Sub-THz Beam-forming using Near-field Coupling of Distributed Active Radiator Arrays

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***Abstract* — The paper demonstrates Distributed Active Radiator (DAR) arrays as a novel way of beam-forming at sub-THz frequencies in CMOS. Near-field coupling is shown to be a scalable method for mutually locking multiple DARs to beam-form and generate high EIRP. As proofs of concept, 2x1 and 2x2 arrays of DARs, mutually synchronized through near-field coupling, are implemented in 65nm bulk CMOS. The paper also shows beam-forming near 200GHz for the 2x2 array with broadside EIRP of -1.9 dBm, total radiated power of 54 µW and beam-scanning range for approximately ± 30° in each of the two orthogonal directions in 2D space.**

***Index Terms* — CMOS, terahertz, sub-millimeter wave, radiation, near-field, oscillator, beam-steering, doubler, VCO.**

I. Introduction

Fully integrated terahertz systems in CMOS can provide significantly lower cost alternatives to current technology and could revolutionize, in among other things, communication, computation, security, medical diagnostics, global environment monitoring and industrial safety. However, generation of high enough THz power in silicon has been a major bottleneck and meeting the challenge requires rethinking of system design from fundamentals.

In our previous work [1], we showed how a holistic approach to system design and removal of the various artificial levels of partition in conventional design strategies, such as electromagnetics, circuits, device physics, radiation opens up a new design space [2]. The Distributed Active Radiator (DAR), presented as an example, combined signal generation, frequency multiplication, quasi-optical filtering and desired harmonic radiation in the same electromagnetic structure [1]. This allowed generation of three orders of magnitude more radiated power at THz frequencies in CMOS than previously reported [3]. DAR decouples power scaling from efficiency, removes the need for additional circuitry for filtering and matching network and has very low power lost to substrate modes. This enables us to achieve such high DC to THz conversion efficiency without the need of expensive post-processing such as substrate thinning or the use of external silicon lens [4].

In DAR, therefore, we have a highly efficient radiating THz source and in theory, many such DARs can be potentially coherently locked to achieve higher THz power and much higher EIRP. While transmission line based coupling was employed in [1] to synchronize a 2x2 array to achieve an almost 1 mW EIRP at 0.3 THz, a larger array of coherently locked 10x10 DARs is required to generate near 500mW EIRP. The physical layout constraints make it difficult to scale transmission line based locking to such large arrays. It also restricts the spacing of DARs in 2D arrays which should be optimized for partial cancellation of the dominant TM_0 substrate mode for higher radiation efficiency.

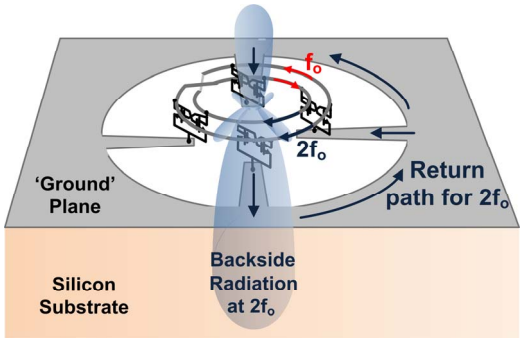

Fig 1. Working principle of Distributed Active Radiator (DAR).

In this paper, we extend the philosophy of holistic system design, and present a method to exploit near-field electromagnetics to coherently lock DARs and beam-form at sub-THz frequencies. This method is truly scalable since it removes the task of synchronization from the DARs to another level of abstraction, as explained in Section III. As proofs-of-concept, we demonstrate 2x1 and 2x2 arrays of locked DARs, using near-field sensing and coupling, which radiate at 198 GHz and 191.2 GHz with a boresight EIRP of -9.2 dBm and -1.9 dBm respectively. The 2x2 array has additional varactor tuning which allows beam-forming at 191.2 GHz with a measured scanning range of approximately ± 30° in each of the two orthogonal directions in 2D space.

II. Distributed Active Radiator (DAR)

The DAR sustains a fundamental oscillation at a design frequency near f_{max},and while doing so, efficiently radiates out the second harmonic, quasi-optically cancels the first harmonic, enabling harmonic generation, radiation, filtering in a low-loss compact footprint, without any external lens [4].

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Fig. 1 shows the principle of operation of a DAR. DAR consists of a mobius metallic strip with cross-coupled pairs that sustains a traveling wave oscillation at a designed fundamental frequency. As the wave at the fundamental mode travels along the loop, it generates harmonics due to the nonlinear capacitance and transconductance. DAR extracts these harmonics very efficiently and filters quasi-optically the undesired fundamental mode through a careful manipulation of current loops at different harmonics. In this implementation, we are interested in the second harmonic radiation in order to achieve efficient doubling.

If observed carefully, the first harmonic currents, in the two adjacent branches of the mobius loop, are out of phase, since one is the return current of the other. Such closely placed out-of-phase currents ensure that radiation at the first harmonic is minimal, thereby achieving low-loss filtering of the undesired first harmonic without additional circuitry. The second harmonic currents, in both the branches, however travel in the same direction and therefore reinforce each other's radiated fields. The return currents of the second harmonic go through the ground plane (connected to the sources of the cross-coupled transistors) which is removed from underneath as shown in Fig. 1. This separates and phase-rotates (by 90°) the second harmonic return current from the forward current facilitating efficient radiation of the second harmonic as illustrated in Fig. 1. The same mobius strip therefore acts as a coplanar stripline at the first harmonic and distributed radiator at the second harmonic. No additional matching or filtering circuitry is therefore needed. In this implementation, the fundamental oscillation frequency is designed to be 100GHz, with desired radiation at 200GHz.

DAR is particularly suitable for integrated implementation. The radiating traveling wave generates circularly polarized radiation leading to a 54% simulated radiation efficiency at 200GHz over a 300μm thick silicon substrate of 10 ohm-cm resistivity without using external lens, compared to 5-10% of that of a dipole supported by a silicon lens [4]. Radiation occurs primarily from the backside due to the high dielectric constant of the silicon substrate. Unlike a conventional system, signal is not generated in a block and then propagated with loss to the lossy radiating element. In DAR, everything happens at the same place and at the same time which enables it to achieve high harmonic conversion and radiation efficiency at sub-THz frequencies.

III. Near-field Coupling, Beam-Forming and Bias

DARs are particularly suitable for implementation in 2D arrays where many such DARs can be locked to generate higher power with higher EIRP. Having phase control in each element also gives an additional possibility of beam-forming.

A. Near-Field Sensing and Locking

In order to coherently lock two DARs. the phase of the fundamental frequency at each corresponding point on both the DARs has to be same. In this section, we show how co-design of circuits and electromagnetics together can help us develop a truly scalable method to synchronize large arrays for coherent combination in space.

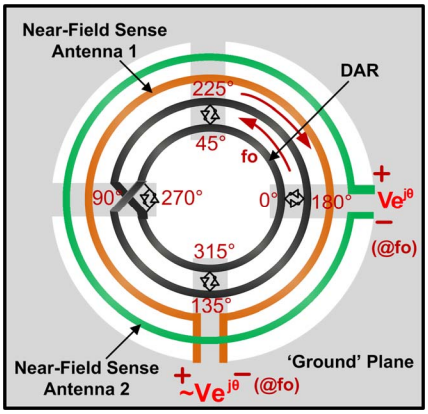

Fig 2. Near-field sense antennas for coherent locking of DARs.

Imagine two uncoupled oscillators running at similar frequencies and radiating power at their fundamental frequencies, each radiated signal being picked up by separate receiver antennas. The received signals, therefore, have one-to-one relationships with the phase and frequency of the corresponding radiating oscillator. Now, instead of physically coupling the two oscillators, if the receiver antennas are coupled together with suitable impedance, then the parent oscillators can be made to 'wirelessly' lock to each other if the radiative coupling is strong enough. This removes the locking mechanism to a different level of abstraction allowing independent optimization and placement of the power generating elements while synchronization happens wirelessly at the 'background'. This is unlike other radiative coupling methods where radiating oscillators are constrained to be placed in close proximity to ensure locking [5].

A DAR, however, as explained in Section II, quasi-optically filters off the fundamental power, in the far-field at distances much greater than the wavelength. However, in the near-field, the two out-of phase fundamental currents in the adjacent branches do not cancel off their fields. The near-field zone within the silicon die contains rich information about phase and frequency of DAR operation and this is used to synchronize and beam-form at sub-THz frequencies.

Two antennas which sense the near-field at the fundamental frequency are placed close to the DAR as shown in Fig 2. Since the voltage at the sense antenna terminal is proportional to the time derivative of the coupled magnetic flux, rotating a sense antenna about the boresight axis, does not affect the terminal voltage. In order to lock adjacent DARs, the sense antennas are coupled to each other as shown in Fig. 3. The resistor values are chosen to maximize the power dissipated in the sense loops under unlocked condition.

This makes all unlocked conditions unstable and the lowest energy state of the system is when both the DARs sustain traveling waves in the same direction and each corresponding point has exactly the same phase. The system will finally settle down to this state even if it starts from a different initial condition.

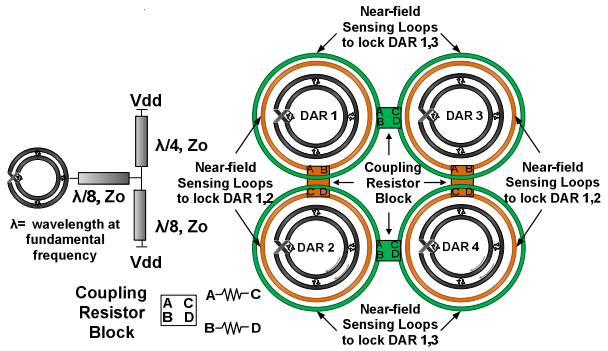

Fig 3. Bias network and mutual locking mechanism using near-field coupling for locking and beam-forming for 2x2 array.

It should be emphasized that this form of distributed coupling is very different from lumped transformer coupling, since the phase of the fundamental frequency changes by almost 180° over the sense antenna circumference. The traveling wave structure in DAR requires careful scrutiny to avoid false locking. If the DAR were a single loop sustaining a radiating traveling wave, then the near-field distribution in space at any time is essentially a rotational transformation of the field configuration at an earlier time about the boresight axis. For such a structure, the magnetic flux would have been constant over time. However, the inherent asymmetry of the two branches of the DAR with respect to the sense loop antenna at the first harmonic, and the cross-over in the DAR, make the magnetic flux and therefore the sense antenna voltage periodically change at the fundamental frequency. If carefully observed, it can be shown that only two possible fundamental current distributions over the DAR, traveling in opposite directions, have similar signatures on the terminal voltage of the sense antenna. However, simulations show inherent substrate coupling makes the coherently locked state the preferred state and under proposed coupling, all the DARs combine coherently in space under locked condition. This is also confirmed by measurements of polarization of the radiated beam.

Each DAR is biased using a t-line network which does not load the DAR at both the fundamental and second harmonic as shown in Fig 3.

B. Beam-forming

Beam-forming is included in the 2x2 array by adding varactor tuning element with each cross-coupled pair in each DAR. When the natural resonant frequency of each DAR is changed, coupling due to the near-field sensor antennas causes the DARs to pull toward a common frequency. This causes an additional phase shift in each element within the locking range which is exploited in beam-forming. The 2x2 array can steer the beam independently in 2D space, with individual control over resonant frequency of each DAR. The simulated locking range is 3.9 GHz with a beam-steering capability of ± 35° in two orthogonal directions.

IV. Measurement Results

The chip is implemented in 65nm bulk CMOS with an estimated f_{max} of near 200 GHz with 3.25μm thick Cu layer.

The die micrographs of the 2x1 array and 2x2 array with varactors are shown in Fig. 4. The measurement set-up is shown in Fig. 5. Radiation is captured from the backside of the chip through the 300μm thick silicon substrate. No external lens is used to correct for substrate modes.

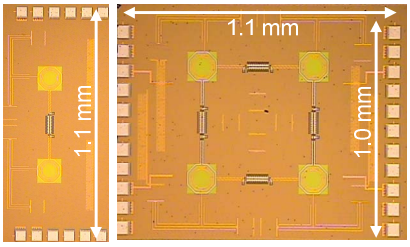

Fig 4. Die photos of 2x1 and 2x2 arrays of DARs.

The radiation from the backside is captured by WR-5 (140-220 GHz) antenna and then down-converted by a harmonic mixer by the 10th harmonic of the LO. The IF is amplified by LNAs and analyzed in a spectrum analyzer. The whole set-up is calibrated using a calorimeter based Erickson power-meter which gives absolute power measurements from 75-2000 GHz. Each DAR is biased at 0.8V drawing 24mA of current. The total radiated power is calculated from the measured radiation pattern, while the EIRP is enumerated directly from the power measured at the far-field (at d=20mm) by the 25dB gain standard horn receiver antenna.

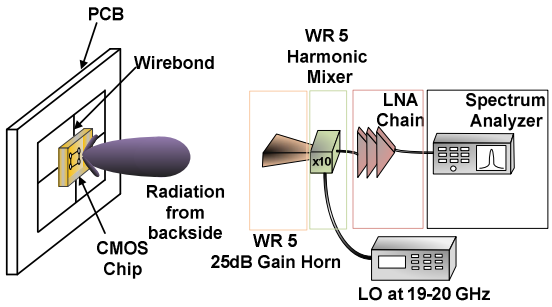

Fig. 5. Measurement setup.

For the 2x1 array, power is detected at the second harmonic frequency of 198 GHz. The radiation pattern is shown in Fig. 6. The measured boresight EIRP is -9.2dBm. The total radiated power, is 24 µW and the boresight directivity is 7dBi. The beam is verified to be almost circularly polarized.

For the 2x2 array with varactors, radiation is detected at 191.2 GHz at the nominal tuning. The calibrated THz spectrum for the locked array at a far-field distance of 20mm is shown in Fig 7. When the array goes out of locking range the spectrum splits as also shown in Fig 7. The array is capable of beam-forming in 2D space as illustrated in Fig. 8, which shows the far-field radiation patterns in the two orthogonal directions for the center frequency and at the edges of locking range. The locking range is measured to be 3.6 GHz with a scanning range of approximately ± 30° in each direction. In the broadside setting, the total radiated power is measured to be 58 µW with a net EIRP of -1.9 dBm. The radiated beam is also nearly circularly polarized.

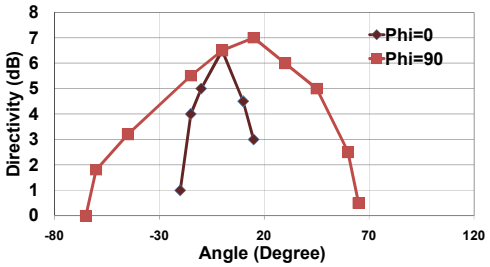

Fig. 6. Measured far-field radiation pattern at 198 GHz for the 2x1 array in the two orthogonal planes.

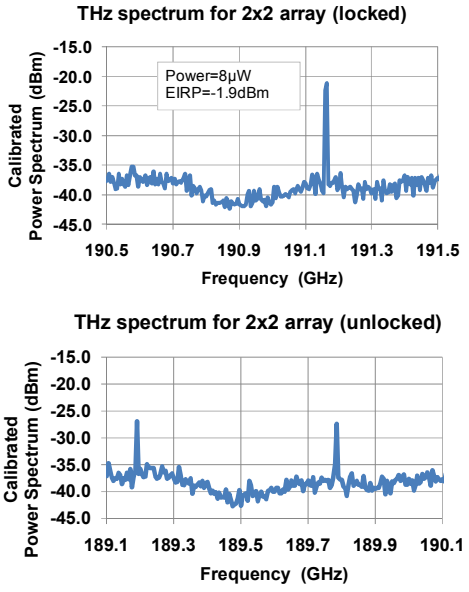

Fig 7. Detected far-field (d=20mm) output spectrum for the 2x2 array under locked and unlocked conditions at the 25dB gain standard horn receiver antenna.

V. CONCLUSION

Array of mutually locked DARs is shown as a novel method of beam-forming in CMOS which combine harmonic generation, radiation, filtering in the same electromagnetic structure, without using any silicon lens. Near-field coupling is proposed as a scalable method of mutually locking multiple DARs for 2D array implementation for generating high EIRP in sub-THz frequencies. Beam-forming is demonstrated near 200 GHz in 65nm CMOS for a 2x2 array with a broadside EIRP of -1.9 dBm, total radiated power of 54 µW and a beam-scanning of ± 30° in each of the two orthogonal directions in 2D space.

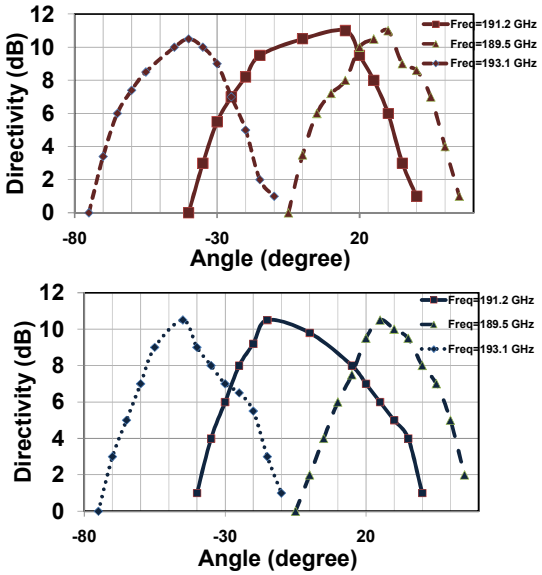

Fig. 8. Measured far-field radiation pattern and beam-forming at 191.2 GHz for the 2x2 array in the two orthogonal planes at φ=0° and φ=90° respectively.

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