Distributed Active Radiator Arrays for Efficient Doubling, Filtering, and Beam-forming

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***Abstract* — Distributed Active Radiator (DAR) arrays are demonstrated as novel ways of harmonic generation, radiation, and filtration to generate power at frequencies above the cut-off frequency of a technology. As proofs-of-concept, 2x1 and 2x2 arrays of DAR with beam-forming are implemented on PCB, which are designed to oscillate at the fundamental frequency of 1.25GHz, while radiating (circularly-polarized) at the doubling frequency of 2.5GHz. The measured EIRP of 2x1 and 2x2 arrays are 7.46dBm and 12.96dBm, respectively, at 2.5GHz with a DC-to-radiated 2^{nd} harmonic conversion of 0.8%. Almost 40° of beam-steering at 2.5GHz was measured in 2D space for the 2x2 array and more than 15dB suppression of the first and third harmonic compared to the desired second harmonic was measured in the radiated far-field.**

***Index Terms* — distributed active radiation, doubling, antenna, on-chip radiation, mutual locking, phased array, beam steering**

I. INTRODUCTION

Efficient generation of RF signal, at frequency above the cut-off frequency of a technology, has always been of interest to designers, either in the integrated or discrete form of implementation [1-3]. The problem definition is very general and even though design solutions may be tailored towards the absolute frequency of operation, some of the innovations can be applied to a wide variety of technologically challenging problems. Such efficient generation of high-frequency signals above the f_{max} of a technology would allow the state-of-the-art processes in silicon, to break the THz barrier and realize fully integrated THz systems in CMOS. It can also potentially allow cheaper integrated technology to be used in many higher-frequency applications, cutting down a major fraction of the production cost.

There are two equally distinct components of signal generation, namely, power generation at the desired RF and coupling of the signal to the external world in an efficient way, that need to be addressed [1]. Traditional design methodologies have kept the partitions separate, whereby a power generating block is designed independently from the radiating element, only accounting for the loading effect. In the end, the two components are connected together, either directly or through a matching network. Such an artificial partition leads to a sub-optimal design space, and in this paper, we show an example of how removing these boundaries between these self-imposed layers of abstraction, such as circuits, EM, and antenna, leads to a novel architecture that is capable of solving many of the short-comings of the more conventional checkered approaches [4].

Traditional ways of generating high-frequency signal above the f_{max} of devices have been to generate a lower frequency signal, multiply the frequency through nonlinear devices, and then radiate out using conventional tuned antennas [3]. Such is the case of diode multipliers, push-push oscillators, or nonlinear transmission lines, where part of the energy from the fundamental gets converted into desired higher frequency mode. However, due to the significant losses in the matching network and varactors and in the additional filtering required to remove the harmonics, the conversion efficiency of such methods is considerably poor. They also suffer from a lack of power scalability due to parasitic scaling. In integrated implementation, this is further exacerbated by the leaky substrate modes of integrated antenna and sensitivity to modeling inaccuracies due to the narrow band matching between the antenna and the power generating element.

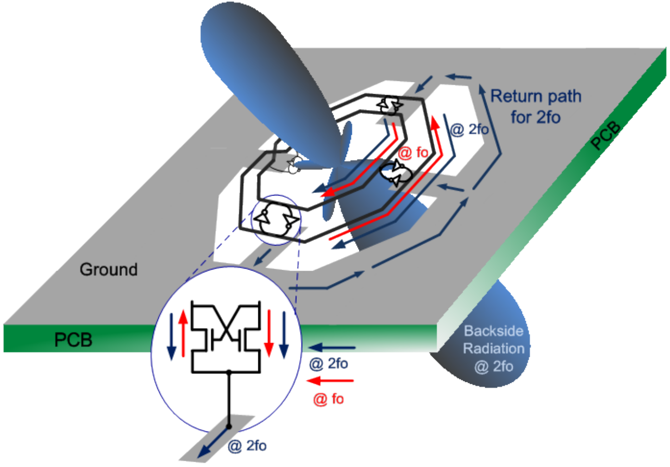

Fig. 1. Configuration and working principle of Distributed Active Radiator (DAR).

In this paper, we present a discrete implementation of a novel approach for harmonic generation, radiation, and filtration, which we call Distributed Active Radiator (DAR), as shown in Fig. 1 [1]. The single electromagnetic structure sustains a traveling wave oscillation at the fundamental frequency of 1.25GHz, radiates the second harmonic efficiently at 2.5GHz, and quasi-optically cancels the first and all odd harmonics to achieve efficient doubling, filtration, and radiation in a compact low-loss footprint. The concept of distributed radiation is particularly suitable for integrated implementation as explained in the following sections. In this paper, we present an array of DARs with beam-forming functionality. The implemented 2x1 and 2x2 arrays achieve a DC to total 2^{nd} harmonic radiated power conversion efficiency of around 0.8%, 7.46dBm and 12.96dBm of EIRP at 2.5GHz, respectively, and the 2x2 array is capable of nearly 40° degree of beam-steering in two orthogonal directions.

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The quasi-optical filtering also results in more than 15dB suppression of the first and third harmonic, showing the effectiveness of DAR in efficient second harmonic generation (doubling), radiation, and filtering.

II. BEAM-FORMING WITH DISTRIBUTED ACTIVE RADIATOR

A distributed active radiator, shown in Fig. 1, takes a distributed approach to signal generation and radiation, thereby decoupling the problems of power scaling and sensitivity from mismatch, modeling inaccuracies, and frequency of operation. This also enables implementation of 2D arrays where a number of such radiators can be synchronized, leading to an almost lossless quasi-optical power combination and high EIRP. In this implementation, we also demonstrate phase control in 2x1 and 2x2 arrays of mutually locked DARs to achieve beam-forming.

A. Distributed Active Radiation (DAR)

The principle of operation of a DAR is shown in Fig. 1. Generation of RF signal at frequency above the f_{max} of a technology necessarily relies on harmonic generation through device or varactor nonlinearities. DAR extracts this inherent nonlinearity generated very efficiently through a close-knit association of signal generation and radiation.

Two closely spaced current elements which are opposite in phase cancel off radiation in far-field and therefore is a poor radiator, while two elements in phase coherently add their radiated fields. This is achieved in DAR by ensuring that the currents at the fundamental frequency are always opposite in phase, thereby achieving quasi-optical suppression of the first harmonic [1]. The mobius loop structure with distributed cross-coupled transistors sustains a rotary traveling-wave oscillation at the fundamental frequency with metal lines behaving as coplanar striplines as shown in Fig. 1 [5]. As the fundamental mode travels, the transistor trans-conductance and capacitance nonlinearity generate higher harmonics. In this form of implementation of DAR, we are interested in extracting the second harmonic power.

If carefully observed, it can be seen that the second harmonic currents in both arms of the loops travel in the same direction and its return current comes through the ground plane to which the sources of the transistors are connected. In DAR, therefore, the ground is removed from underneath, which separates and phase rotates (by 90°) the second harmonic return current from the forward current. This leads to a traveling second harmonic wave that gets radiated (circularly polarized) in a distributed fashion as it traverses along the loop as shown in Fig. 1. The wave at the fundamental frequency completes a 180° phase change in one loop while the second harmonic completes a 360°. In this way of manipulating current elements, the same electromagnetic structure acts as an oscillator in the fundamental mode and a radiator in the second, negating the need for any additional circuitry for filtration, radiation, and matching. All transistor drains see the same second harmonic radiative impedance which can be maximized for second harmonic generation, by adjusting the ground loop diameter. In this implementation, the oscillation frequency is designed to be 1.25GHz and the simulated efficiency of radiation at second harmonic was 65% with directivity of 4.2dBi.

B. Mutual inter-locking for power combining

To achieve higher power and EIRP, many such radiating elements can be synchronously locked to each other as they coherently combine in space. In integrated implementation, such an array design can also lead to a partial cancellation of TM_0 substrate mode, leading to a cleaner radiation pattern and higher efficiency. Phase control in each element gives an additional capability of beam-forming for radar and imaging applications. In this section, we describe the locking mechanism and beam-forming functionalities of 2x1 and 2x2 arrays of DARs.

The mutual locking scheme is shown in Fig. 2. For the 2x1 array, the locking circuit consists of a network of transmission lines employed at two distinct sites on two DARs. This enforces the required boundary condition, which ensures both the direction and phase of the fundamental, and therefore all harmonics at each corresponding point on two DARs are the same. From Fig. 2, it can be seen that under the locked condition, when the phases at each end of the coupling network are the same, then at the fundamental frequency, each DAR sees a shorted transmission line of impedance $2Z_o$ and length $\lambda/4$. This results in an open circuit at the fundamental and therefore does not load the DAR and affect the frequency of oscillation. At the desired second harmonic, which needs to be radiated, the $\lambda/4$ line ($\lambda/2$ at 2^{nd} harmonic) results in a short at the junction of the four t-lines. Therefore, under the locked condition, each DAR again sees a shorted quarter-wavelength stub at the second harmonic. Hence, the network does not affect the radiation of individual DARs under the locked condition. As shown in Fig. 2, the locking network is also used to provide bias for the DARs.

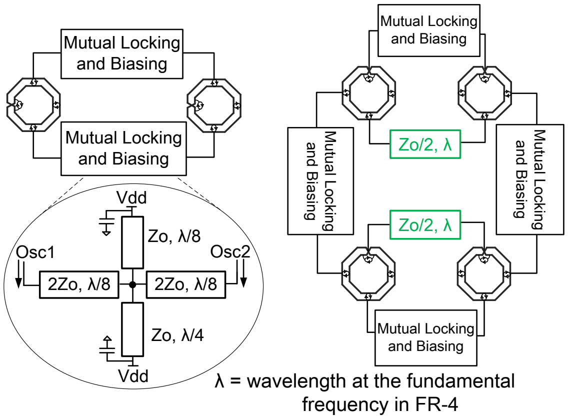

Fig. 2. Mutual locking mechanism among multiple DARs for quasi-optical power combination, harmonic filtering, and beam-forming.

The 2x2 array needs additional boundary conditions which are provided with two t-lines of length λ at the fundamental frequency. These t-line networks also result in open-circuit conditions at both the fundamental and second harmonic under the locked conditions, in order to prevent loading to the DARs. The implementation of DARs with the locking network can be seen in the PCB photos in Fig. 3.

C. Varactor tuning for beam forming

In order to include beam-forming functionality, each NMOS cross-coupled pair within a DAR contains varactor tuning port to allow additional phase shifts through changes in the oscillator resonant frequency [6]. As the resonant frequency of each DAR is tuned, the transmission line locking network, as previously described, causes the four DARs to pull each other towards a common frequency. While this is only possible within a certain locking range, as the varactor voltages are tuned, the resonant frequency change results in additional phase shifts in each element, which are exploited in beam-forming. The 2x1 linear array is capable of beam-steering in one direction while the 2x2 array can steer the beam throughout the 2D space by individually controlling resonant frequencies of the four DARs. The fractional locking bandwidth is limited by the coupling strength of the t-line locking network as well as the resonator quality factor. The simulated beam-forming range is ±37.5° and a locking bandwidth of 50MHz for the 2x1 and ±32° and 45MHz for the 2x2 array at f_o = 2.5GHz.

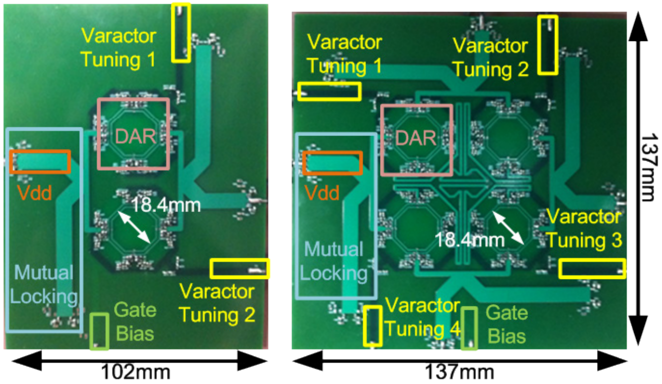

Fig. 3. Photos of PCB implementation of 2x1 (left) and 2x2 (right) arrays of mutually locked DARs with beam-forming functionality at 2.5 GHz.

III. MEASUREMENTS

In this implementation, the distributed active radiator arrays are realized on a 1.6mm thick four-layer FR-4 board. The transistors in the cross-coupled pairs are implemented with low noise enhancement-mode HEMT ATF-58143 from Avago Technologies Semiconductors and varactors are implemented with diodes SMV-2019 from Skyworks Solutions. A photo of the PCB implementation of the mutually-inter locked 2x1 and 2x2 arrays, with dimensions 102mm x 137mm and 137mm x 137mm, respectively, are shown in Fig. 3. The loop diameter of the DAR is 18.4mm for the fundamental frequency oscillation to be at 1.25GHz and the ground plane diameter is 30mm for efficient radiation of the doubling frequency of 2.5GHz. All transmission lines are implemented as microstrip lines.

Fig. 4 outlines the measurement setup. All measurements are carried out in an anechoic chamber. DAR array is placed on a stage inside the chamber that is attached to a stepper motor. A wideband 1-18GHz receiver horn antenna with a gain of 6.22dB at 2.5GHz is placed at the top of the chamber, at a far-field distance of 1.33m, to capture the backside radiation of the DAR array. The spectrum analyzer connected to the receiver antenna displays the spectrum of the received signal.

In order to obtain the radiation pattern at the second harmonic, a laptop controls the stepper motor to rotate the stage in a θ direction while the power at the second harmonic is noted on the spectrum analyzer. The drain and gate of cross-coupled NMOS pairs are biased at 1.8V and 0.4V, respectively. Each DAR draws 34.5mA and therefore consumes 62mW of DC power, resulting in 124mW and 248mW of total DC power dissipation for 2x1 and 2x2 arrays.

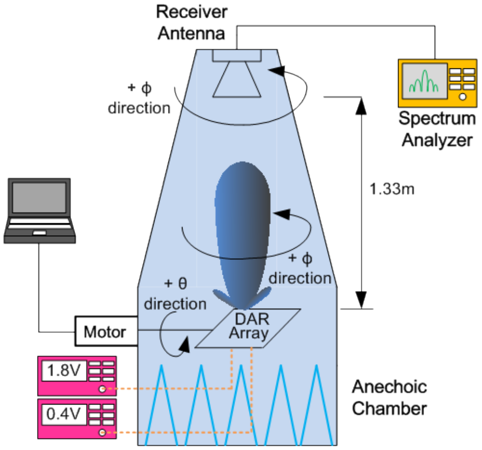

Fig. 4. Measurement setup

A. Harmonic cancellation

The spectra of received far-field radiations for both 2x1 and 2x2 arrays are shown in Fig. 5 to illustrate the effectiveness of quasi-optical filtering of the first harmonic and effective radiation of the desired second harmonic. Fig. 5 shows that 2x1 array achieves a first and third harmonic suppression of 20.6dBm and 16.2dBm, respectively, compared to the second harmonic. Since the simulated first harmonic power generated was 8dB more than the second harmonic, the electromagnetic property of the DAR itself suppresses the first harmonic by 28.6dB compared to the desired second. The 2x2 array achieves first and third harmonic rejection of 15.6dBm and 19.6dBm, respectively.

The linearly polarized receiver antenna was rotated in the φ direction and the received second harmonic power did not change significantly, showing that the radiation is almost circularly polarized. EIRP is measured directly from the power captured at the receiver antenna with known aperture size. EIRP of 2x1 and 2x2 arrays are measured to be 7.46dBm and 12.96dBm at 2.5GHz after calibrating the cable loss. The total radiated power for the second harmonic is measured from the radiation pattern and is calculated to be 1mW for the 2x1 and 1.8mW for the 2x2, resulting in DC-to-radiated 2nd harmonic conversion efficiency of 0.8%. This indicates that mWs of EIRP at THz frequencies may be achieved using silicon IC process technologies through such efficient doubling mechanism [1].

B. Radiation Patterns

The measured far-field radiation patterns of the 2x1 and 2x2 arrays at the doubling frequency of 2.5GHz are shown in Fig. 6 and Fig. 7, respectively. The radiation patterns are measured at two orthogonal axes (at φ = 0° and φ = 90°) corresponding to the PCB plane. The measurement results match closely with

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simulation and as expected, the 2x1 has a 1D beam-forming capacity and the 2x2 array has a 2D beam-forming functionality. The measured beam-steering range of the 2x1 array is nearly ±15° with a locking bandwidth of 25MHz, while that of the 2x2 array is nearly ±20° in each of the two orthogonal axes in 2D space with a bandwidth 35MHz at 2.5GHz.

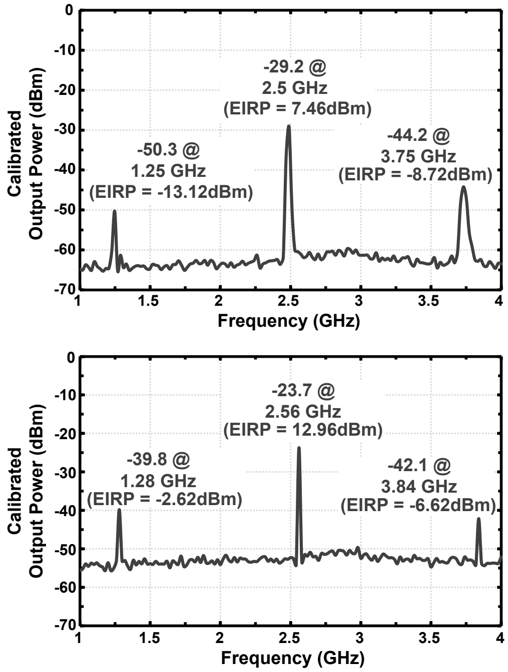

Fig. 5. Measured boresight far-field spectrum of 2x1 (top) and 2x2 arrays (bottom) with a linearly polarized receiver antenna.

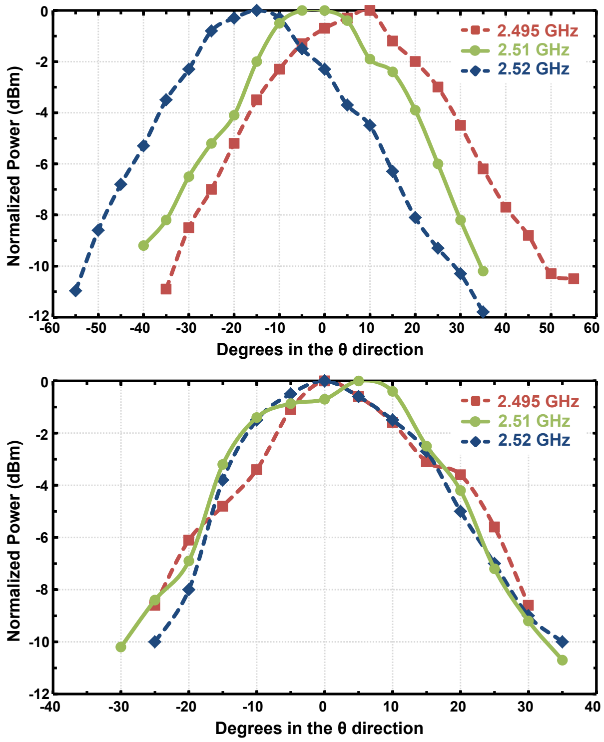

Fig. 6. Measured far-field radiation patterns showing 1D beam-forming at 2.5GHz of the 2x1 array for φ = 0° (top) and φ = 90° (bottom)

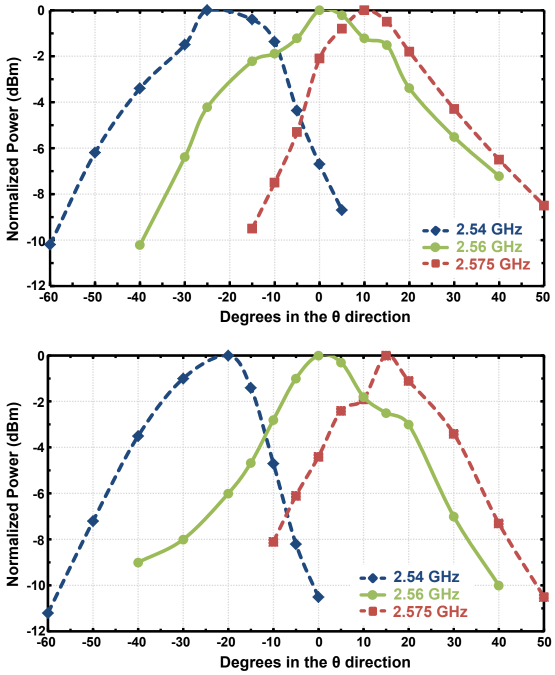

Fig. 7. Measured far-field radiation patterns showing 2D beam-forming at 2.5GHz of the 2x2 array for φ = 0° (top) and φ = 90° (bottom)

IV. CONCLUSION

This paper presents proofs-of-concept Distributed Active Radiator (DAR) arrays on PCB that illustrate a novel method of generating high efficiency desired *harmonic generation*, *filtering*, and *radiation* quasi-optically in a single electromagnetically coupled structure. The DARs are designed to oscillate at 1.25GHz and radiate (circularly-polarized) at the doubling frequency of 2.5GHz. The measured EIRP of 2x1 and 2x2 arrays are 7.46dBm and 12.96dBm at 2.5GHz with a DC-to-radiated 2^{nd} harmonic conversion efficiency of 0.8%. Nearly 40° of beam-steering is measured at 2.5GHz for the 2x2 array in 2D space and more than 15dB first and third harmonic suppression is achieved compared to the desired doubling frequency of 2.5GHz.

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