Optimization of the Array Parameters In Waveguide-based Spatial Power Combiners with Hard Horn Feeds

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Abstract — **A generalized scattering matrix (GSM) approach, which utilizes finite difference time domain (FDTD) and mode matching (MM) techniques, is used to analyze waveguide based spatial power combiners with hard horn feeds. The simulation results are experimentally verified for a complete spatial power dividing/combining system with a 3x3 patch antenna array and a hard horn. Different array parameters are varied in order to optimize a 3x3 spatial power combining array.**

I. INTRODUCTION

Despite the continuous advances in vacuum electronics [1], due to their fault tolerance against device failures, low bias requirement and linearity, spatial power amplifiers have the potential to replace traveling wave tubes (TWTs) in moderate power communications applications at millimeter wave frequencies. After a decade of developmental stage, the latest research in spatial power combining has been concentrating on understanding the fundamental concepts in spatial power amplifiers.

Accurate modeling of spatial power amplifiers is essential for optimal design, and due to the complex electromagnetic structures involved, full wave analysis is required. Even with today's powerful computers, full wave analysis of spatial power combiners with custom codes can be hampered by large memory requirements, so modeling of spatial combining arrays continue to be a very challenging task. Although significant progress has been made in modeling of spatial amplifiers, most of the designs are still based on the unit cell approach. For grid structures, it is more convenient to follow this approach with an infinite array assumption, which neglects the edge effects [2]. Modeling of a finite grid array [3] as well as a finite folded slot array [4] has also been demonstrated. There have been successful attempts at modeling waveguide-based spatial power combining arrays as shown in Fig. 1 using the GSM approach as well [5,6]. GSM approach suits well to the waveguide problems since the complexity is reduced by partioning the system into smaller blocks that can be simulated using different numerical techniques. There has been limited amount of work that relates the performance of the spatial power amplifiers to the array parameters [7-9]. Issues that have not been previously addressed are the detailed modeling of spatial power combining arrays inside dielectric loaded oversized waveguides, optimization of array parameters (such as inter-element spacing) for higher power combining efficiency,

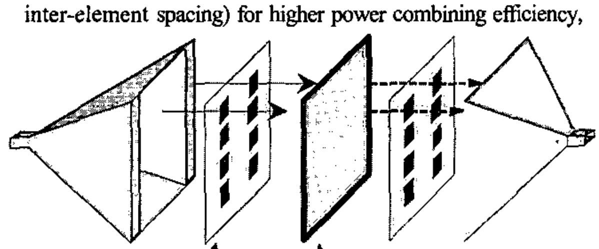

Fig. 1 A general waveguide-based spatial power combining system.

the effect of the proximity of the array to the hard horn walls on the array behavior (bandwidth, driving point impedances of the array elements).

In this paper, a GSM approach, which combines FDTD and MM techniques, is used to analyze a waveguide based spatial power combiner that consists of coaxial fed patch antenna arrays and hard horn feeds. The GSM analysis tool is used to better understand the effects of some of the design parameters on the amplifier performance.

II. THEORY AND EXPERIMENTAL VERIFICATION

In this section, a spatial power combiner system consisting of a 3×3 array of coax fed patch antennas inside a hard horn will be considered. A comparison between simulation and experimental results for this system will be presented. A single coax fed microstrip patch antenna (as the unit cell) was designed to resonate around 10 GHz using a *Rogers Duroid 4003* substrate. The other array parameters in Fig. 2 are vertical spacing (dy), horizontal spacing (dx) and aperture dimensions (X and Y). The array was placed at the hard horn aperture (with

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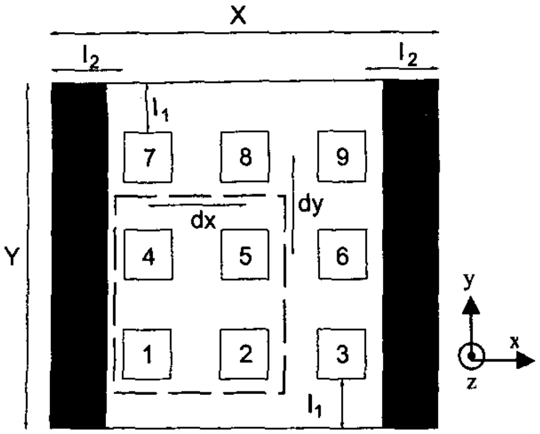
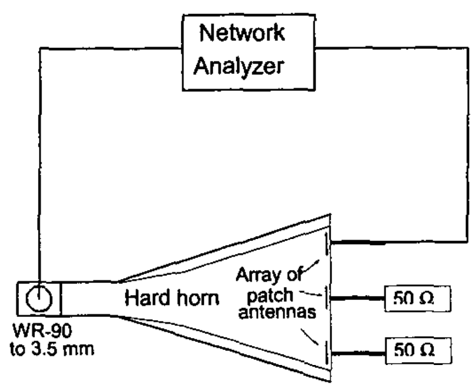


Fig. 2 A top view of the 3×3 array at the transverse plane of a dielectric loaded waveguide showing the array parameters.

the dimensions 7.3025 cm and 5.398 cm) with a uniform horizontal spacing of 0.32λ, a uniform vertical spacing of 0.28λ. The hard horn was fabricated using a *Rogers Duroid 5880* dielectric and a standard gain horn with a length of 8.6 cm. A near field scan performed at the aperture of the hard horn at a frequency of 9.7 GHz showed a uniform field distribution in the absence of the array.

The coax fed patch antenna array was put in front of the hard horn as shown in the experimental setup in Fig. 3. A network analyzer *(HP 8510C)* was used to obtain the scattering parameters. One of the ports was connected to the waveguide that feeds the hard horn antenna. The second port was connected to one of the coaxial connectors that feed the patch antennas while the rest of the coaxial connectors were terminated with 50Ω loads.

The same structure was also simulated using the generalized scattering matrix cascading approach. The GSM for the hard horn was obtained through mode



matching with a staircase approximation. The coax fed patch antenna array inside an overmoded waveguide was analyzed using the FDTD technique with D, E, and H updates. A modified version of PML was used to terminate the oversized waveguide port. The coaxial lines were terminated with Mur's first order absorbing boundary condition.

In FDTD, upon incident voltages, the time domain reflected modal voltages were calculated from the total field as:

$$V_s(z_0,t) = \iint \bar{E}(x,y,z_0,t)\cdot \bar{e}_s(x,y)\,dx\,dy \qquad (1)$$

where V_s is the time domain modal voltage for the mode s, E is the time domain total electric field resulting due to an excitation across the oversized waveguide aperture, e_s is the modal vector and the integral is over the transverse plane of the waveguide port. The S parameters are ratios of the frequency domain modal or port voltages scaled by characteristic impedances and the GSM of the waveguide section with coax fed patch antennas is given by:

$$[S] = \begin{bmatrix} S_{pp'} & S_{ph} & S_{pe} \\ S_{hp'} & S_{hh} & S_{he} \\ S_{ep'} & S_{eh} & S_{ee} \end{bmatrix} \qquad (2)$$

$$S_{pp'} = \frac{V_p^{ref}}{V_{p'}^{inc}},\ S_{hp'} = \frac{V_{h_{mn}}^{ref}}{V_{p'}^{inc}}\sqrt{\frac{Z_{p'}}{Z_{h_{mn}}}},\ S_{ep'} = \frac{V_{e_{mn}}^{ref}}{V_{p'}^{inc}}\sqrt{\frac{Z_{p'}}{Z_{e_{mn}}}}$$

$$S_{pe} = \frac{V_p^{ref}}{V_{e_{s'}}^{inc}}\sqrt{\frac{Z_{e_{s'}}}{Z_p}},\ S_{he} = \frac{V_{h_s}^{ref}}{V_{e_{s'}}^{inc}}\sqrt{\frac{Z_{e_{s'}}}{Z_{h_s}}},\ S_{ee} = \frac{V_{e_s}^{ref}}{V_{e_{s'}}^{inc}}\sqrt{\frac{Z_{e_{s'}}}{Z_{h_s}}}$$

$$S_{ph} = \frac{V_p^{ref}}{V_{h_{s'}}^{inc}}\sqrt{\frac{Z_{h_{s'}}}{Z_p}},\ S_{hh} = \frac{V_{h_s}^{ref}}{V_{h_{s'}}^{inc}}\sqrt{\frac{Z_{h_{s'}}}{Z_{h_s}}},\ S_{he} = \frac{V_{e_s}^{ref}}{V_{h_{s'}}^{inc}}\sqrt{\frac{Z_{h_{s'}}}{Z_{e_s}}}$$

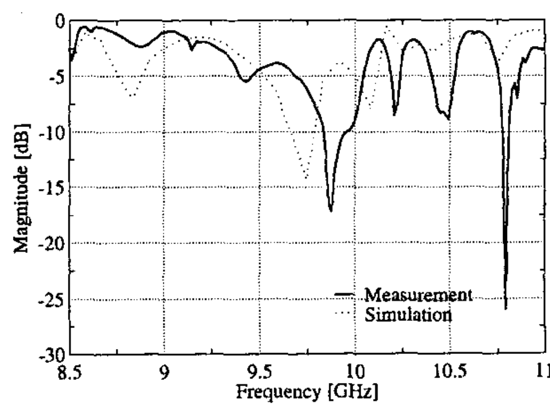


Fig. 4 Reflection coefficient looking into the input of the hard horn in the presence of the array.

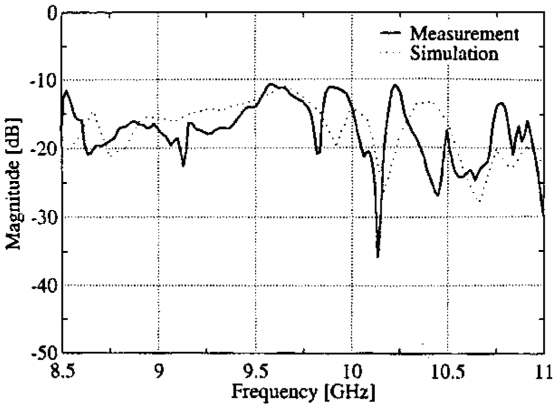


Fig. 5 Tranmission coefficient from the input of the hard horn to coax port at antenna element 4.

where s, s', p and p' refer to the different mode indices and ports, e and h correspond to the TM and TE modes, respectively, and Z's are the characteristic impedances.

The GSM from the FDTD simulations consisted of a generalized scattering matrix with TE^z/TM^z modes and coax ports. An additional junction between dielectric loaded waveguide section and the hollow waveguide section with the patch array provided the conversion between TE^x/TM^x (LSE and LSM) modes and TE^z/TM^z modes. The GSMs from the mode matching and FDTD simulations were then cascaded using the commercially available circuit simulator, *Agilent ADS^{TM}*, where each mode was treated as a separate circuit port.

Both the measured and simulated results for the reflection coefficients at the input of the horn and the transmission coefficients from the input of the horn to the two of the array elements are shown in Fig. 4-6. As can be seen there is good agreement between measured and simulated results of this 3×3 passive system. The small disagreements can be attributed to the fact that the simulated structure

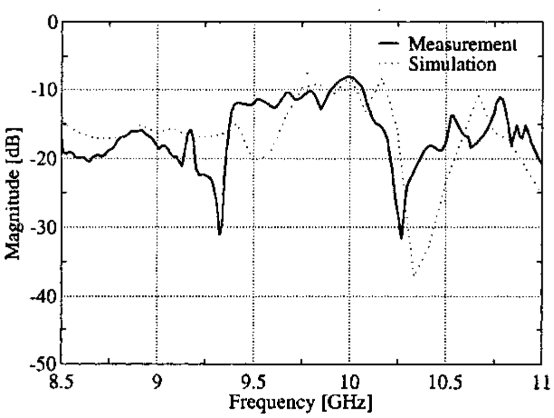


Fig. 6 Transmission coefficient from the input of the hard horn to coax port at antenna element 2.

and the measured and built structure were not quite the same. One major difference was that the ground plane of the patch array was not electrically connected to the metal walls of the horn in the measurements. Also, the GSM simulation did not include any conductor or dielectric losses and furthermore fabrication errors in hard horn construction or in building the coax fed patch antenna array could exist. Nevertheless, the GSM model predicts the system behavior quite well and can be used to design and optimize spatial power combiners with hard horn feeds. Next section will be presenting an investigation on the effect of the array parameter values on the system behavior.

III. Optimization

The goal of this investigation is to understand how dx and dy affect the coupling from the array to the LSE_{10} mode in the oversized dielectric loaded waveguide. LSE_{10} is the mode that provides the uniform field distribution for coherent power combining [10]. Most of the spatial power combiners with patch arrays have been designed with square unit cells and the design of patch arrays in spatial power amplifiers have so far resided on the widely accepted rules for free space arrays such as the 0.5λ array spacing for maximum directivity [11]. However, far field concepts such as directivity are not of concern in spatial power combiners.

Different cases of the array spacing for a waveguide based spatial power combiner were investigated with the developed simulation tool. As seen from Table 1 in cases a-c, the horizontal spacing was kept constant and vertical spacing was changed. Fig. 7 shows the insertion loss of two arrays connected back to back as in an active power combiner/divider structure. The insertion loss was minimized to as low as -1 dB in the back to back connection. An improvement of 4 dB was achieved from case a to case c. In cases c-e, the vertical spacing was kept constant and the horizontal spacing was varied. It is observed that the effect of changing the horizontal spacing was not as critical as that of changing the vertical spacing. In all cases, the X and Y dimensions of the oversized dielectric loaded waveguide were 7.3025 by 5.398 cm.

It was also interesting to observe that the reflection coefficients of the different array elements for case c were

TABLE 1
PARAMETERS THAT ARE VARIED WHILE X& Y WERE CONSTANT

Cases	$l_1(\lambda)$	$l_2(\lambda)$	$dx(\lambda)$	$dy(\lambda)$
a	0.47	0.7	0.32	0.28
b	0.38	0.7	0.32	0.37
c	0.28	0.7	0.32	0.47
d	0.28	0.62	0.40	0.47
e	0.28	0.54	0.48	0.47

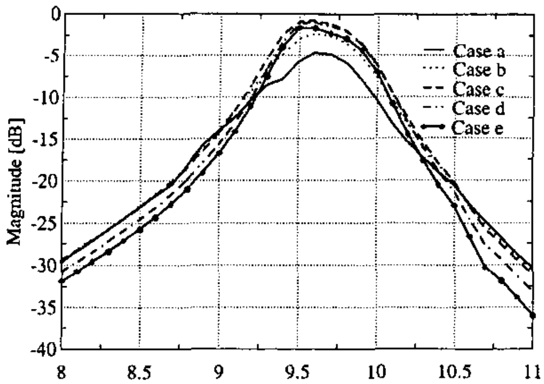


Fig. 7 Transmission coefficients between LSE_{10} modes in the back to back connection of the 3×3 array for various cases.

consistent with the previous results. The active reflection coefficients were obtained through the simultaneous excitation of all elements with a sinusoidally modulated Gaussian pulse while terminating the oversized hard waveguide. Fig. 8 shows the active reflection coefficients for different elements as numbered in Fig. 2. It can be seen that the resonance frequencies for all of the elements are centered around the desired design frequency of 9.7 GHz. This indicates an even division of power among the elements around the design frequency and further justifies the better results of the design in case c, which was found in the previous analysis. For other cases, it was observed that the active reflection coefficients shifted around rather than being centered at the design frequency, which accounts for uneven power division among unit cells and more insertion loss.

IV. CONCLUSION

Tools for analyzing and understanding a waveguide based spatial power combiner with patch antenna arrays and hard horns were developed in this work. The analysis developed here involved breaking the system into smaller modules and the use of the GSM cascading method. This analysis makes it possible to improve the designs of spatial power combiners for optimum array spacing and geometry, and higher power combining efficiencies. It was shown that the requirement for optimum performance of spatial power amplifiers does not match conventional free space array design guides.

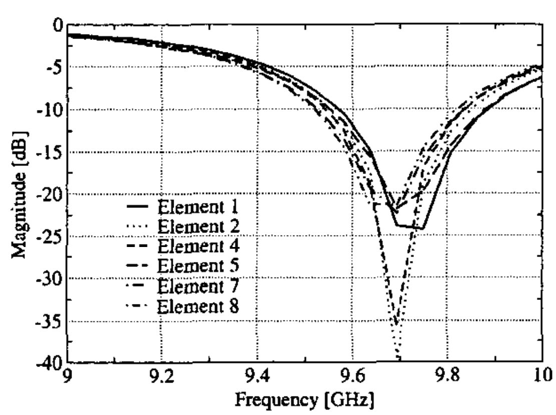


Fig. 8 Active reflection coefficients for different elements of the array for case c.

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