Paper

Spatial power combiner using a planar active transmitarray of stacked patches

Feng-Chi E. Tsai and Marek E. Bialkowski

Abstract—An X-band spatial power combiner, which uses a planar transmitarray (TXA) of orthogonally polarized stacked microstrip patches integrated with input and output ports of transistor amplifiers is described. In order to obtain an increased operational bandwidth, the unit cell of the combiner with various stacked patch (SP) configurations is investigated. The configuration showing the smallest insertion losses is chosen for developing a TXA. The constructed spatial combiner includes a 4×4 cell TXA placed between two hard horn antennas. Its performance is assessed experimentally in terms of amplification gain and combining efficiency.

Keywords— active antennas, amplifiers, microstrip antennas, planar arrays, power combiners.

1. Introduction

A very rapid growth of terrestrial and satellite communications in the last few decades of the 20th century and the resulting heavy congestion of low microwave bands have been a major driving force for exploring upper microwave and millimetre-wave frequencies. One of the main requirements for a successful shift to the new frequency spectrum is availability of high power solid-state transmitters. Solid-state devices such as diodes or transistors are able to meet such demand when their output signals are combined using spatial power combining methods. These methods avoid conduction losses, which become pronounced at millimetre wave frequencies.

The space-level power combining was first demonstrated by Staiman *et al*. [1] in 1968. Since that time, varieties of spatial power combining structures have been proposed and established [2, 3]. Although at the initial stages both oscillators and amplifiers were considered, most of the recent activities have been devoted to amplifiers. This is because of the ease of their control and tuning. Due to the technological reasons most of recent investigations have been committed to planar, tile and tray, configurations of space-level combiners. The tile configuration offers the fully planar format and ease of development. Its disadvantage is due to narrow-band operation, which is caused by the narrow-band operation of typical planar antenna elements, which are employed in this type of power combiner [4–11].

The goal of the work undertaken here is obtaining an increased operational bandwidth of the tile type power combiner by employing stacked patch (SP) microstrip antennas [12] as receiving and transmitting elements in the active planar transmitarray (TXA). An X-band prototype, which can be easily scaled to higher frequencies, is investigated. First, various configurations of SP antennas for integration with amplifiers are studied in the unit cell arrangement. After making suitable selections, 4×4 cell passive and active SP TXA are designed and developed. Two identical hard horn antennas with an approximately uniform aperture field for signal launching and collecting complete the design of this space-level power combiner. Its performance is assessed in terms of amplification gain and combining efficiency.

2. Stacked patch antenna unit cell design

In order to develop an amplifying TXA with an increased operational bandwidth, edge-fed stacked patch (EFSP) and aperture-coupled stacked patch (ACSP) antennas for integration with input and output amplifier ports were selected and studied using the full-wave electromagnetic (EM) commercial simulation software, Ensemble® of Ansoft®. The investigations were performed at 10 GHz by assuming 9.5 GHz as the design frequency. The full design details of the chosen antennas were reported in [13] and are not repeated here. The 10 dB-return loss bandwidths for these antenna elements were 1.9 and 3 GHz respectively, as confirmed both by simulations and measurements [13].

An increased return loss performance of these SP antennas was not sufficient to make the claim that they would be good candidates for developing an active TXA with increased operational bandwidth. In addition to high return loss, these antennas have to provide minium insertion losses when they form the power combiner structure. In order to obtain a more appropriate assessment, these antenna candidates were used to develop three configurations of the unit cell prototype of the planned TXA. Only one of the three investigated configurations of the unit cell provided minimum insertion loss and thus an optimal performance [13]. This configuration has been selected to develop 4×4 element passive and active TXAs. The design and development details of these two antenna systems are presented next.

3. The 4×4 array design

The configuration of an X-band power combiner configuration including the 4×4 cell TXA, which is investigated here, is shown in Fig. 1. In this figure, the transmitting hard horn on the left illuminates the receiving (TXA-R) patch antennas. The signal is received by stacked patches, coupled through the slots in the ground plane, amplified in the feed layer before being reradiated by the transmitting (TXA-T) stacked patch antennas of edge-feed type. As seen in the figure, in each unit cell the TXA-R and TXA-T antennas are placed orthogonally back-to-back to each other. The cross polarized antennas are used purposely in order to increase isolation between input and output ports of the amplifiers. The amplified signal is combined by a pyramidal hard horn, which is orthogonally polarized to its input counterpart. The perspective view of the complete passive unit cell (in which the through connection is used in place of an amplifier) of TXA is shown in Fig. 2. In turn, Fig. 3 reveals the schematic of the active unit cell including the biasing circuitry. The active devices chosen and implemented in the array are 50 Ω-pre-matched ERA-1 low power monolithic amplifier manufactured by Mini-Circuits®. The required bias condition of 3.6 V and 40 mA at the drain of the ERA-1 amplifier are easily accomplished with a bias voltage of 5 V and a 33 Ω biasing resistor. A simple radio frequency (RF) biasing circuitry consisting of a high impedance line and a fan stub are designed and implemented. Normally, this amplifier is aimed for operation from DC to 8 GHz with gain not worse than 10 dB. The measurements performed on this amplifier revealed that it could be used beyond this band with an acceptable gain of 8.97 dB at 10 GHz.

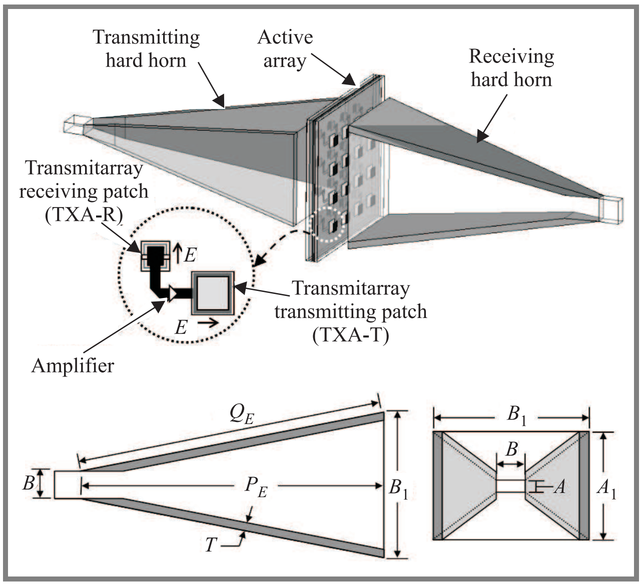

Fig. 1. A stacked patch (SP) transmitarray (TXA) spatial power combiner with transmitting and receiving hard horns. Parameters: $A = 10.16$ mm, $B = 22.86$ mm, $A_1 = 94$ mm, $B_1 = 126$ mm, $P_E = 240$ mm, $Q_E = 248.5$ mm, $T = 7.2$ mm.

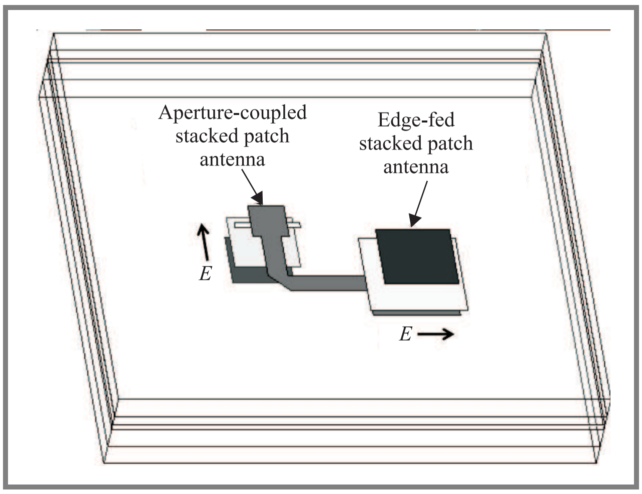

Fig. 2. Perspective view of the SP microstrip antenna unit when a through connection replaces an amplifier.

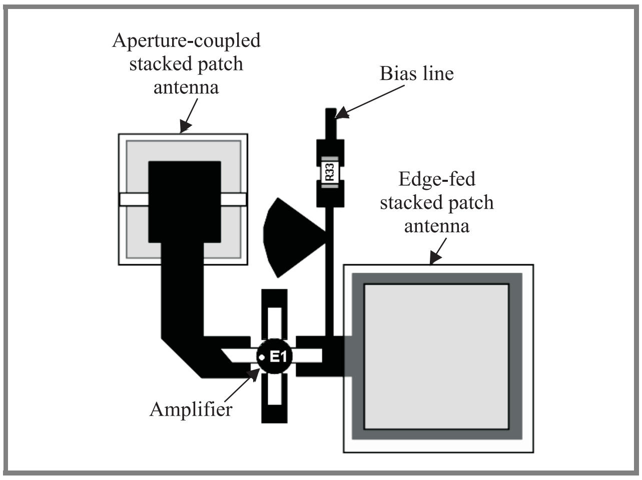

Fig. 3. Active unit cell of the SP TXA.

In order to launch and receive the signal, two identical X-band pyramidal hard horns are designed and manufactured. The chosen aperture dimensions are 126 mm × 94 mm and the axial horn length is 240 mm. Dielectric slabs made using Rogers® RT/duroid® 5880 with $\varepsilon_r = 2.2$ are placed in the inner H-plane walls of the pyramidal horn to create hard surfaces. For operation at the centre frequency of 9.5 GHz, thickness of 7.2 mm was used, as obtained from the formula given in [14]. Parameters of the two hard horns are shown in Fig. 1.

Due to the fact that the computer resources currently available to the authors did not allow for simulating of the entire power combiner, further investigations were carried out using experimental means.

4. Results

First, two co-polarized hard horns spaced by the distance suitable for accommodating a passive or active transmitarray were measured to quantify the level of insertion loss. The average measured insertion loss was found to be 2.7 dB over a bandwidth of 2 GHz from 8.5 to 10.5 GHz. The 10 dB return loss was obtained across the entire X-band.

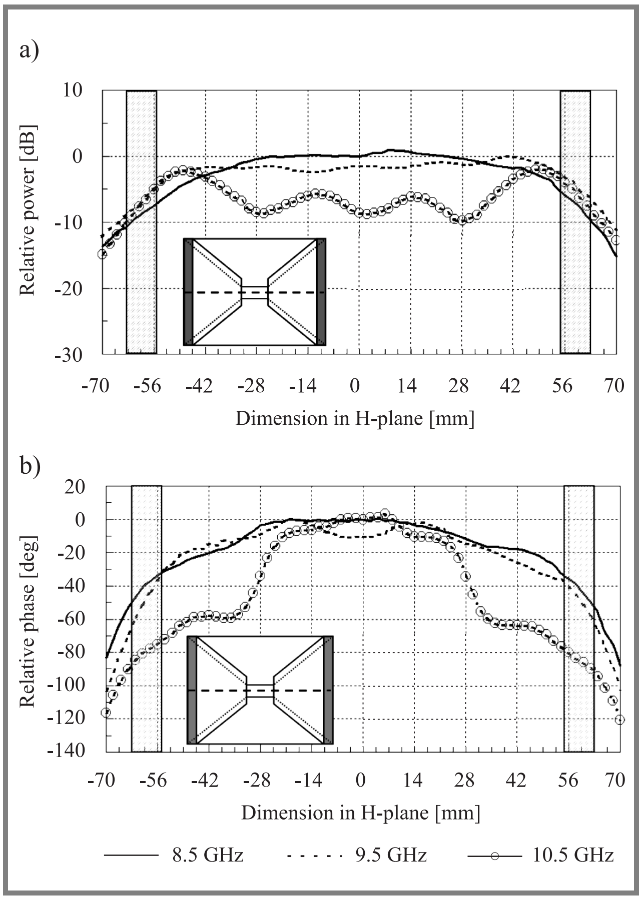

Fig. 4. (a) Magnitude and (b) phase distribution of hard horns along the H-plane cut through the centre of aperture at three selected frequencies. Shaded regions indicate the position and thickness of the dielectric slabs.

The two hard horns were also tested in terms of magnitude and phase uniformity across their apertures over the investigated frequency band. The measured field magnitude and phase distribution in H-plane cut for the horn aperture at three selected frequencies are shown in Fig. 4. From Fig. 4a, it is observed that the designed hard horn provides a uniform field magnitude distribution with less than ± 2 dB variation for more than 90% of the horn aperture at the design frequency of 9.5 GHz. However at 10.5 GHz, a ripple of 7 dB on average is formed over the aperture. In Fig. 4b, it is observed that an approximately uniform phase distribution is obtained at 8.5 and 9.5 GHz. At 10.5 GHz, a sharp change of phase occurs at about half way between the centre to both edges of the hard horn in H-plane cut. This indicates that the workable range for the hard horn, at which uniform magnitude and phase distribution are attained, is limited up to or slightly above the centre frequency at which the dielectric slabs are designed at.

Following the hard horns assessment, a full power combining structure including a passive or active TXA was measured. A 4×4 cell active SP TXA, based on the unit cell configuration of Fig. 3, is shown in Fig. 5. The array element spacing of $0.9\lambda_0$ or 28.42 mm at 9.5 GHz was chosen in order to accommodate the integrated active circuitry.

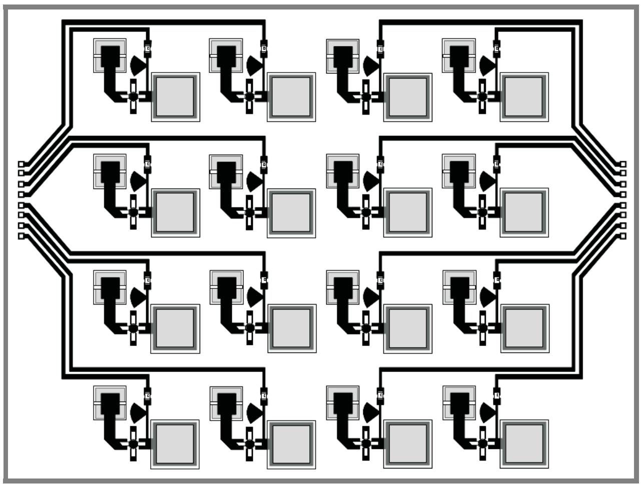

Fig. 5. A complete active 4×4 SP TXA.

In the first step, the structure including a passive 4×4 array was assessed. The array was placed in a horn-to-horn setup between two cross-polarized hard horns on a height adjustable mounting jig along a steel rail. A separation distance of 15 mm between the transmitting/receiving horn and the amplifier array was determined by manually adjusting the distance until good return loss level was achieved over at least 2 GHz bandwidth about the centre frequency of 9.5 GHz. The measured results of the 4×4 passive array are shown in Fig. 6. The minimum insertion loss

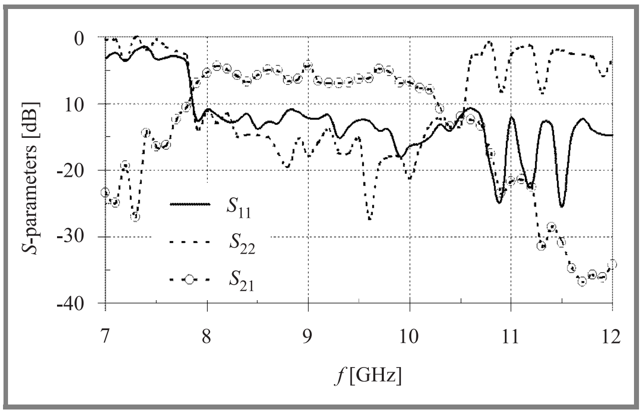

Fig. 6. Measured *S*-parameters of the passive 4×4 SP TXA.

is 4.3 dB at 9 GHz with a 3 dB-gain bandwidth of about 2.2 GHz and a maximum ripple of 2.7 dB across this band. This result indicates that the minimum insertion loss incurred by the passive array is 1.6 dB. However, this value varies with frequency, and the average value across the 3 dB-gain bandwidth is 3.74 dB. Using the same setup, measurements were performed on the active array and results are shown in Fig. 7. The maximum small signal gain is 3.46 dB at 8.7 GHz with a 3 dB-bandwidth of about 1.9 GHz. By taking into considerations of losses associated with the hard horns and passive array, the amplifier gain at 8.7 GHz is 8.53 dB, while the average value across this bandwidth is 7.9 dB. The 3 dB-bandwidth of the active array is reduced by 0.4 GHz, which can be attributed

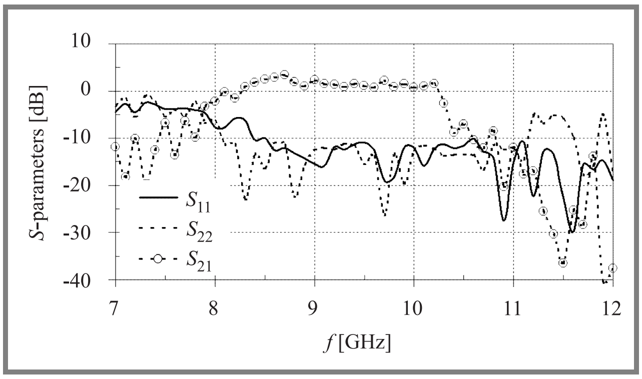

Fig. 7. Measured S-parameters of the active 4×4 SP TXA.

to the frequency shift of operation of antenna elements caused by the integration of the amplifier and biasing circuitry into the multi-layer passive TXA.

5. Discussion

The results presented in Figs. 6 and 7 show a reduced amplification gain. This gain reduction is because of insertion losses of the investigated power combining structure. The observed power loss is mainly due to leakage through the edge elements of the active array and is expected because the SPC investigated here is not a fully closed conducting structure. This power loss can be reduced by placing the active TXA into a waveguide between the launching and receiving horn antennas. Alternatively, it could be minimized by increasing the number of active array elements so there would be a smaller (in terms of percentage) group of elements responsible for leaking power outside the receiving horn.

The evaluation of performance of an amplifying power combiner is usually completed by making power compression measurements, in which the 1 dB-compression point is determined [2–9]. For a space level combiner, an alternative approach of assessing the same can be done through the near-field uniformity measurement of the transmitting side of an active aperture. The reason is that the uniform field distribution at the transmitting side of active aperture indicates that all of the elements of the active array are able to efficiently amplify both weak and large level signals. In particular, this condition facilitates simultaneous saturation of individual amplifiers under the large signal scenario. As a result, this condition enables the largest dynamic range of a space-level power combiner.

The measured near-field magnitude distribution across the E- and H-plane cuts at the output side of the 4×4 cell TXA (when the output hard horn is removed) at three selected frequencies is shown in Fig. 8, respectively. As seen in Fig. 8, there is a general degradation of uniformity across both the E- and H-plane of the array aperture at 10.5 GHz. Comparatively, stronger coupling is seen in H-plane, as this is due to the slot radiation of TXA-R, which is orthogonally polarized to TXA-T. Experimental observations of Fig. 8 follow that of Fig. 4 in which it is found that the hard horn supports uniform field aperture between 8.5 GHz and up to about 10 GHz. The results of Figs. 6 and 7 follow this trend, where it can be seen that the insertion loss performance begins to degrade beyond 10.3 GHz.

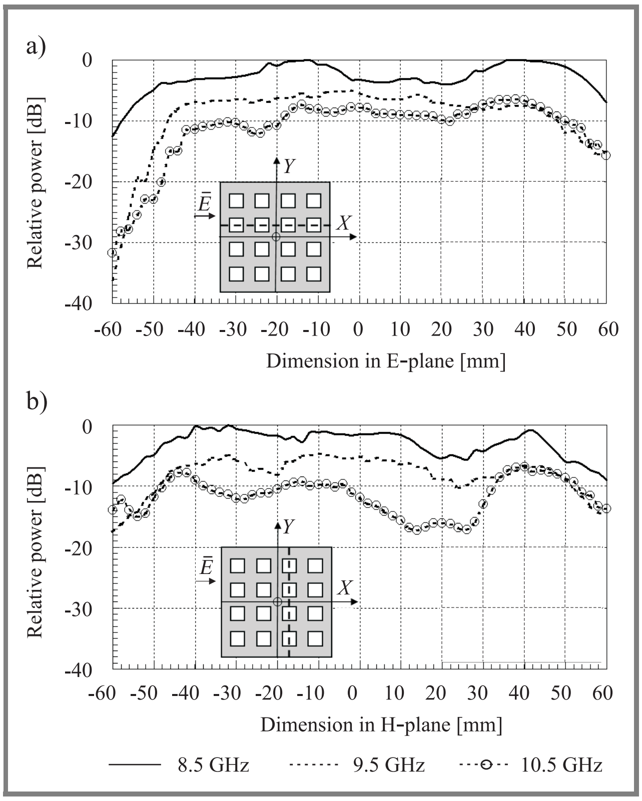

Fig. 8. Measured near-field magnitude distribution in (a) E-plane cut and (b) H-plane cut at the output side of the active 4×4 SP TXA illuminated by a hard horn at three selected frequencies.

6. Conclusion

In this paper, stacked patch antenna elements connected to input and output ports of individual amplifiers have been proposed to increase the operational bandwidth of a space-level combiner employing a planar amplifying transmitarray. Two configurations of a unit cell prototype using three different SP antennas have been designed and investigated. Only the one showing a small insertion loss over an increased operational bandwidth has been used to form a 4×4 cell planar array for an X-band power combiner. Two hard horns for signal launching and combining have been designed, manufactured and tested to complete the design of the spatial power combiner. The structure has shown a minimum insertion loss of 4.3 dB at 9 GHz with 3 dB-gain bandwidth of 2.2 GHz when the passive array is placed between the two horns. The combiner with an active array has demonstrated a maximum small signal gain of 3.46 dB at 8.7 GHz, while taking into account all associated losses, with a 3 dB-bandwidth of about 1.9 GHz. This operational bandwidth could not be achieved using a transmitarray of edge-fed microstrip patches.

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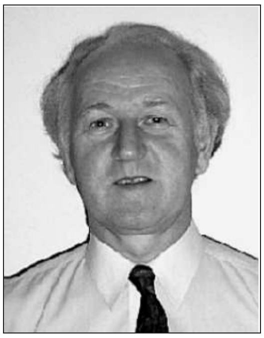

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