Transmit Array of Transistor Amplifiers Illuminated by a Patch Array in the Reactive Near-Field Region

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***Abstract*—In this paper, a small transmit array of transistor amplifiers illuminated by a passive array of microstrip patches in the reactive near-field region is investigated as a power-combining structure. The two cases considered are when the transmit array radiates in a free space and when a passive array similar to the one used for illumination collects the radiated power. A comparison of the performance of the proposed structure against the alternative one, which uses a conventional horn antenna as a power-launching/receiving device, is also presented.**

***Index Terms*—Active antennas, active arrays, amplifiers, antenna arrays, power combiners.**

I. Introduction

RECENT years have seen significant advances in spatial power-combining methods of microwave and millimeter-wave solid-state devices [1]–[6]. Particular attention has been given to planar structures with a large number of identical active elements arranged in two-dimensional arrays to generate increased power levels. Although both oscillators and amplifiers can be used in such configurations, the preference is given to amplifiers because of the more predictable design and other attributes such as a larger operational bandwidth. Particular interest has focused on transistor amplifiers due to their considerably higher dc–RF conversion efficiency in comparison with two-terminal devices like Gunn or IMPATT diodes. In order to combine power in space, these amplifiers are equipped with receiving and transmitting antenna elements.

In early research, most of the emphasis has been placed on maximizing the added power of an active array without considering losses in the launching and receiving stages. For example, in order to obtain maximum power-combining efficiency (defined as the output power of the active array divided by the number of elements and the output power of a single element in isolation—note that this definition may lead to the efficiency larger than 100% [2]) individual devices require an in-phase operation, and such a condition has often been realized using an illuminating horn antenna in the far-field region of the array. The horn located in this region produces a spherical wavefront, which becomes approximately planar and uniform in the vicinity of the array. With this condition and the condition that mutual interactions between elements do not perturb the illumination pattern (which is valid for weakly interacting elements), the output signals combine with approximately equal magnitude and phase leading to high power-combining efficiency. Despite the considerable amount of added power, such power combiners have hardly shown any gain with respect to their input/output ports because of significant losses due to spillover.

Recent papers have recognized the deficiency of not considering launching and receiving stages in the power-combining process. With the aim of avoiding spillover, which reduces the available output power, a hard horn placed in the reactive near-field zone [3] of the active array has been proposed as an efficient power-launching and receiving device. This type of antenna provides more uniform aperture illumination than an ordinary horn [2, Ch. 6]. Hence, it enables more efficient in-phase power combining. Despite allowing high power-combining efficiency, one drawback of a horn as a power-launching and collecting device is its nonplanar and bulky shape. Another matter is its operational bandwidth in conjunction with an active array, which has not been fully investigated. Many of the published results (e.g., [7]–[9]) have shown a narrow-band performance of the combiner using a horn in the near-field zone of the active stage, indicating that such results could be due to the microstrip patches of the active stage. However, it is possible that the near-field interactions between the microstrip patches and a horn antenna may be the additional reason for the narrow-band performance and, hence, more studies are required to clarify this issue. In this context, other launching and receiving devices are also worth considering.

In [10], a corporate-fed aperture-coupled patch array placed in the near-field region of the active array has been proposed as an alternative power-launching and receiving device. The advantage of this device is that it preserves a planar structure of the entire power combiner while providing highly uniform illumination of an active transmit array for maximum power-combining efficiency.

In this paper, further considerations of the choice between the passive patch array and a horn antenna as a power-launching/receiving component are presented. Next, the performance of a four-element active combiner is shown to demonstrate the capabilities of a corporate-fed aperture-coupled patch array to efficiently excite a small-size active transmit array. The experiment provides a proof of the power-combining concept proposed in [10].

II. Combiner Configuration and Design

The general configuration of the proposed power combiner is shown in Fig. 1. This is a hybrid spatial and circuit-feed system with the near-field cascade/free-space active stage [2, Ch. 2]. This stage is formed by planar arrays of transistor amplifiers

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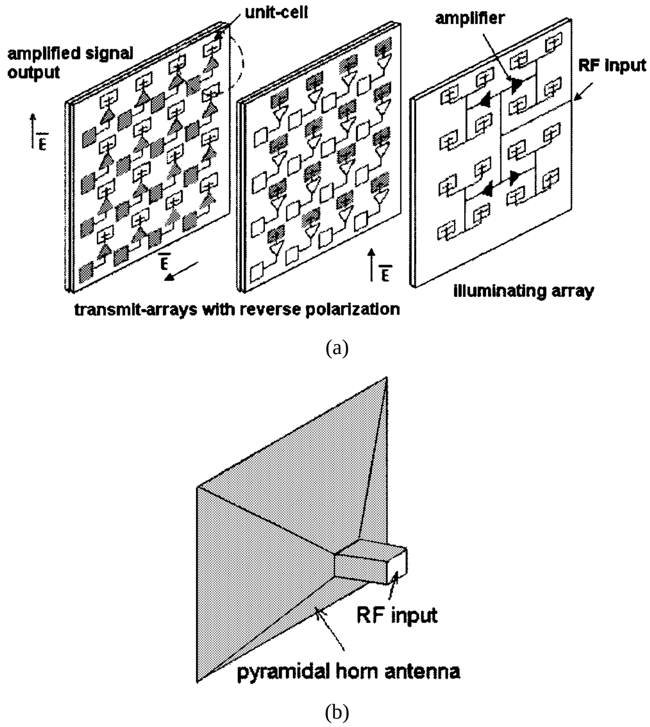

Fig. 1. (a) Configuration of power combiner including a cascade of active microstrip patch transmit arrays and a passive or active illuminating array. (b) An alternative launching device in the form of a pyramidal horn antenna.

whose input and output ports are connected to microstrip patch antennas. These antennas, i.e., an edge fed patch and an aperture-coupled patch, appear on two sides of the ground plane of each array. The reason for placing them on different sides is to achieve isolation between input and output ports of individual amplifiers and, thus, prevent oscillations while keeping inter-element spacing in the order of 0.7–0.8 free-space wavelength. This spacing is required to achieve high power-combining efficiency in terms of suitable radiation pattern (e.g., to avoid grating lobes, which occur when the element spacing reaches or exceeds one free-space wavelength), as well as to get efficient coupling between the launcher and the active stage [9], [10]. Note that, in order to further increase isolation between input and output ports of amplifiers, the two antenna elements use orthogonal linear polarization.

Depending on the choice of receiving stage, the proposed power-combining structure can be divided into two types [10]. The first type is the *nonconnectorized combiner*, as shown in Fig. 1(a). This structure radiates straight into free space and, because of its low profile, it may be attractive for such applications as airborne radar, where low weight and low profile are the desired features. The second type of combiner is the *connectorized combiner*, which uses an additional receiving array similar to the one for launching purposes (not shown in Fig. 1). This type of combiner utilizes connectorized input/output ports similar to a conventional circuit, waveguide, or cavity type combiner [4]. Another configuration, which is promising, but not studied here, is the one that uses a horn for collecting the output power, leaving the corporate-fed array only in the illuminating stage.

An analogous configuration of spatial combiner, which is able to fulfill the requirement of small inter-element spacing in the active stage, was presented in [2, Ch. 6] and [7]. In that case, cross-polarized receiving and transmitting antennas of the active stage were positioned on two sides of a ground plane. However, in contrast to the configuration presented here, each side was active (transistor amplifiers were positioned on both sides) and the coupling between the two stages was achieved using holes in the ground plane. Horn antennas were used as power-launching/intercepting devices. Note that the small inter-element spacing can be also achieved using a reflect array instead of a transmit array [11], [12].

In the present case, the power-launching/illuminating stage for the active transmit array is a corporate-fed aperture-coupled microstrip patch array. As shown in Fig. 1(a), this array can be passive or active. In the active case, due to the limitation of the available space, amplifiers are not connected to individual radiating elements. Instead, they are incorporated with small sub-arrays, e.g., of 2×2 elements. The proposed inclusion of amplifiers in the launching array follows the general design principles of conventional power combiners, which, in the input stages, use circuit-type power combiners [4]. Note that the proposed configuration is the type of hybrid circuit-spatial combiner, considered as a viable configuration in the most recent reports on spatial power combiners [2, Ch. 2]).

A. Patch Array Versus Horn as an Illuminating Device

As already stated, in many investigated spatial combiners involving active microstrip patch arrays, a conventional horn antenna has been chosen as an illuminating/receiving device [2], [3]. This component makes the combiner bulky [see Fig. 1(b)], especially in the case of large-size arrays. This may be found inconvenient in applications requiring low profile and lightweight devices. Disregarding the size and shape, one would like to compare the two alternative power-launching/receiving devices of Fig. 1 (the array and horn) in terms of other parameters such as insertion loss and achievable bandwidth. A brief comparison concerning these parameters is presented in this section in the examples of 4×1 and 4×2 element passive transmit arrays. Only connectorized-type combiners using passive arrays or horns as power-launching/receiving devices are considered. The comparison in terms of power-combining efficiency is not covered here. This parameter, related to the uniformity of excitation of the array, is addressed below in the following section. The test setup to perform the required comparisons is shown in Fig. 2. In this setup, the spacing between arrays is established using a specially designed jig with rails. In the present study, tests are performed in Ku-band centered at about 12.5 GHz.

The arrays are designed assuming a 0.483-mm-thick low-loss Ultralam substrate ($\varepsilon_r = 2.45$) from Rogers. In order to increase the operational bandwidth, a 0.8-mm-thick layer of air (in practice, created by small plastic spacers located on four corners of the substrate) is applied between the patch and aperture layers. Both aperture-coupled patch elements and edge-fed patch elements are designed for 50-Ω operation. For the edge-fed patch antenna, an inset in the patch is used to obtain the 50-Ω input impedance match. The design of the two varieties of antenna elements and arrays is aided with Ansoft's antenna design package Ensemble. Following a manual optimization using Ensemble, the resulting

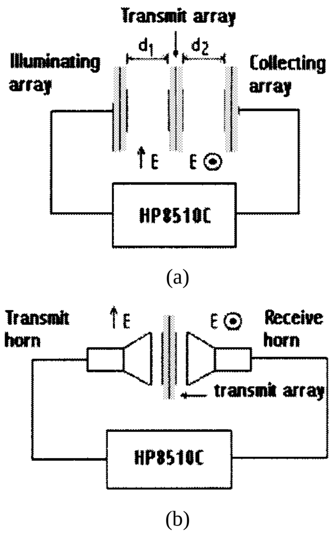

Fig. 2. HP8510C VNA measurement setup for a connectorized power combiner using: (a) arrays and (b) horns in the launching and receiving stages.

dimensions of the aperture-coupled patch are $\mathrm{width} = 7.2$ mm and $\mathrm{length} = 7.6$ mm, with a rectangular slot 0.3 mm $\times$ 6.9 mm. Similarly, the dimensions of the edge-fed patch were 7.4-mm width and 7.63-mm length and a 2.5-mm inset. These antenna elements feature 0.6 and 0.2 GHz, respectively, 10-dB return-loss bandwidth when tested in isolation. The resulting 4 $\times$ 1 element transmit arrays dimensions are about 65 mm $\times$ 10 mm using inter-element spacing of 0.8 free-space wavelength (λ_0). Similarly, the 4 $\times$ 2 element transmit arrays' dimensions are approximately 70 mm $\times$ 30 mm using identical inter-element spacing of 0.8 free-space wavelength (λ_0). Both the 4 $\times$ 1 and 4 $\times$ 2 element transmit arrays are developed on a 120 mm $\times$ 80 mm ground plane. The reason for choosing such a ground plane is to obtain a good match with dimensions of apertures of the available horns. The two sets of horns available to the authors featured the following dimensions. Set I having aperture dimensions of 124 and 92 mm in H- and E-planes and axial length of about 30 cm from apex to aperture and Set II having aperture dimensions of 70 and 70 mm in H- and E-planes and axial length of about 15 cm from apex to aperture. During measurements, transmit arrays were centered with respect to the apertures of the transmitting and receiving arrays or horns.

Fig. 3 shows the insertion loss performance of the 4 $\times$ 1 and 4 $\times$ 2 element passive transmit arrays in the connectorized configurations. These results are for spacing between the transmit arrays and the launching/receiving arrays of 8 and 10 mm, respectively, which produced minimum insertion loss at frequencies close to the design frequency of 12.5 GHz. As observed in Fig. 3, the measured insertion loss (S_{21}) of the complete 4 $\times$ 1 element passive combiner, which includes the passive transmit array and illuminating and collecting arrays is -5.2 dB at the design frequency of 12.5 GHz. This value is consistent with the value of insertion loss obtained in the theoretical investigations in [10]. As shown in Fig. 3, using the 4 $\times$ 2 element transmit array, the losses of launching and intercepting stages including the loss due to spillover are minimized to -4.8 dB. It can be noticed that the 4 $\times$ 2 element array produces smaller insertion

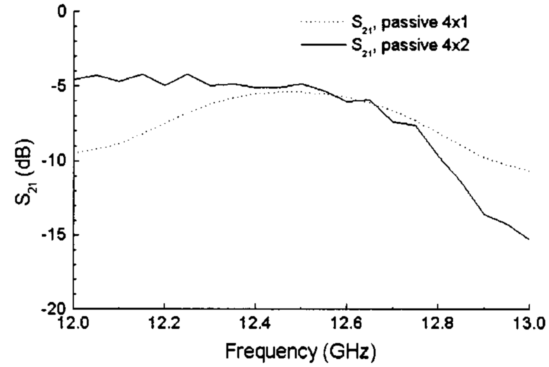

Fig. 3. Comparison of measured insertion loss between the passive 4 $\times$ 1 and 4 $\times$ 2 element combiners.

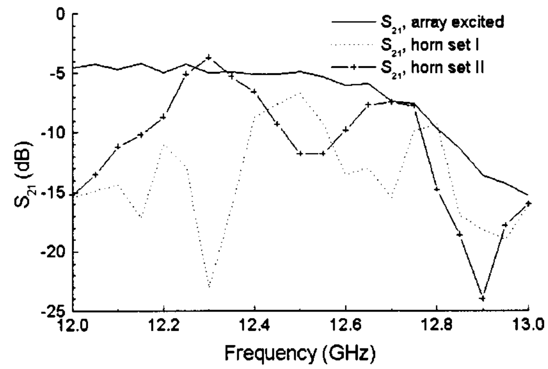

Fig. 4. Comparison of measured insertion loss of the passive 4 $\times$ 2 element combiner when either the corporate-fed arrays and two sets of pyramidal horns are used as launching and receiving devices.

losses and provides a broader bandwidth than the 4 $\times$ 1 element array. According to our early investigations in [10], the complete combiner losses are expected to be further reduced to about -4.2 dB by increasing the array size to 4 $\times$ 4 elements.

In the next tests, the horn antennas replaced launching and receiving arrays and only the 4 $\times$ 2 element array was tested. The reason for selecting only this array was that it better matched the apertures of the available horns and, hence, it led to smaller insertion losses. In order to perform satisfactory comparisons against the corporate-fed launching/receiving arrays, the horns were placed in the near-field zone of the transmit array at distances producing minimum insertion losses at frequencies close to the design frequency of 12.5 GHz. The distances on the launching and receiving sides were 8 and 7 mm, respectively, for horn Set I and 6 and 6 mm, respectively, for horn Set II.

Fig. 4 shows the measured insertion loss as a function of frequency for the 4 $\times$ 2 element passive combiner with either the corporate-fed arrays or the pyramidal horn as a signal launching/receiving device. The combiner with corporate-fed arrays produces a relatively flat insertion loss as a function of frequency with the minimum value of -4.2 dB. The combiner with the horn Set I produces a varying insertion loss with the minimum value of -6.7 dB at 12.5-GHz frequency. This insertion loss is larger than the one obtained when the corporate-fed arrays are used as launching/receiving devices. The combiner with the horn Set II produces insertion loss as a

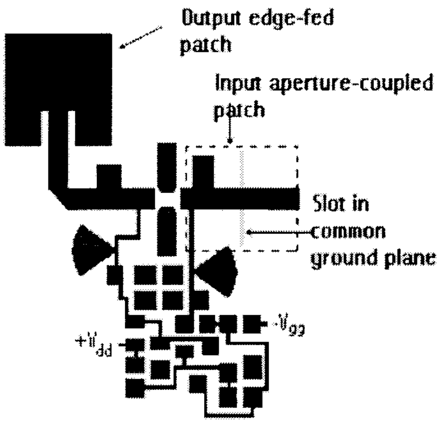

Fig. 5. Layout of the spatial power-combiner unit cell with the auto-bias circuit.

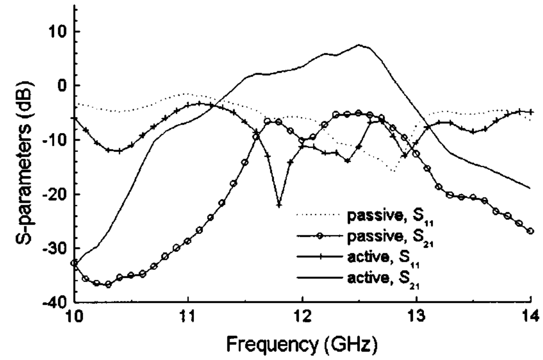

Fig. 6. Measured return loss (S_{11}) and insertion loss/gain (S_{21}) of the passive and active 4 × 1 element connectorized power combiner.

varying function of frequency. The minimum insertion loss of −3.7 dB occurs at about 12.3 GHz and is narrow band.

The overall comparison between the three sets of measured results shows that the microstrip patch antennas employed in the transmit array are not entirely responsible for the narrow-band performance of the investigated power-combining structures. In the case of horns, it is the near-field interaction between the patches and horns that reduce the operational bandwidth of the combiner. In the presented cases, it is apparent that the power combiner including corporate-fed arrays as power-launching/receiving devices provides the largest operational bandwidth for the minimum value of insertion losses.

B. 4 × 1 Element Active Transmit Array

After accomplishing the tests of passive 4 × 1 and 4 × 2 element transmit arrays using different power-launching/receiving devices, the next stage concerned investigations of an active transmit array. The designed array consists of four active unit cells arranged in a linear fashion with inter-unit-cell spacing of 0.8 λ_0. Each unit cell has one low-noise NEC NE32484A FET amplifier with an auto-bias circuit, which is integrated with aperture-coupled and edge-fed patch antennas, as shown in Fig. 5. The aperture-coupled patch located on one side of the substrate receives the incoming signal, which is coupled via a rectangular slot in a common ground plane to the input of the FET amplifier. Here, it is amplified and then transmitted into free space using an edge-fed patch antenna.

In the present case, the unit-cell amplifier was designed using manufacturer's data and HP-EEsof design tools assuming a 0.483-mm-thick low-loss Ultralam substrate with $\varepsilon_r = 2.45$. This amplifier was manufactured and its performance was tested prior to its integration with patch antennas using an HP8510C vector network analyzer (VNA). The measured gain was 11.5 dB at 12.5 GHz when the FET was biased at $V_{\rm DS} = 2$ V and $I_D = 10$ mA. This gain stayed approximately constant from 11.5 to 13 GHz.

Following its successful testing, the amplifier was integrated with patches identical to those used in the passive prototypes. The design of a unit-cell amplifier was repeated to form an active 4 × 1 element transmit array, which was then tested in connectorized and nonconnectorized power-combining configurations. The spacing between illuminating, transmit, and intercepting arrays was selected for optimal performance at 12.5 GHz, as already established for the passive transmit array.

III. Results for Active Array

The connectorized 4 × 1 element active combiner was tested using the same test jig as for the passive combining structures. The nonconnectorized active combiner was tested in terms of gain and radiation pattern in an anechoic chamber using an HP8530A receiver. This receiver is effectively the HP8510C VNA, which uses different calibration and measurement software. The results for return loss and insertion loss/gain of the passive and active 4 × 1 element connectorized combiners, as measured over the frequency band from 10 to 14 GHz, are presented in Fig. 6. The array separation between the illuminating array and the active transmit array was 8 mm, which was very close to the optimum value obtained in the passive case.

As seen in Fig. 6, when the active transmit array replaces the passive one, the measured gain (S_{21}) of the combiner is 7.5 dB. This value indicates approximately 12.7 dB of relative small-signal gain of the active array over the passive one. Note that this value is slightly higher than the measured 11.5 dB gain of the connectorized FET amplifier prior to its inclusion in the unit cell. The 3-dB bandwidth of the active combiner is 650 MHz, which is from 12.05 to 12.7 GHz. The return loss of the active combiner is better than 10 dB from 11.65 to 12.6 GHz.

Due to the difficulty of comparing insertion losses under different conditions of launching and receiving power for a single and arrayed amplifier, an indirect method of estimating power-combining efficiency by measuring the radiation pattern was applied. The usual requirement for high power-combining efficiency is uniform (equal magnitude and phase) excitation of the active array. Under such a condition, individual amplifiers equally contribute to the output power and none of them becomes prematurely saturated when a large signal enters the input port of the combiner. Investigating the measured near- or far-field radiation pattern of the array can identify this type of excitation [13].

Figs. 7 and 8 show measured E- and H-plane far-field radiation patterns of the 4 × 1 element passive and active transmit arrays in the nonconnectorized configurations at 12.5 GHz. The 3-dB beamwidth of the E- and H-plane patterns of the active transmit array is 15.8° and 79.2°, respectively, which is very

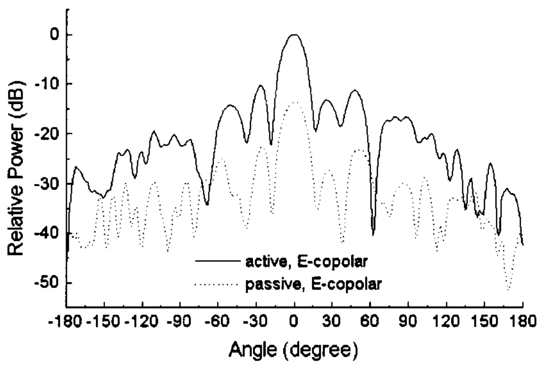

Fig. 7. Measured E-plane far-field radiation patterns of 4 × 1 element passive (· · ·) and active (—) nonconnectorized power combiners.

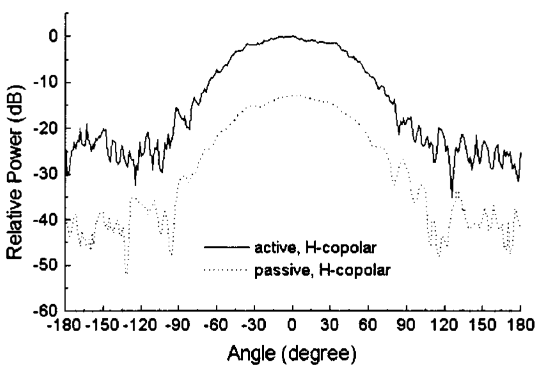

Fig. 8. Measured H-plane far-field radiation patterns of 4 × 1 element passive (· · ·) and active (—) nonconnectorized power combiners.

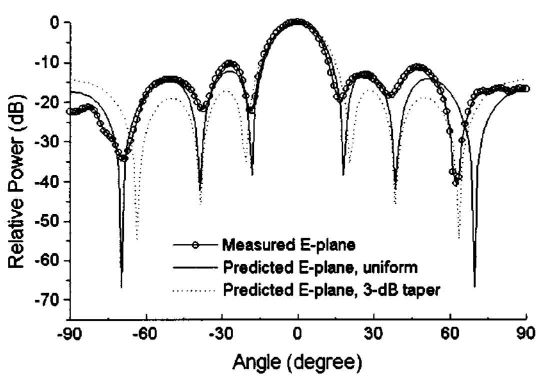

Fig. 9. Comparisons of the measured E-plane radiation pattern of the 4 × 1 element nonconnectorized combiner with the predicted radiation assuming uniform excitation and −3-dB taper of the two outer antenna elements.

close to the predicted values of 16.1° and 81.5° by PCAAD software[1] for uniform excitation. In Figs. 9 and 10, the measured E- and H-plane radiation patterns of the active 4 × 1 element transmit array are also compared to theoretical patterns, as predicted by the PCAAD software for a uniformly excited four-element patch linear array. The E-plane plots also include the radiation pattern of the array when the magnitude taper of −3 dB is applied to the two outer elements.

[1]D. M. Pozar, *Personal Computer Aided Antenna Design* (PCADD), ver. 2.1, Dec. 1991

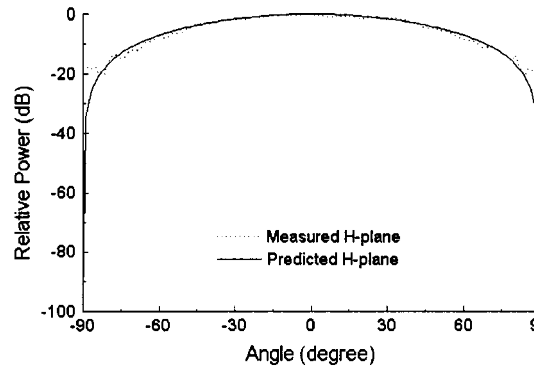

Fig. 10. Comparisons of the measured H-plane radiation pattern of the 4 × 1 element nonconnectorized combiner with the predicted radiation pattern.

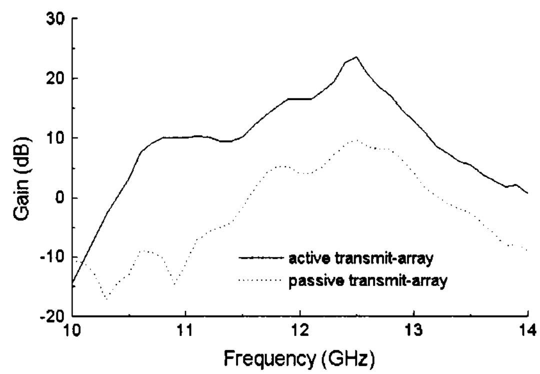

Fig. 11. Measured gain of the 4 × 1 element passive (· · ·) and active (—) nonconnectorized power combiners including losses of the illuminating array.

Fig. 7 shows that the first sidelobes of the measured E-plane pattern are all close to the theoretical value of −12.2 dB for uniform excitation. This result indicates that the passive aperture-coupled patch array uniformly excites the active transmit array and, hence, each amplifier in the array equally and in-phase contributes to the output power leading to high power-combining efficiency. The theoretical pattern of the array with the magnitude taper applied to the outer elements (which is the case of nonuniform illumination) shows sidelobes lower than for the uniform excitation.

Fig. 11 shows the gain of the passive and active 4 × 1 element nonconnectorized power combiners as referenced to the gain of two X-band standard horns. Peak gains of the passive and active combiners are 9.7 and 23.5 dB, respectively, and they both occur at the design frequency of 12.5 GHz. The 13.8-dB relative gain of the active nonconnectorized power combiner over the passive one is slightly larger than the 12.7-dB small-signal gain, which was obtained for the 4 × 1 element active connectorized combiner. This small discrepancy could be due to the fact that the separation between the illuminating and the transmit arrays for optimal power combining was slightly different for the connectorized and nonconnectorized cases. During measurements, this spacing was kept constant and equal to the optimal one for the active case. A 3-dB gain bandwidth of the active nonconnectorized combiner is 0.35 GHz from 12.3 to 12.65 GHz. This narrow-band operation can be improved by using antenna elements with increased operational bandwidth in place of the edge-fed patch antennas.

IV. CONCLUSIONS

This paper has presented a novel configuration of a planar combiner using an active transmit array of transistor amplifiers with microstrip patches at input/output ports illuminated by a passive or active array of corporate-fed aperture-coupled patches. The receiving and transmitting antennas of the active array are positioned on the two sides of substrate to provide suitable isolation of input and output ports of transistor amplifiers and to meet small inter-element spacing for the optimal power-combining conditions. The proposed power-combining structure has been investigated in two configurations: one (nonconnectorized)—in which power has been radiated in free space, and two (connectorized)—when a passive array similar to the one for illumination purposes has been additionally included to receive the radiated power. In order to investigate advantages and disadvantages of the corporate-fed array against a horn antenna as an illuminating/receiving device, comparisons have been performed in terms of insertion loss and available bandwidth for passive 4×1 and 4×2 element transmit arrays. These comparisons have taken place after selecting the optimal spacing between illuminating/receiving devices and transmit arrays at the design frequency. The experimental results have shown that, in terms of insertion loss or gain, a passive array used as an illuminating device provides similar performance as an ordinary horn. However, in terms of operational bandwidth, the array seems to outperform the horn. The minimum insertion loss is approximately uniform with respect to frequency for the power-combining structure utilizing corporate-fed patch arrays. In contrast, the structure using horns in the near-field zone of the transmit array as power-launching/receiving devices shows a narrow-band minimum insertion-loss performance. This can be due to adverse near-field interactions between the outer most elements of the transmit array and the conductive surface of the horns.

As a next step, an active 4×1 element transmit array has been developed and investigated. The nonconnectorized and connectorized versions of a 4×1 element array have shown highly uniform aperture illumination as confirmed by the measured gain and radiation patterns, indicating high power-combining efficiency. The array shows a positive gain reduced by losses in the power-launching/intercepting stages. The measured value of insertion losses is consistent with the one obtained from the theoretical investigations of passive transmit arrays.

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