11.8 Electrical Funnel: A Broadband Signal Combining Method

Ehsan Afshari¹, Harish Bhat², Xiaofeng Li³, and Ali Hajimiri¹

¹California Institute of Technology, Pasadena, CA
²Columbia University, New York, NY
³Harvard University, Cambridge, MA

Recently, there has been growing interest in using silicon-based integrated circuits at high microwave and millimeter-wave frequencies. The high level of integration offered by silicon enables numerous new topologies and architectures for low-cost reliable SoC applications at microwave and millimeter-wave bands, such as broadband wireless access (e.g., WiMax), vehicular radars at 24GHz and 77GHz [1], short range communications at 24GHz and 60GHz, and ultra narrow pulse generation for UWB radar.

Power generation and amplification is one of the major challenges at millimeter-wave frequencies. This is particularly critical in silicon integrated circuits due to the limited gain, efficiency, and breakdown voltages for active devices and the lower quality factor of passive components caused by ohmic and substrate losses.

Efficient power combining is particularly useful in silicon where a large number of smaller power sources and/or amplifiers can generate large output power levels reliably. This would be most beneficial if the power combining function is merged with impedance transformation to allow individual transistors to drive more current with lower voltage swings to avoid breakdown [2]. Most traditional power combining methods use either resonant circuits and are, therefore, narrowband or employ broadband, yet lossy, resistive networks.

In this paper, we propose a general class of two-dimensional passive power combining media that can be used for power combining and impedance transformation among other things. These media take advantage of wave propagation in an inhomogeneous 2-D electrical lattice. Using this approach we show a power amplifier capable of generating 125mW at 85GHz in silicon.

A 1-D LC ladder can be generalized to a 2-D propagation medium by forming a lattice consisting of inductors (L) and capacitors (C). Figure 11.8.1 shows a square lattice. Generally, this lattice can be inhomogeneous where the L's and C's vary in space, and/or nonlinear where they are current and/or voltage dependent. When the L's and C's do not change too abruptly, it is possible to define local propagation delay (τ = \sqrt{LC}) and local characteristic impedances (Z = \sqrt{LC}) at each node. This allows us to define local impedance and velocity as functions of x and y, which can be engineered to achieve the desired propagation and reflection properties [3].

In this paper, we show one application of these 2-D lattices as a means for simultaneous power combining and impedance transformation.

One way these surfaces can be engineered is by keeping the propagation velocity constant vertically (constant LC product for a given y), while increasing the characteristic impedance at the top and bottom of the lattice at a faster rate as we move along the x axis. Figure 11.8.2. A planar wave propagating in the x direction from left to right experiences higher impedances at the edges, creating a lower resistance path for the current in the middle; this funnels more power to the center of the amplifier, keeping the lattice response frequency independent for the frequencies lower than its natural cut-off frequency [3].

We used this combiner to design a power amplifier in a 0.13µm SiGe BiCMOS process with a bipolar cutoff frequency of 200GHz. A die photo of the amplifier is shown in Fig. 11.8.5. In order to obtain a wideband response, we use degenerate cascode distributed amplifiers with emitter degeneration as input drivers. A non-degenerate cascode amplifying stage in this process has a maximum stable power gain of 15dB at 80GHz, as opposed to 7dB for a standard common-emitter amplifier. The cascode stages are emitter degenerated to improve bandwidth and avoid thermal runaway. Each of the four distributed amplifiers consists of eight cascode stages driving the output transmission line, which drive the inputs of the combiner.

The driver amplifiers have two power supplies of -2.5V and 0.8V and draw 750mA of current. Figure 11.8.6 shows the measured peak output power and gain of the amplifier versus frequency. The maximum output power was measured using two different signal sources: a backward wave oscillator (BWO) and a frequency multiplier. The overall small-signal gain is above 8dB at 85GHz where the peak power of 125mW is achieved. The lower measured maximum power in the multiplier measurement is due to its limited output power compared to a BWO and the lower amplifier gain above 86GHz. The output power and drain efficiency as a function of input power are shown in Fig. 11.8.7. At 85GHz, drain efficiency is more than 4% at the 3dB gain compression point. The amplifier has a 3dB power bandwidth of 24GHz (between 73GHz and 97GHz).

References:
Figure 11.8.1: 2-D square electrical lattice.

Figure 11.8.2: Illustration of the operation of a funnel.

Figure 11.8.3: Simulation results for an ideal funnel with $30 \text{pH} < L < 150 \text{pH}$ and $30 \text{fF} < C < 300 \text{fF}$.

Figure 11.8.4: Combiner structure.

Figure 11.8.5: Die photo.

Figure 11.8.6: Measured saturated power and gain versus frequency.

Continued on Page
Figure 11.8.7: Measured large-signal parameters of the amplifier at 85GHz.