Numerical and Experimental Investigation of Losses in a Tray Based Spatial Power Amplifier

Ayman Al-Zayed[1], Sean Ortiz[2], Mete Ozkar[3], and Amir Mortazawi[4]

[1]North Carolina State University, Department of Electrical and Computer Engineering, Raleigh, NC; 27606; [2]Harris Corp, Melbourne, FL, 32904; [3]Sony Ericsson Mobile Communications, NC 27709; [4]University of Michigan, Department of Electrical and Computer Engineering, Ann Arbor, MI 48109.

***Abstract* — This paper presents experimental and numerical investigations on a 49-element Ka-band amplifier array. This study is aimed at determining the origin of various losses in the amplifier array. Passive simulation data confirms that the load seen by the active devices is well matched and that most of the power is coupled to the LSE_{10} mode. This means that coherent power combining should take place if there is no phase and amplitude variation due to the active devices and phase correcting dielectric lenses.**

I. INTRODUCTION

Spatial (quasi-optical) power combining refers to combining the outputs of many active devices in free space. Several architectures have been developed for spatial power combining, integrating solid state devices to generate noteworthy power levels at a different range of frequency bands. Spatial combining also encompasses a broad rage of microwave circuits. These include amplifier, oscillators, beam controllers, and frequency converters.

After much success in demonstrating the principles and concepts of spatial combining, researchers have directed there efforts on improving the structures and addressing important disadvantages and limitations associated with spatial power-combining techniques. These research investigations include increasing operating frequencies [1]-[2], optimizing for power and efficiency [3]-[4], improving bandwidth [5], the removal of excess heat produced by the active devices [6], minimizing substrate mode effects [7] and others.

The performance of a spatial amplifier array is affected by many factors. These factors are highly dependent on the type of amplifier array as well as the method of exciting the array. This paper studies the performance of the Ka-band perpendicularly-fed patch amplifier array that is excited using a hard-horn antenna [2]. This amplifier can produce 6 watts of power, with a power combining efficiency of 39%.

A drawing illustrating the concept for this amplifier array configuration is shown in Fig. 1. The patch antennas on the left of the diagram receive a signal radiated from the transmitting hard horn. Each of the microstrip patch antennas is coupled to slot aperture, which then feeds a dielectric filled waveguide. The dielectric filled waveguide is then coupled to a microstrip line, which then feeds the MMIC amplifier. After amplification, the signal is radiated through the transmitting patch antenna in the same way that it was received. Finally, the signal radiated from the patch antennas are collected by a receiving hard horn located at the right of the figure. Hard-horns and dielectric lenses are used to provide a uniform amplitude and phase to the array of patch antennas, improving the combining efficiency of the system [8]-[9].

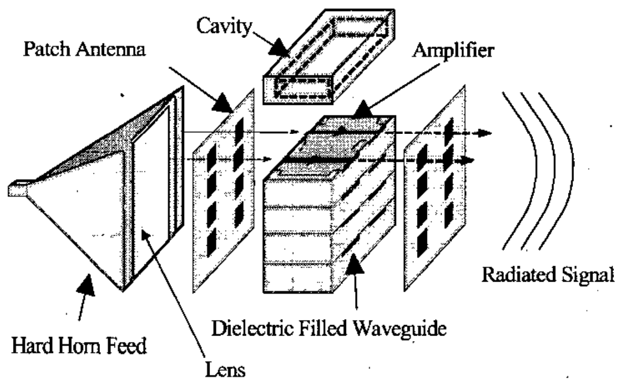

Figure 1: A conceptual drawing of the quasi-optical array employing perpendicular feed structures.

To determine the origin of various loss mechanisms in the array the following studies were performed:

- Experimental study of unit cell spacing and its effect on the combining efficiency.
- FDTD (Finite difference time domain) simulations on the structure.
- Characterization of the unit cell amplitude and phase variation, and its effect on the combining efficiency.
- Recalculation of the power combining efficiency by assuming no phase and amplitude variation among the active devices based on the above observations.

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II. STUDY OF THE CELL SPACING

Optimal array spacing may be determined either numerically or experimentally. Since the numerical formulation of large arrays on the order of ($4\lambda_o$ x $4\lambda_o$) within close proximity to hard-horn feeds is prohibitively time consuming, some simple experiments were undertaken. The purpose of the experiments was to determine the passive insertion loss of an array of antennas placed between two hard-horn feeds as shown in Fig. 2.

A simple passive spatial combiner was designed and fabricated. The array topology is the same as that used for the active amplifier. Each unit cell of the array consists of a receiving microstrip patch antenna, slot in the groundplane, and radiating microstrip patch antenna. The losses therefore are limited to the antenna efficiency and the hard-horn feed insertion loss. A Rogers TMM3 substrate with $\varepsilon_r = 3.27$, a dissipation factor of 0.002, and a thickness of 0.381 mm was used. The microstrip patch antenna has a length of 2.1 mm and a width of 3 mm, while the slot dimensions are 1.6 mm x 0.254 mm. Several experiments were performed as outlined in Fig. 2. First the insertion loss of the two hard-horn feeds was measured by measuring the system without the antenna array. The loss at 31.9 GHz is approximately 1 dB [2]. The loss of the antenna array, including the hard-horn feeds, was then measured. Each antenna array had different array spacing and a different number of cells, since a maximum number of cells were placed within the horn aperture. Fig. 3 shows the insertion loss versus frequency for several arrays with different spacing values. The loss with a cell spacing of $0.5\lambda_o$ and smaller is less than 2 dB at 31.9 GHz. Note that half of this loss contribute to the power combining. From this point, the losses increase significantly with an increase in unit cell spacing. It is to be noted that the ripple level is reasonably low; it is ± 0.5 dB over a bandwidth of more than 2.5GHz. The phase correcting lenses used in these measurements as well as in the active array are home made with a phase uniformity of ± 15° across the aperture of the hard horn. The lens imperfection is contributing to the ripples in Fig. 3. Therefore accurate machining of these lenses (currently underway) should improve the ripple level.

The amplifier under investigation [2] was designed with a unit cell spacing of $0.5\lambda_o$. Therefore the total loss of this amplifier should be equal to this 2 dB plus losses due to the microstrip transmission lines (0.59 dB) within the active array, the two input and output dielectric filled waveguides (0.28 dB) and any mismatch losses. This 7x7 spatial amplifier uses 49 *Triquint TGA1073A*™ PHEMT MMIC amplifiers, which have 19 dB of gain and an output power of 25 dBm under 1-dB compression. Assuming that there are no mismatch losses in this spatial amplifier system, the expected output power is 11.13 watts, and the power combining efficiency is 72% based on half of the active array losses (1.435 dB).

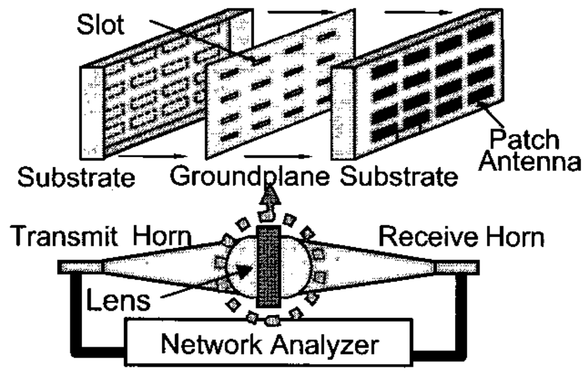

Fig. 2: The setup for measuring the loss of the spatial power combining array and the array topology.

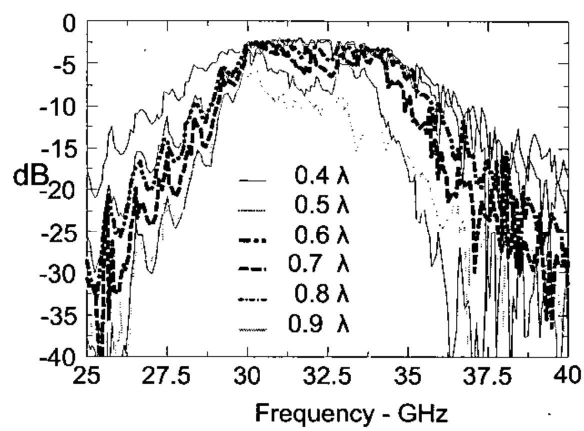

Fig. 3: The insertion loss of several array spacing values versus frequency.

III. FDTD SIMULATIONS

The purpose of the passive FDTD simulations was to better understand the origin of losses in the 49-element spatial power divider/combiner. The active reflection coefficients in the passive structure were obtained through the simultaneous excitation of all elements with a sinusoidally modulated Gaussian pulse while terminating the oversized hard waveguide. The unit cell size was set to $0.5\lambda_o$. As can be seen in Fig. 4, the resonance frequencies for all of the elements are centered around 32.9 GHz with a 10 dB bandwidth of 2.5 GHz (from 31.6 to 34.1 GHz). This indicates an even division of power among the elements around this frequency. This also shows that the active devices would see nearly the same load impedance. In addition, time domain field plots were obtained across the aperture of the hard walled waveguide, when all of the passive elements were excited with equal phase and amplitude signals. The uniform field distribution across the aperture in Fig. 5 means that the antenna array couples very well to the LSE_{10} mode of the hard horn and there was no indication of higher order modes excitations. Therefore, the passive simulations tend to support the experimental observations seen in Fig.3 that the losses due to power combining structure are quite low.

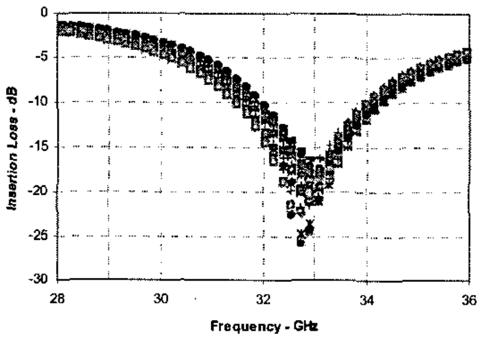

Fig. 4: The active reflection coefficients of the 49 cells Ka-band amplifier that is under investigation [2].

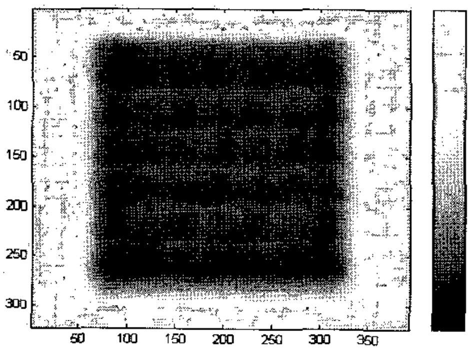

Fig. 5: Normalized field distribution across the aperture of the array.

IV. Effect of Unit Cell Amplitude and Phase Variation

There are many factors, which can cause variations in the unit cell performance, such as variations in transmission line lengths and widths, bondwire lengths and loop heights, and the active device parameter variations. A statistical analysis is conducted by cascading the various components of a quasi-optical amplifier array, within a none-linear simulator such as Agilent – Advanced Design System (ADS)™. These components include a non-linear device model for the amplifier, with an attenuator and phase shifter to simulate device phase and amplitude variations. The attenuator and phase shifter are then adjusted to represent the change in amplitude and phase from one cell to another. The phase and amplitude variations of the unit cell are modeled by Gaussian distribution with mean m and standard deviation σ. Each cell is then chosen randomly using this distribution. It is assumed that the average phase and amplitude variations are equal to zero.

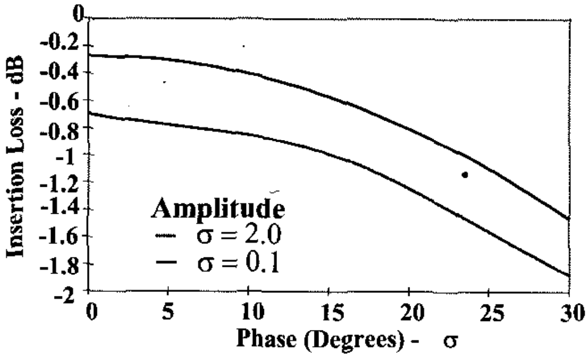

Fig. 6: The simulated insertion loss of the array fed by an ideal hard-horn versus the standard deviation of the phase

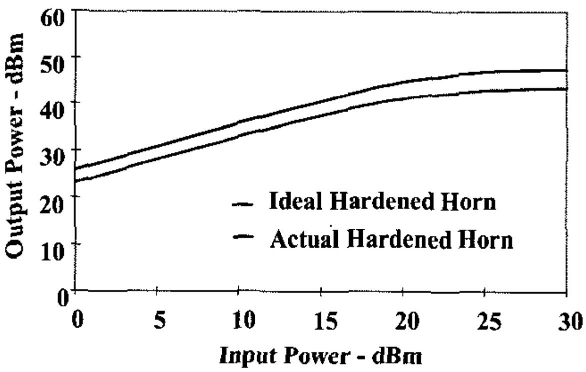

Fig. 7: The simulated power compression of the array for a standard deviation of 20° in phase and 0.5 dB in gain.

Figure. 6 illustrates the insertion loss versus the standard deviation of the phase for two different values of the amplitude's σ. As expected, the loss increases as the probability of phase variation in the unit cells increases for a large phase variation in the unit cells. This is also the case for a larger variation in the insertion loss or gain of the unit cell.

A second test was conducted to investigate the effects of the hard horn phase and amplitude variations on the active array performance, as the non-uniformity of the hard horn causes non-uniform power distribution to the amplifiers, which in effect degrades the output power. The simulated ideal hard-horn (having ±1 dB amplitude variation over 90 % of the aperture), is compared with an actual hard horn, for an amplitude σ of 0.5 dB and a phase σ of 20°. As shown in Fig. 7 the output power of the array with the actual hard-horn data is approximately 2.5 dB lower than the power with the ideal field distribution. This large drop in power is due to an accumulation of phase and amplitude errors as is apparent when observing the accelerated roll-off in the insertion loss of Fig. 6.

The unit cells were measured for both the passive and active array (amplifier under investigation [2]), using waveguide probes at the operating frequency of 31.9 GHz. The waveguide probes are placed nearly in contact with the antenna substrate. For the passive array, a variation of ± 1.1 dB in magnitude and ± 30° in phase was observed over the 49 unit cells. As for the active amplifier the magnitude varied by ± 1.8 dB and the phase by ± 40°. It is to be mentioned that only the amplifier that was probed was turned on, and the other 48 amplifier were turned off. The results provide some insight into the effect of the device variations on the gain and combining efficiency of the system. The unit cell variations certainly affect the ka-band amplifier performance in many ways, such as low gain, high ripple level, and low power combining efficiency. These effects should therefore be accounted for when determining the system performance. Thus one can set a tolerable system performance goal (gain, ripple level and power combining efficiency) and determine the maximum unit cell variation necessary to meet this goal.

V. Conclusion

In this paper the performance of a 7x7 Ka-band spatial power combining amplifier array fed by hard-horns was analyzed and the cause of the low combining efficiency was determined. Various design parameters were studied. A unit cell spacing study indicated that it is important that this spatial amplifier array fed by hard-horns have a unit cell spacing below 0.5λ, if losses are to be kept to a minimum. This amplifier should produce up to 11.13 watts of power, with a power combining efficiency of 72% under ideal unit cell variations. FDTD simulations were performed on the passive array structure. It was found that the array has a uniform field distribution across its aperture and that the load seen by each of the amplifiers is similar. Large unit cell variations were measured for both the active and passive structures. It was determined that large amplitude and phase unit cell variations are the cause of this low combining efficiency. For a tolerable system performance, set in terms of gain, ripple lever and power combining efficiency, the maximum unit cell variations can be found.

Acknowledgement

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