16.6 Distributed Active Radiation for THz Signal Generation

Kaushik Sengupta, Ali Hajimiri

California Institute of Technology, Pasadena, CA

Despite the aggressive scaling of silicon-based IC's over the past few decades, the transistor characteristics have yet to improve so that the 'THz'-range (~300GHz-to-3THz) circuits can be effectively designed using the conventional techniques. This has led the few attempts at signal generation at these frequencies in CMOS to produce very small power levels (e.g., tens of nano-watts)[1,2]. The broad range of applications that could benefit from efficient power generation justifies novel approaches that allow high power generation and efficient radiation in CMOS. This can be achieved by removing the artificial boundaries between levels of abstraction such as electromagnetics, antenna, propagation and circuits; when we can truly leverage the advantages of the new design space that lies in the confluence of these separate treatments leading to more optimal design [3].

Two major challenges to a fully integrated 'THz' signal source with high enough power for practical applications in CMOS are: effective signal generation above transistor cut-off frequencies and efficient electromagnetic radiation out of silicon. Traditional ways to generate high-frequency signals above f_{max} of devices such as using varactors, nonlinear transmission lines or push-push oscillators [1] and radiating through conventional tuned antennas suffer from lack of power scalability due to parasitic scaling, modeling inaccuracies leading to poor efficiency and low power. Also radiation through traditional antennas (e.g., dipole) in silicon leads to leaky substrate modes that are often remedied with off-chip structures such as dielectric lenses.

In this paper, we introduce the distributed-active-radiator (DAR) structures which consolidate the signal generation, multiplication, filtering, and radiation in a single active electromagnetically coupled structure. As examples of distributed active radiators, we demonstrate 2x1 and 2x2 arrays of DAR structures radiating at 300GHz, which achieve three orders of magnitude higher total radiated power than previously reported.

Cancellation of the fundamental and radiation of the second harmonic can be done quasi-optically with low loss to perform several functions in one place. One key observation in devising a DAR structure capable of doing this is that two small electrical current elements in instantaneously opposite directions separated by a distance much less than the wavelength of interest cancel each other's EM radiations in the far-field, while two such elements propagating in phase will reinforce their radiated field as shown in Fig. 16.6.1. Therefore, to achieve quasi-optical filtration, the fundamental currents should be constrained to travel in opposite directions while the second harmonic should be in phase. This can be done effectively by forming a closed loop as shown in Fig. 16.6.1 where a traveling wave at the right frequency would produce these conditions. The radiation and ohmic energy losses of such system can be compensated by introduction of active elements that simultaneously sustain fundamental signal and generate harmonic content through their nonlinear transconductances and capacitances. This is a special kind of the traveling-wave oscillator [4,5] where the transmission lines and the ground plane are placed in such a way as to maximize the attenuation of the fundamental radiation and facilitate the radiation of the second harmonic.

The regenerative elements are realized as cross-coupled NMOS pairs that force the fundamental currents in the adjacent branches of the loop to be in opposite directions while they either source or sink second-harmonic currents in the same direction, as shown in Fig. 16.6.1. The return path of the second-harmonic currents goes through the source of the cross-coupled pair. Therefore in order for the second harmonic to radiate we 'separate' its return path removing the ground from underneath the loop and providing a local ground path for the second-harmonic current to propagate. This causes the same loop to behave as a coplanar stripline for the first harmonic but a distributed radiating structure for the second and therefore achieves *generation, radiation* and *filtering* simultaneously. The drains of all the transistors see the same second-harmonic radiative impedance, thereby such a distributed arrangement overcomes the traditional narrowband-antenna impedance match for larger device sizes. In this implementation the loop is realized on a 2.1μm thick aluminum layer, where the inner loop diameter is 70μm while the ground plane diameter is 140μm. Four cross-coupled pairs are laid out equidistant along the loop circumference (Fig. 16.6.1). The fundamental frequency of oscillation is designed at 150GHz, radiating at 300GHz.

Such a traveling-wave radiating electromagnetic structure is particularly suitable for integrated implementation. The radiation is circularly polarized with very low fraction of the total power lost in substrate modes. The simulated radiation efficiency of 35% at 300 GHz from the backside of a 300μm thick silicon substrate of 10Ω-cm resistivity, without any lens, is much higher than the typical 5-10% efficiency of an on-chip half-wavelength dipole supported by a silicon lens [6].. Moreover such a distributed implementation eases the way for power combining where arrays of such radiating structures can be mutually locked, leading to lossless quasi-optical power combination and high E.I.R.P. Phase control in each individual element can also be potentially implemented for beam forming. Simulated radiation efficiency of the 2x1 and 2x2 arrays are 45% and 53% at 300GHz, respectively.

Figure 16.6.2 shows the mutual locking mechanism through a transmission line network, which also provides bias for the structure. The transmission line network provides an open circuit under phase-locked condition both at the fundamental (@150GHz) and second harmonic (@300GHz) so as not to load the structure. The multiple coupling networks at various points on the circumference impose the boundary conditions that ensure phase locking of corresponding points on all the radiators.

The measurement setup is show in Fig. 16.6.3. The radiation from the backside of the silicon die is captured by a WR-3 standard gain horn antenna and then down-converted in a harmonic mixer by the 16th harmonic of the LO. The IF is amplified by low noise amplifiers and analyzed using a spectrum analyzer. The heterodyne receiver setup is calibrated using a calibrated source from 290 to 300GHz with a calorimeter-based power meter giving absolute power measurements from 75 to 2000GHz. The total power radiated is calculated from the measurement of the far-field radiation pattern. EIRP is calculated directly from the far-field power-density captured at the receiver antenna with known aperture. The LO frequencies of 18.65GHz and 18.21GHz for down-conversion for the 2x1 and 2x2 arrays imply radiation at 299GHz and 292GHz respectively because of the 16th harmonic mixing. The absolute total power radiated from the backside for the 2x1 array at 299GHz is measured to be 12μW at an EIRP of -13 dBm. The measured output IF spectrum is shown in Fig. 16.6.4. Figure 16.6.5 shows its measured far-field radiation pattern. The measured boresight directivity of the array was found to be 6dB, which compares well against a simulated value of 5.6dB. This implies an EIRP of -13dBm. The 2x2 array radiated at 291GHz with a measured total output power of 80μW. The measured directivity of 10dB results in a net EIRP of -1dBm. The chips draw 22mA from 0.85V supply per DAR. The active area of the 2x1 array is 500x650μm^2 while that of the 2x2 array measures 800x800μm^2 as shown in Fig. 16.6.6.

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References:

[1] D.Huang *et al.,* "324 GHz CMOS Frequency Generator Using Linear Superposition Technique," *ISSCC Dig. Tech. Papers,* pp. 476-477, Feb. 2008.

[2] E.Seok *et al.,* "A 410 GHz CMOS Push-Push Oscillator with an On-Chip Patch Antenna" *ISSCC Dig. Tech. Papers,* pp. 472-473, Feb. 2008.

[3] A.Hajimiri, "mm-Wave silicon ICs: An opportunity for holistic design," *RFIC Symp. Dig.,* pp. 357-360, June 2008.

[4] H. Wu and A. Hajimiri, "Silicon-based distributed voltage-controlled oscillators," *IEEE JSSC,* vol. 36, No.3 pp 493-502, March 2001.

[5] J. Wood *et al.,* "Rotary Traveling-Wave Oscillator Arrays: A New Clock Technology," *IEEE JSSC* vol. 36, No. 11, pp 1654-1665, Nov. 2001.

[6] A.Babakhani *et al.,* " A 77 GHz Phased-Array transceiver with on-chip antennas in silicon: receivers and antennas," *ISSCC Dig. Tech. Papers,* pp. 2795-2806, Feb. 2006.

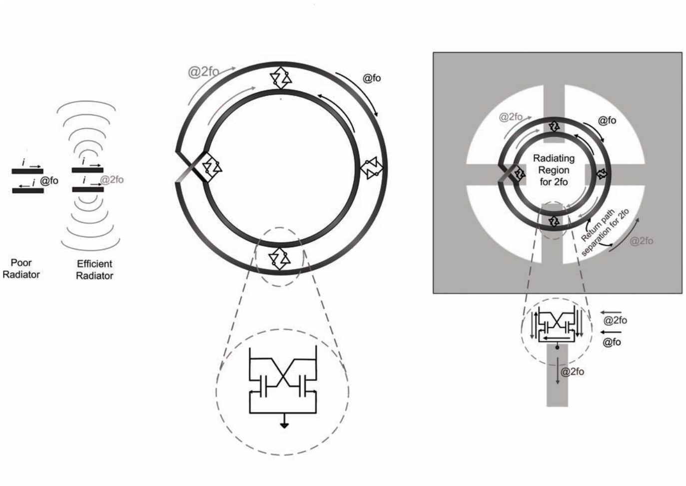

Figure 16.6.1: The conceptual idea depicting distributed active radiation.

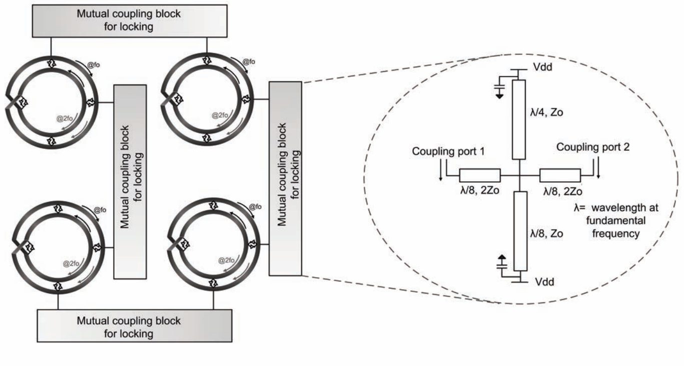

Figure 16.6.2: Mutual locking between different elements for coherent quasi-optical power combination generating high EIRP in array implementation.

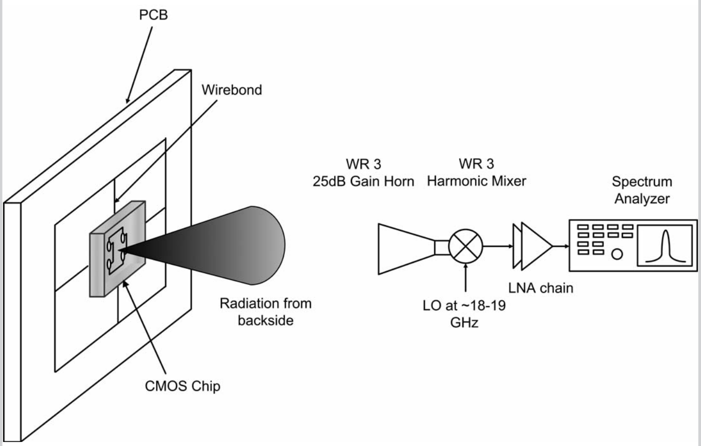

Figure 16.6.3: Chip, board and receiver setup configuration. Radiation is detected without lens from the backside of the 300µm thick silicon die.

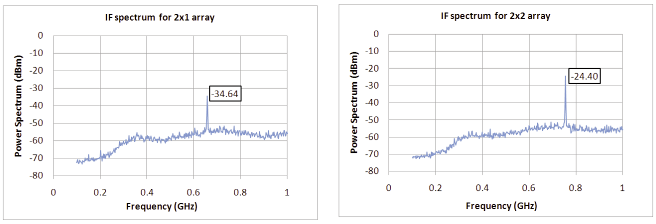

Figure 16.6.4: Detected output IF spectrum for the 2x1 and 2x2 array at the baseband respectively. LO frequencies at 18.65GHz and 18.21GHz imply radiation at 299GHz and 292GHz respectively because of the 16th harmonic mixing of the LO.

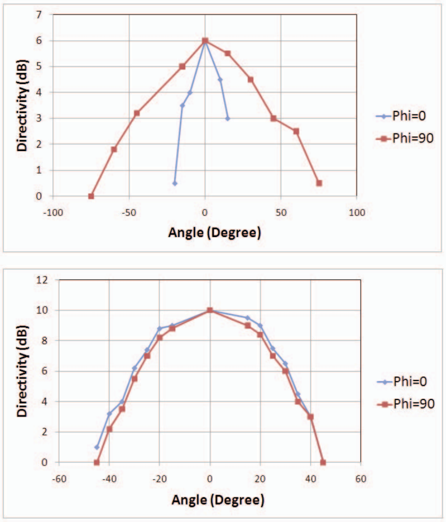

Figure 16.6.5: Measured far-field THz radiation patterns for the 2x1 and 2x2 arrays respectively.

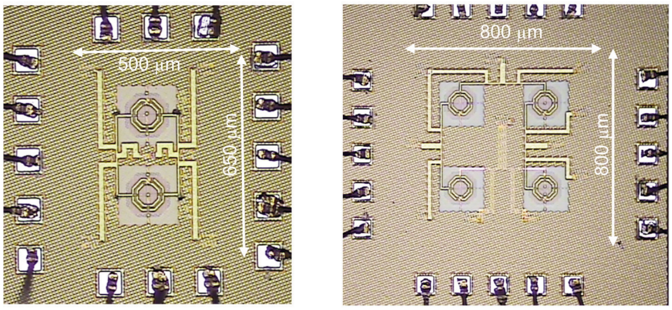

Figure 16.6.6: Die micrographs of the 2x1 and 2x2 arrays radiating at 300 GHz.