Paper

A broadband uniplanar quasi-Yagi antenna – parameter study in application to a spatial power combiner

Marek E. Białkowski, Hyok J. Song, and Paweł Kabacik

Abstract — A parameter study is performed of a broadband uniplanar quasi-Yagi antenna with regard to its design and use in a spatial power combiner. A 3D full-wave electromagnetic field analysis is applied to identify parameters, which mostly affect the design frequency and operational bandwidth of this antenna. Optimal design conditions are determined. Using these design criteria a passive spatial power combiner employing trays of back-to-back connected quasi-Yagi antennas is developed. This combiner is investigated in terms of insertion losses and field uniformity, which are key factors in obtaining high power combining efficiency.

Keywords — broadband quasi-Yagi antenna, passive spatial power combiner.

1. Introduction

In recent years a lot of interest has been shown in spatial power combining methods to overcome difficulties in generating high power levels from solid-state devices at millimeter-wave frequencies [1]. Although oscillators and amplifiers can be spatially combined, most of the recent research activities have been devoted to amplifiers due to their more predictable performance and a larger operational bandwidth. In order to obtain low manufacturing costs, **tile** and **brick** configurations of planar antenna arrays have attracted a lot of attention [2] as suitable power combining structures. In these arrays antenna elements are connected to the input and output ports of the individual amplifiers. The input antenna element receives the signal and passes it to the amplifier. The amplifier passes the amplified signal to the output antenna where it is radiated. Power from the array is intercepted in free space by a receiving/collecting antenna such as a horn antenna. Due to the fact that the tile configuration usually employs resonant type antenna elements, such as microstrip patch antennas, this type of power combiner is narrow-band in operation. The resulting operational bandwidth is usually smaller than that of the individual amplifiers when they are assessed without radiating elements [3, 4]. The motivation of the work presented in this paper is to explore new antenna elements arranged in the brick configuration to fully utilize the surplus bandwidth of transistor amplifiers.

One possible choice, which has already been explored in [5], is a planar-type linear tapered slot antenna (LTSA). This antenna element, when properly designed, features large (multi-octave) operational bandwidth and because of an end-fire radiation characteristic it is suitable for inclusion as an element of a brick or tray array. One flaw of this solution is that the LTSA features a relatively large size with length L being in the order of $2\lambda_0 \leq L \leq 12\lambda_0$ and the termination width of $W \geq \lambda_0/2$ [6]. In [7] Qian *et al.* proposed an uniplanar quasi-Yagi antenna whose size is significantly smaller than that of the LTSA. A large operational bandwidth in the order of 48% for VSWR < 2 was demonstrated in X-band [8]. Although this antenna element is compact and provides a suitable bandwidth to match individual transistor amplifiers its design strategy has not been well documented.

This paper investigates the effects of five main design parameters of the uniplanar quasi-Yagi antenna on its operational frequency and impedance bandwidth. The study identifies parameters most affecting the performance of this antenna. The presented findings should be of interest to the designers of the quasi-Yagi antenna for applications such as a spatial power combining and other wireless communications applications.

2. Configuration

Figure 1 shows the configuration of the uniplanar quasi-Yagi antenna, which consists of a director and a driver fed by a broadband microstrip to coplanar strip transition [7]. A delay of half wavelength introduced in one of the two microstrip arms is required to obtain the odd mode coupling. The truncated ground plane on the backside of the substrate is used as a reflector. The operation of this antenna has been described in [7, 8] and hence it is not repeated here. Instead, the effects of different parameters of this antenna on its performance are studied here.

3. Parameter study

Due to the complex structure of the quasi-Yagi antenna, a 3D full-wave electromagnetic simulation package is necessary to efficiently carry out the parameter study. A commercially available 3D full-wave EM package, IE3D of Zeland Software, based on the method of moment (MoM) is used here to analyze the antenna performance in terms of its return loss.

Five design parameters considered in the present study include: parameter *1* – length of the director, parameter *2* – distance between the director and the driver, parameter *3* – distance between the coupled microstrip lines, parameter *4* – length of the driver, parameter *5* – distance from the driver to the reflector. All these parameters are respectively shown in Fig. 1.

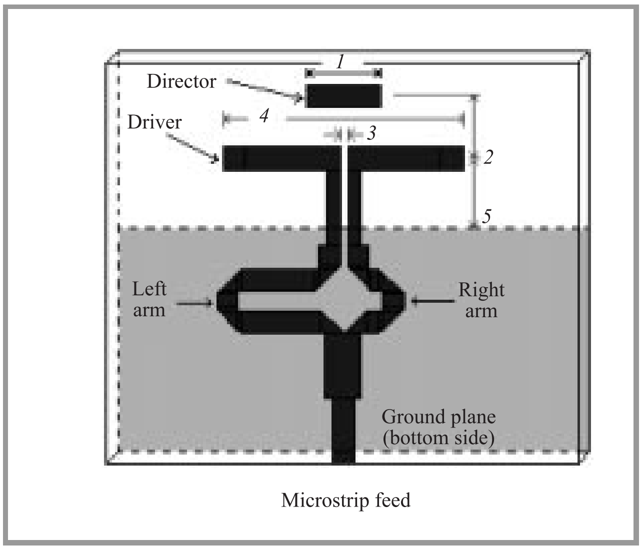

Fig. 1. Configuration of uniplanar quasi-Yagi antenna.

In order to gain the confidence in the accuracy of the EM software used in this study, a prototype quasi-Yagi antenna was designed, developed and tested and the measured results were compared against the theoretical ones. The design frequency was selected as 12.5 GHz and the initial antenna dimensions were chosen by referring to the design of a normal Yagi-Uda antenna. A substrate with a relative dielectric constant of 2.45 and thickness of 0.48 mm was assumed. The design was performed using IE3D. A manual iteration procedure was applied to achieve impedance bandwidth comparable to that demonstrated in [8]. The final antenna dimensions included: length of director (parameter *1*) = 4.8 mm, distance between the director and the driver (parameter *2*) = 4.0 mm, distance between the coupled microstrip lines (parameter *3*) = 0.5 mm, length of the driver (parameter *4*) = 15.5 mm, and distance from the driver to the reflector (parameter *5*) = 4.13 mm. Figure 2 shows both simulated and measured return loss of the final design. It can be seen that the simulation result closely follows the measured one. The frequency shift can be due to an insufficiently fine grid of the structure used in simulations. Nevertheless, a relatively good agreement confirms the validity of the chosen software to be used in the parameter study.

The results of simulations for the return loss with respect to parameters *1* to *5* are presented in Fig. 3(a−e). Figure 3a shows the results when parameter *1* is varied by 1 mm from 3.8 mm to 5.8 mm. The results show that the return loss is not sensitive to the changes of parameter *1*. Figure 3b shows the results when parameter *2* is varied

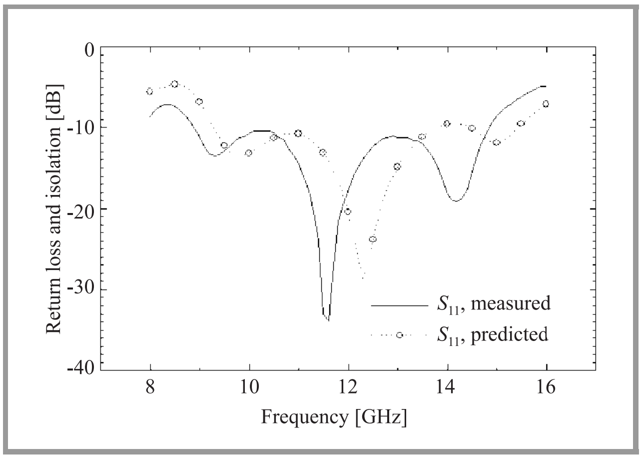

Fig. 2. Measured return loss of the optimized Ku-band quasi-Yagi antenna.

by 1 mm from 3 mm to 5 mm. The results show that parameter *2* only slightly affects the return loss. Figure 3c shows the results for the return loss when the gap between the coupled microstrip lines (parameter *3*) is varied in steps of 0.2 mm from 0.5 mm to 0.7 mm. The results reveal that the return loss degrades when the gap between the two microstrip lines is reduced. Figure 3d shows the results when the length of the driver (parameter *4*) is varied by increments of 2 mm from 13.5 mm to 17.5 mm. As observed in Fig. 3d the return loss is very sensitive to the changes of this parameter. This parameter affects both the impedance bandwidth and the center frequency. Finally Fig. 3e shows the results when parameter *5*, which is the distance from the driver to the reflector, is varied by increments of 1 mm from 3.13 mm to 5.13 mm. As seen in Fig. 3e the return loss is sensitive to this parameter. It affects the impedance bandwidth as well as the design frequency. The results presented in Fig. 3(a−e) reveal that the length of the driver (parameter *4*) is optimum when it is about a guide wavelength and the distance between the driver and the reflector (parameter *5*) is about a quarter guide wavelength.

4. Design of a power combiner

Having successfully designed a single quasi-Yagi antenna, the next step is to show that this antenna can properly operate when used as an element of a spatial power combiner. Here only a passive power combining structure is investigated. The investigations are restricted to practical experiments because the highly complicated 3D structure of the combiner is difficult to study theoretically.

Figure 4a shows the construction of a power combiner that includes two horn antennas for power launching and receiving purposes and several trays each consisting of two Yagi antennas positioned back-to-back, as shown in Fig. 4b.

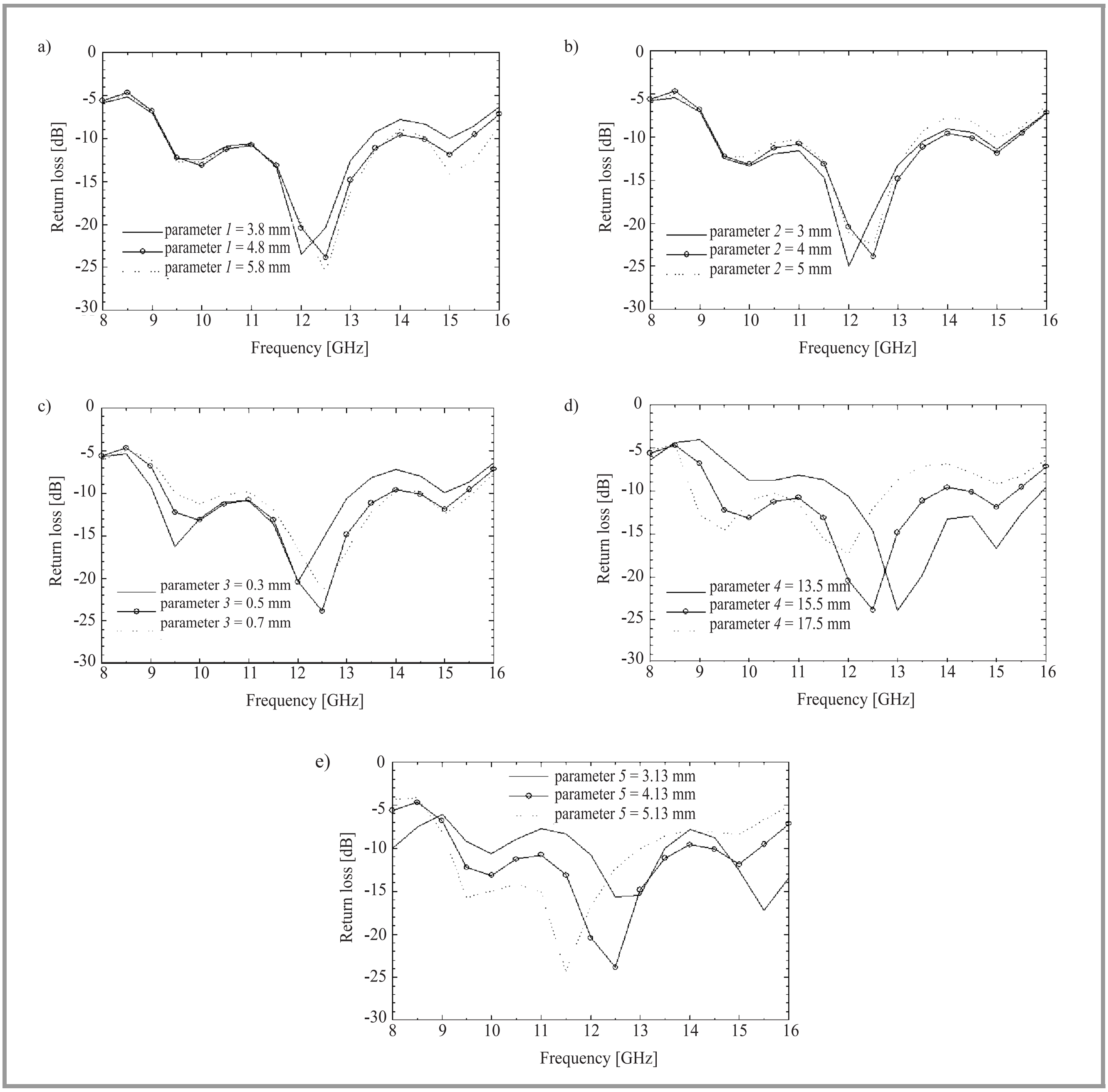

Fig. 3. Simulations results for the return loss of an uniplanar quasi-Yagi antenna when: (a) parameter *1* – length of the director; (b) parameter *2* – distance between the director and the driver; (c) parameter *3* – distance between the coupled microstrip lines; (d) parameter *4* – length of the driver, and (e) parameter *5* – distance from the driver to the reflector are varied.

As seen in Fig. 4a the trays are positioned parallel to the E-plane of the horns and hence they are stacked along the H-plane. The space between the input ports of the antennas in the tray in Fig. 4b is left to test the tray for isolation between the two ports. High isolation is required when an amplifier is included so that possible oscillations due to the feedback between amplifier's input and output ports are not present. Blocks of 6.4 mm Rohacell foam featuring the relative constant of 1.07 located on the sides of the trays are used to support the trays. The replacement of these foam spacers by spacers made in copper did not show any significant difference in all the measured results. The overall setup dimensions are as follows. The two horns feature aperture dimensions of 34 mm $\times$ 48 mm respectively in the direction of E- and H-field. The single tray features physical dimensions of 60 mm $\times$ 60 mm with its aperture width of about 16 mm that corresponds to the length of the driven element of the Yagi antenna.

Figure 5 shows the measured isolation for the tray configuration of Fig. 4. Note that in the experiment, the input ports to the two antennas were separated by 8 mm to enable their input ports to be connected to the vector network

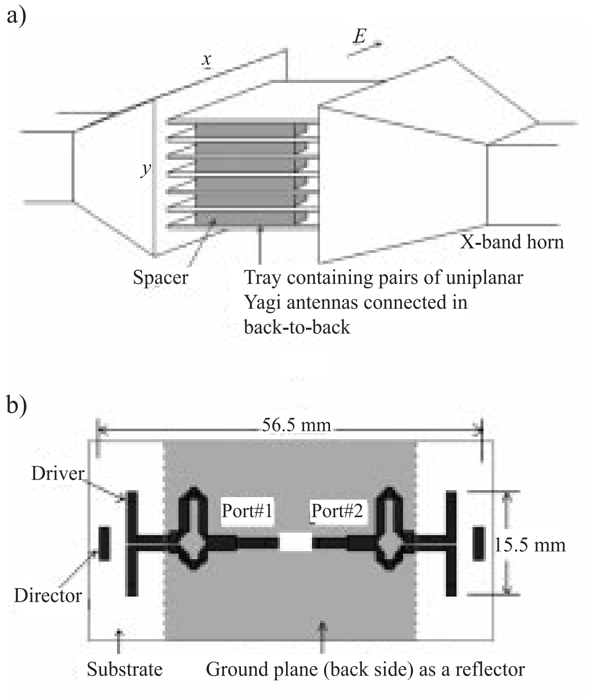

Fig. 4. (a) A perspective view of the power combiner consisting of 7 passive trays with horn antennas as distributing/combining devices, and (b) a layout of a passive tray containing two uniplanar quasi-Yagi antennas connected back-to-back.

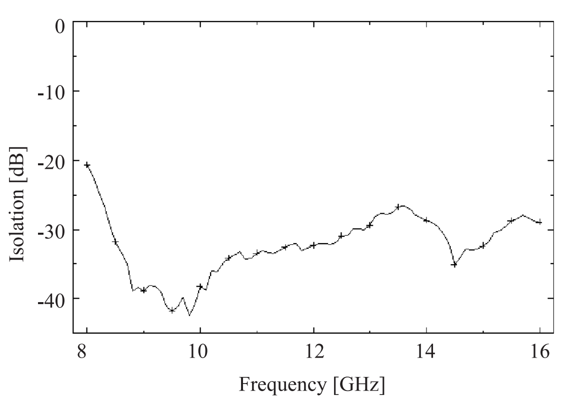

Fig. 5. Measured isolation (S_{12}) between input ports of the passive tray formed by two back-to-back connected quasi-Yagi antennas.

analyzer. High value of isolation, being greater than 25 dB over the frequency band from 8.5 GHz to 16 GHz is observed. This result indicates that the developed passive tray is ready to accommodate a broadband amplifier designed for the 50-ohm input/output operation whose gain does not exceed 25 dB across the frequency band from about 9 GHz to 15 GHz.

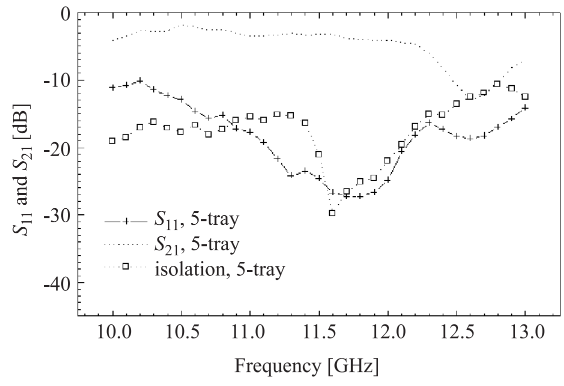

Fig. 6. Return loss (S_{11}) and insertion loss (S_{21}) as measured with respect to the horn ports for the 5-tray combiner. Also shown is isolation for this combiner when driven elements of Yagi antennas are short-circuited.

Figure 6 shows the measured results for return loss and insertion loss as observed from the coaxial ports of the transmitting and receiving horns of the 5-tray combiner.

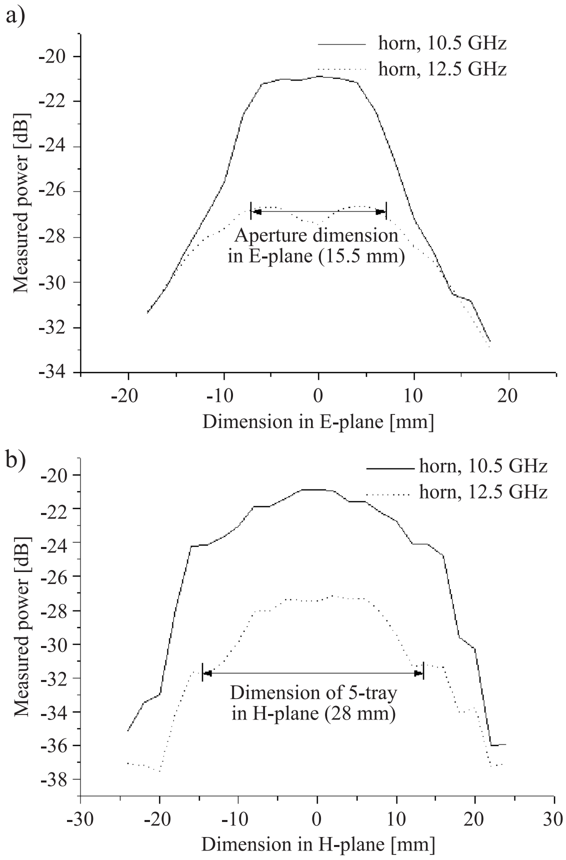

Fig. 7. Measured power distribution across two principal planes at the aperture of the X-band pyramidal horn, having dimensions 34 mm × 48 mm respectively in the E- and H-planes, at 10.5 GHz and 12.5 GHz: (a) E-plane cut, (b) H-plane cut.

Also shown in Fig. 6 is the isolation when the quasi-Yagi antennas of the 5-tray combiner become short-circuited. The lowest insertion loss of 1.8 dB occurs at 10.5 GHz with 3 dB bandwidth covering from 10 to 12.2 GHz. It is also observed that the insertion loss curve rolls off as frequency increases toward 12.5 GHz. It was found that the rise of insertion loss was mainly due to the near-field interaction between the tray and the horns. When the separation between the tray and the horns was slightly increased, the roll-off at 12.5 GHz in the insertion loss plot disappeared. The isolation between the receiving and transmitting horn ports when the Yagi antennas are short-circuited in the 5-tray structure takes a minimum value of 16 dB. This result shows that the back-to-back connected Yagi antennas are indeed responsible for power transmission between the two horns.

The next step to assess the performance of the combiner is to measure field uniformity across the stack. Obtaining a highly uniform field across the stack (which is in the H-plane of the quasi-Yagi antenna) is important from the point of view of achieving high power combining efficiency. If excitations of individual trays in the stack are uniform (constant in magnitude and phase), each amplifier contributes equally to the output power. Also when large power levels are established all the amplifiers reach their saturation simultaneously.

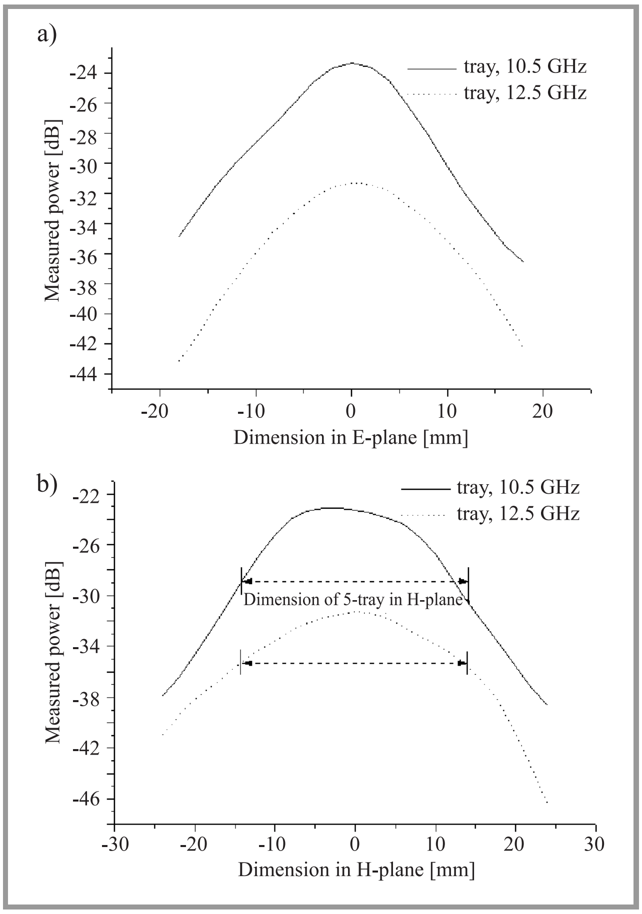

Fig. 8. Measured power distribution across two principal planes at the output of the 5-tray structure at 10.5 GHz and 12.5 GHz: (a) E-plane cut, (b) H-plane cut.

The measured amplitude of the field distribution across the launching horn aperture at 10.5 GHz and 12.5 GHz using a near-field measurement facility is shown in Fig. 7. An open-ended circular waveguide probe was used to scan the near field. As observed in Fig. 7, the 5-tray combiner fits well the region of uniform amplitude distribution at the horn aperture at 10.5 GHz compared with that at 12.5 GHz.

The measured amplitude of the field distribution across the output aperture of the 5-tray structure when excited by the horn at 10.5 GHz and 12.5 GHz is shown in Fig. 8.

As can be seen in Fig. 8, the outer trays are not excited as strong as the central trays. The measured phase variation across the stack (not shown here) was only within $\pm 15°$. The uniformity of the field amplitude can be improved by using a hard horn as the launching/receiving horns [9].

5. Conclusions

A parameter study has been performed of a broadband uniplanar quasi-Yagi antenna with regard to its design and use in a spatial power combiner. It has been found that the design frequency and the operational bandwidth are insensitive to the changes in the length of director (parameter *1*) and the distance between the director and the driver (parameter *2*). The length of gap between the coupled microstrip lines (parameter *3*) affects the bandwidth moderately. The most sensitive parameters of the quasi-Yagi antenna have been found the length of the driver (parameter *4*) and the distance from the driver to the reflector (parameter *5*). These two parameters affect both the antenna's design frequency and its operational bandwidth.

Following this theoretical study, a single tray consisting of two back-to-back connected quasi-Yagi antennas and a 5-tray combiner for operation in X/Ku-band have been developed and tested. Two ordinary pyramidal horn antennas have been used to distribute and receive microwave power. Investigated parameters have included return loss, insertion loss and field uniformity across the trays to achieve optimal combining conditions. The overall results for the single tray of two elements and the 5-tray configuration have shown that the quasi-Yagi antenna is a suitable element to develop a broadband spatial power combiner.

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