45-GHz MMIC Power Combining Using a Circuit-Fed, Spatially Combined Array

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Abstract— **We describe the design and measurement of a hybrid-circuit, tile-approach subarray for use in spatial power-combined transmitters. The subarray consists of 16 monolithic millimeter-wave integrated circuit (MMIC) amplifiers, each feeding a circularly polarized cavity-backed microstrip antenna. The average performance across the 43.5–45.5 GHz band is as follows: EIRP 18.3 dBW, dc-RF efficiency 10.3%, effective transmitter power 530 mW, system gain 13.2 dB, and combining efficiency of 46.2%. The minimum axial ratio is 1.2 dB at 43.9 GHz, and the array has a 3% 3-dB axial ratio bandwidth.**

I. Introduction

SPATIAL POWER combining is being pursued as an alternative to circuit combining for constructing moderate power amplifiers and transmitters at microwave and millimeter-wave frequencies [1]. In this work, a circuit-fed, spatially combined approach is followed. Circuit-fed arrays avoid a number of the disadvantages inherent in the spatially fed, tile-approach arrays that have received most of the interest for spatial and quasioptical power combining [2]–[4]. The two most significant advantages of the circuit-fed approach is that it is relatively straightforward to provide equal amplitude and phase at the input of the amplifiers, and it is well suited for thermal management. The fan-out and resistive losses of the corporate feed network can be offset by using a driver amplifier with minimal impact on the overall system performance.

The subarray described in this work is intended for use in a transmitter array. Multiple subarrays could be placed on a common base plate in a tile-approach configuration [5]. The subarray is intentionally constructed as a hybrid-circuit because it offers several advantages over a monolithic construction approach. It permits chip-level measurements of the monolithic millimeter-wave integrated circuit (MMIC) amplifiers to characterize their phase and amplitude performance before insertion into the subarray. It also permits flexibility in the circuit layout and the choice of circuit board materials. The added flexibility can be used to increase performance, such as the radiation efficiency of the antennas.

II. Design

An illustration of the 4 × 4 element subarray is shown in Fig. 1. Each element consists of a MMIC amplifier and a cavity-backed, proximity-coupled microstrip antenna. A corporate feed network distributes the input signal to each of the MMIC amplifiers on a lower RF (radio frequency) level. The outputs of the amplifiers are connected by ribbon bonds to an upper RF level that contains impedance matching circuitry and the cavity-backed patch antennas [6]. The ground plane of the RF output layer acts as a shield to increase isolation between the fields radiated by the microstrip antennas and the RF input network.

III. Measured Results

The hybrid subarray is composed of three circuit boards and 16 MMIC amplifiers integrated on a Silvar metal carrier. The MMIC amplifiers are attached directly to the carrier to provide a low thermal resistance path to the heat sink. The RF input layer and dc bias layer are constructed on 0.127-mm-thick alumina substrates. The RF output layer is constructed from three layers of 0.127 mm Duriod 6002. The Duriod multilayer is fabricated with standard circuit board techniques. This permits fabrication of the cavity-backed patch antenna using standard plated-through-hole processing.

Circuit components were designed and individually verified prior to being integrated into the subarray. A blind mate connector brings the RF signal into the subarray. The power dividers in the RF input feed network are Wilkinson dividers to provide isolation between the elements, which improves the graceful degradation performance. The antennas in this subarray are circularly polarized. They are constructed by feeding the patch on two orthogonal sides and in phase quadrature. The antenna elements are configured in a 4 × 4 rectangular lattice with λ_O element spacing. The patches, however, are oriented 45° to the array lattice to fit within the allotted area. Photographs of the subarray are shown in Fig. 2. This subarray was designed with individual bias lines to each amplifier for added diagnostic capability. Subarrays under development use a common bias network and are appropriately sized for tiling into a larger array.

The subarray was characterized using a farfield range from 42.5–46.1 GHz. The measured equivalent isotropic radiated power (EIRP), effective transmitter power, and dc–RF efficiency, shown in Fig. 3, were measured with a drive level of 14 dBm at the blind mate input connector. The effective transmitter power, $P_{\rm EFF}$, is calculated by taking the measured EIRP and dividing by the theoretical directivity for the array [7]. With this definition, all of the losses present in the array are taken into account. These include phase and amplitude variations among the array elements, losses and discontinuities

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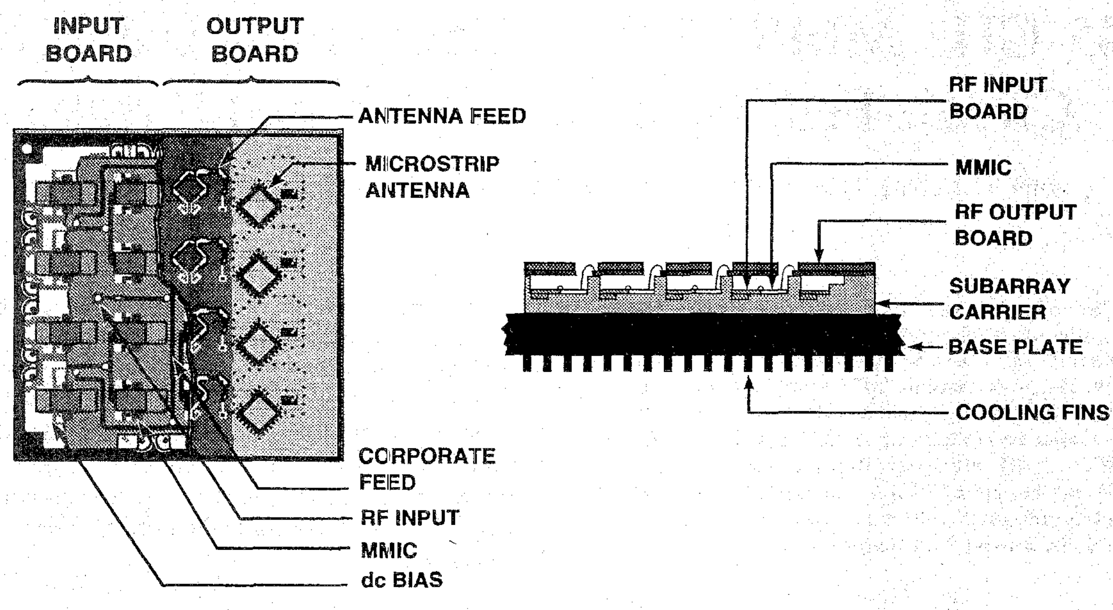
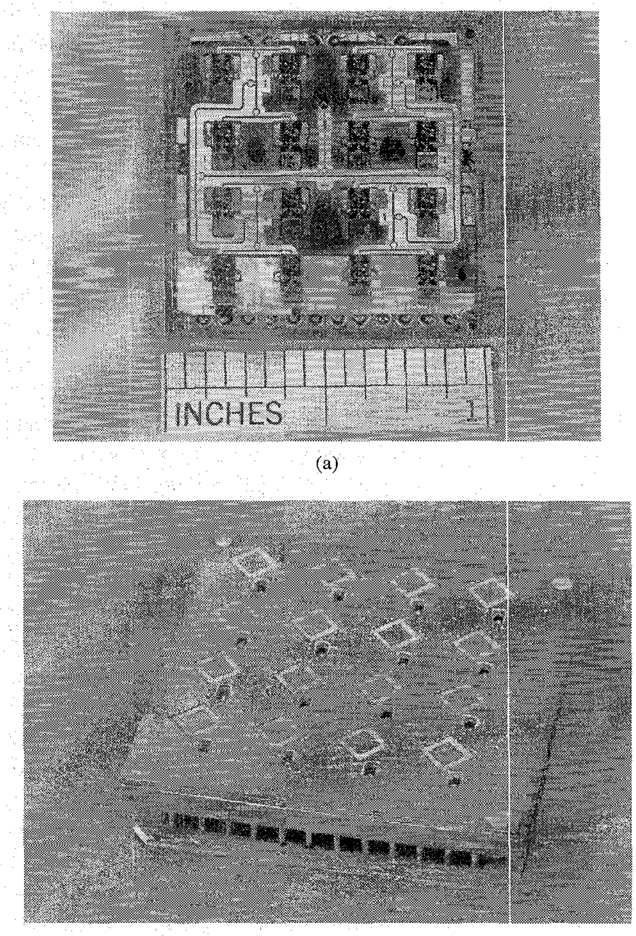


(a) (b)

Fig. 1. Illustration of the subarray design. (a) Top view. There are two input boards, the dc bias board and the RF corporate feed board. The RF output board consists of two layers, the antenna feed layer and antenna patch layer. (b) Side view. The circuit-fed, tile-approach configuration provides a low thermal resistance path from the MMIC's to the heat exchanger.



(a)

(b)

Fig. 2. Photographs of the subarray. (a) Partially assembled view revealing the dc bias layer, RF corporate feed, and four of the 16 MMIC amplifiers. (b) Fully assembled array.

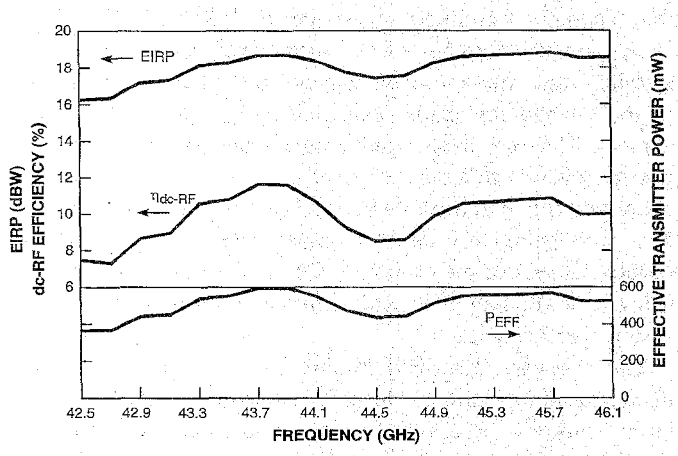


Fig. 3. Measured EIRP, effective transmitter power, and dc–RF efficiency for the 16-element subarray.

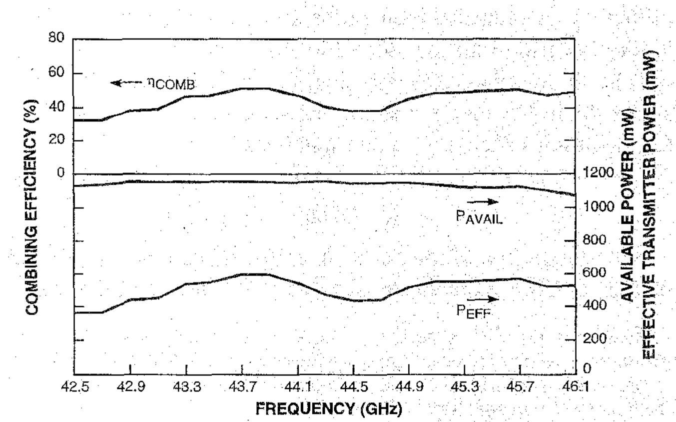


Fig. 4. Combining efficiency, total available power, and effective transmitter power for the 16-element subarray.

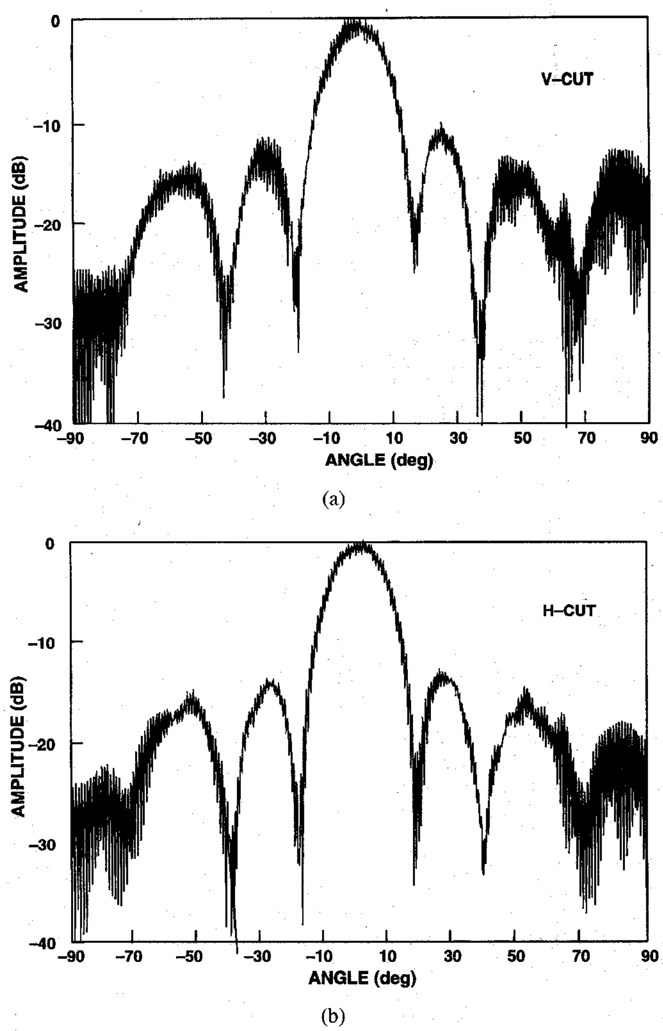


Fig. 5. Spinning linear farfield patterns for the 16-element subarray.

in the feed line from the amplifier to the antenna, and the antenna radiation efficiency. P_{EFF} is also used to calculate the dc–RF efficiency. The averaged results across the 43.5–45.5 GHz band show an EIRP of 18.3 dBW, an effective transmitter power of 530 mW, and a dc–RF efficiency of 10.3%. Peak performance was observed at 43.9 GHz with EIRP of 18.7 dBW, P_{EFF} of 596 mW, dc–RF efficiency of 11.6%, and combining efficiency of 51.4%.

The combining efficiency is calculated by dividing P_{EFF} by the total available power, P_{avail}, from the MMIC's. The total available power is the summation of the MMIC output power when driving an optimum load. In this work the MMIC's were designed with 50-Ω input and output port impedances. Chip-level measurements of the output power were made using a RF probe station, which has a nominal 50-Ω port impedance. Typical chip level performance of the amplifiers is 70 mW output power, 20 dB gain, and 20% PAE. The combining efficiency to free space, which includes all antenna, circuit, and load mismatch losses, is plotted in Fig. 4. For reference, P_{avail} and P_{EFF} are also plotted. The average combining efficiency across the 43.5–45.5 GHz band is 46.2%.

The graceful degradation performance was characterized by measuring the decrease in the EIRP of the array as a function of the percentage of failed elements. The failure of an element is simulated by turning off the drain bias of random elements in the array. The measured graceful degradation follows the theoretical maximum performance (50% failure results in 6 dB decrease in EIRP).

The system gain is defined as the effective transmitter power divided by the RF input power to the array. The system gain averaged across the band 43.5–45.5 GHz is 13.2 dB. An estimate of losses in the subarray, which accounts for this overall system gain, is as follows: 20-dB MMIC gain -1.5 dB for the blind mate connector at the input of the feed network, -1.9-dB loss in the corporate feed network, and -3.4 dB for combining efficiency.

Farfield patterns of the array were measured using a spinning linear measurement configuration. The axial ratio is a minimum of 1.2 dB at 43.9 GHz. The 3-dB axial ratio bandwidth is 3%. Currently, a reactive T-junction divider is used in the antenna feed which causes the narrow axial ratio bandwidth. Designs using a Wilkinson divider, however, are in development and should provide an acceptable axial ratio across the band of interest. Measured patterns for the subarray at 44 GHz are shown in Fig. 5. Both a vertical cut and a horizontal cut, with respect to the array lattice, are shown. The magnitude and uniformity of the side lobes indicate that the elements in the array have nearly the same phase and amplitude.

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