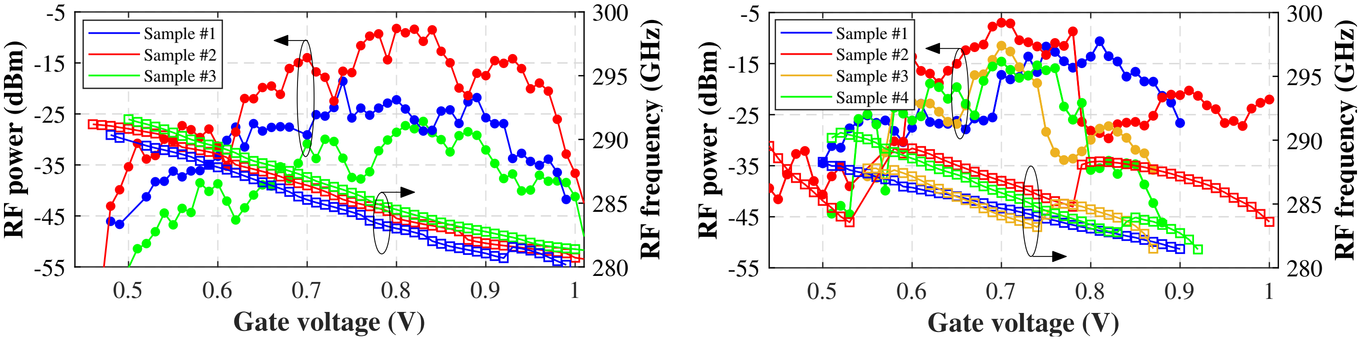
(b)

Fig. 6. Optical measurement setup: (a) scheme, and (b) photograph.

B. *Measurement Results*

The measured RF power and frequency emitted by various samples of the stand-alone and the two-coupled oscillator prototypes are presented in Figs. 7(a) and 7(b), respectively.

Both CMOS circuits exhibit linear frequency curves with good chip-to-chip repeatibility within a limited gate biasing range where all the involved transistors are fully injection-locked. The frequency discontinuities observed for the two-coupled oscillator design (Fig. 7(b)) arise from injection-



(a)

(b)

Fig. 7. Measured second-harmonic radiation of several samples of the prototyped CMOS emitters: (a) stand-alone oscillator, and (b) two-coupled oscillator. Drain voltage is fixed at 1.2 V. The measured power has been integrated in an 8-MHz resolution bandwidth. The setup losses have been corrected.

pulling phenomena, implying that the coupled oscillators are not fully synchronized. The stand-alone oscillator achieves a maximum radiation frequency of 291.6 GHz (Fig. 7(a)), while the two-coupled oscillator reaches 290.6 GHz (Fig. 7(b)). This is only a ∼3.1% frequency offset from the target of 300 GHz. Moreover, it can be observed that the tuning frequency range extends beyond 10 GHz and 6 GHz for all stand-alone and two-coupled VCO prototypes, respectively.

Since the emitters have a radiative interface, the radiated power can only be measured after it has suffered the losses from the integrated antenna, the lossy chip substrate, and the hyper-hemispherical silicon lens. Thus, the power measurements in Fig. 7 shall be compared to the simulated “radiated power” curve in Fig. 4. Noteworthy, one may observe relatively large power differences between samples. These might originate from the delicate manual procedure used to assemble each sample on the lens module (see Fig. 5(b)). The highest measured power is −8.2 dBm for the stand-alone design (Fig. 7(a)) and −7 dBm for the two-coupled oscillator emitter (Fig. 7(b)). Even for the samples with average performance, the measurement significantly exceeds the power values expected from simulation (Fig. 4). We hypothesize this behavior can attributed to limitations in the transistor modeling provided by the foundry for frequencies beyond the $f_{\max}$ of the RF transistors. For the best performing samples, the DC-to-$2\cdot f_0$ conversion efficiency reaches 1.04% and 1.11%, respectively.

Due to a lack of appropriate equipment, we have not yet been able to characterize the spatial distribution of the emitted radiation. Our simulations indicate the directivity is higher than 20 dBi and 23 dBi for the stand-alone and the two-coupled oscillators, respectively.

IV. CONCLUSIONS

We have reported promising results for the development of low-cost CMOS sources of 300 GHz radiation fully compliant with industrial fabrication. In particular, two CMOS harmonic oscillator designs have been presented: the first was a 150-GHz self-feeding oscillator attached to a 300-GHz on-chip slot antenna [5], and the second consisted of two injection-locked oscillators combining their output radiation in free space [6].

The characteristics of the emitted radiation were verified via wireless measurements. All measured samples operated at less than a 4% offset from the target frequency of 300 GHz: an outstanding result for the initial fabrication trial. The unitary source delivered stable oscillation from ∼281 GHz to ∼291 GHz, with peak measured power of −8.2 dBm. This is 5.5 dB lower than the state of the art [8], [9]. In comparison, the two-coupled oscillator exhibited peak radiation of −7 dBm, with frequency tunability of beyond 6 GHz. Thus, the expected improvement of ∼4 dB with respect to the unitary oscillator was not attained. The variability in measured power among samples suggests uncertainties in the characterization method. Therefore, a careful assessment of the die assembling and optical alignment methods is still required.

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