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A 10-GHz High-Efficiency Active Antenna Sub-Array

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Abstract — **This paper presents the design and implementation of a 10-GHz 4-element spatial power combiner. The GaAs-MESFET amplifiers are designed to operate in switched class-E mode, feeding dual-layer patch antennas. A Wilkinson combiner feed was designed for the input with 0.7 dB loss. The individual amplifiers operate at 64 % drain efficiency and deliver 20.6dBm output power. The total output power delivered from the active array is 26.6dBm (0.46W), for 20dBm input power. The average drain efficiency of the amplifiers in the array is 70% and the power added efficiency is 57%.**

I. INTRODUCTION

Spatial power combining has been actively researched in the past decade, with results ranging from hundreds of watts at X-band [1] to 5 and 25W at Ka-band [2], [3]. Most of the published power amplifiers (PAs) operated in saturated class-A mode, with efficiencies limited to at most 30% at X-band [1] and 15% at Ka-band [2]. A class-E amplifier (using Fujitsu GaAs-MESFETs) 4-element slot antenna array was reported in [4] with an output power of 2.4W, a 85% power combining efficiency and an average amplifier efficiency of 74% and PAE of 64% at 5GHz. This approach was later scaled to 8GHz using the same device in a 36-element class-F array with about 10W output power and a decrease in combining efficiency to about 59% and amplifier efficiency to 64% [5]. A lower-frequency single active class-F antenna at 2.5GHz with 24dBm output power and 63% efficiency was also reported in [6]. At 10GHz, a non-resonant slot antenna using an Alpha AFM04P2 GaAs-MESFET was reported to have 21dBm output power at 74% drain efficiency estimated from free-space measurements [7]. In this paper, we present a 4-element 0.5-W sub-array using the Alpha device and with a dual-layer broadband patch antenna radiator. The sub-array is intended to be an element of a multi-watt high-efficiency array, and is shown in Fig.1.

II. AMPLIFIER AND ANTENNA ELEMENTS

The GaAs-MESFET used in this work can operate up to 40GHz in class-A mode. The output capacitance is 0.107pF, the maximum drain current is 140mA, and a maximum drain-to-source voltage of 6V. From these parameters, the maximum operating frequency for class-E operation is 5.5GHz for a bias point of 4.2V and 20mA [4]. The output power at 1-dB gain compression for the device is 21dBm.

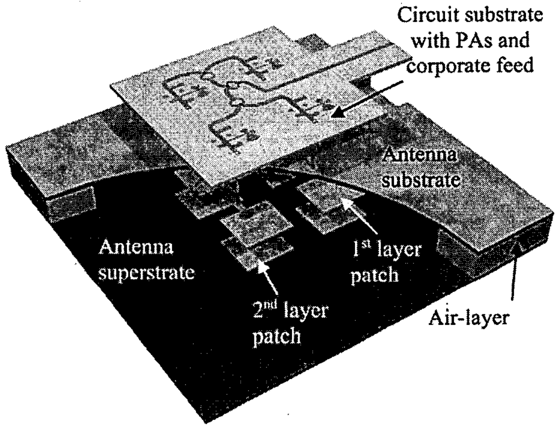

Fig. 1. Sketch of multilayer 4-element 10GHz class-E amplifier sub-array. The top substrate contains the PA circuits and Wilkinson combiners, with via-hole transitions to the antenna substrate with which it shares a common ground plane. Parasitic patch antennas are fabricated on a superstrate with an air layer in between.

	Pout dBm (mW)	G (dB)	η_D(%)	PAE (%)
min	20 (100)	5.5	60	48
max	21 (126)	7.9	67	60

Table 1. Summary of bounds of performance for 10 PAs.

At 10GHz, the amplifier operates in sub-optimal class-E mode. The input matching circuit is designed to maximize the saturated gain, and the output match provides the class-E optimal impedance of $Z_E=27.3+j31.5\Omega$ at 10GHz. Several microstrip 50-ohm PA circuits were fabricated using different packaging techniques, and the resulting efficiency and power bounds

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are given in Table 1. Average measured parameters for a single amplifier are: output power of Pout=20.6dBm (115mW) with G=7.2dB, a drain efficiency of 64% and PAE of over 52%. These numbers include output connector loss, which is not present in the array environment.

The antenna element is a multi-layer patch, which shares the ground plane with the PA substrate, as shown in Fig.2. Both antenna substrates are 0.483mm-thick with a permittivity of 2.43, with a 2.93mm-thick layer of air in between. The active circuits are fabricated on a third substrate, a TMM6 with ε_r=6 and 0.635mm-thick. Via holes with diameters of 0.6mm are used as the RF interconnects between the circuits and antennas. The antennas were designed using Agilent Momentum, and the measured reflection coefficient of the PA and antenna are shown in Fig.3. The 2:1 VSWR bandwidth of the antenna is 11%. The relatively large patch bandwidth improves the average amplifier output power and efficiency, since the 50-Ω impedance of the antenna is ensured for a wide range of fabrication parameter variations.

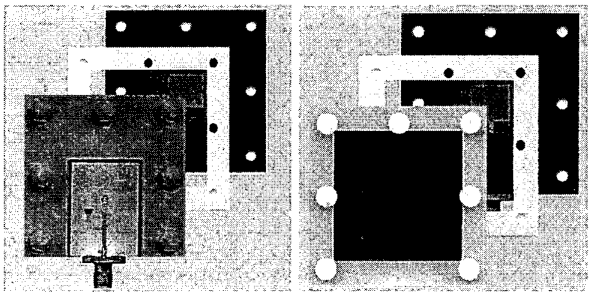

(a) (b)

Fig. 2. Photographs of multilayer active antenna element, feed side (a) and radiating side (b).

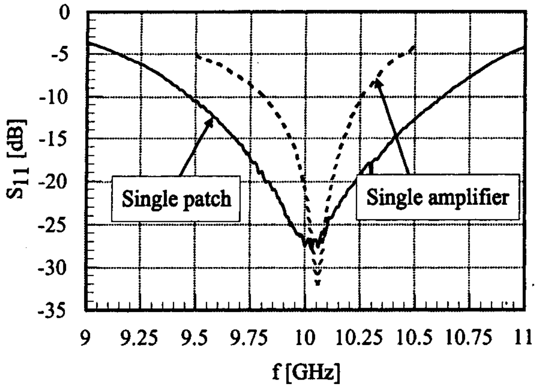
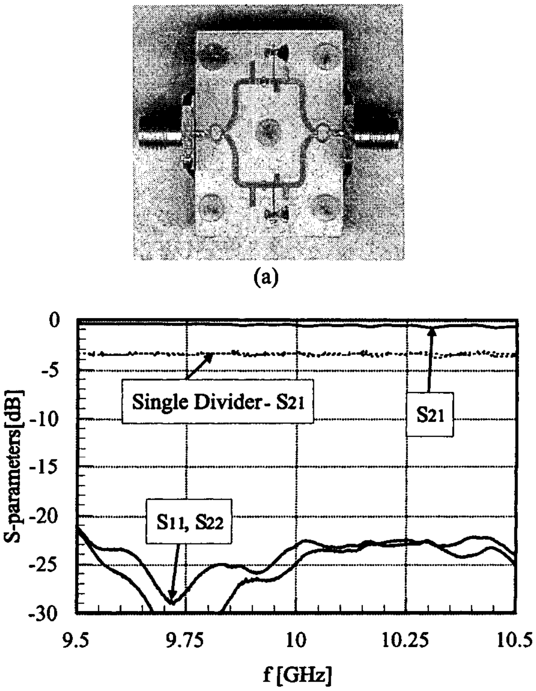


Fig.3. Measured input reflection coefficient of multi-layer patch antenna (solid line) and class-E PA (dashed line) at the operating bias point.

III. Input Feeds

The 4-element array shown in Fig.1 has a corporate input feed consisting of Wilkinson power combiners. Fig.4a shows a 2-amplifier combiner with a measured output power of 23.1dBm (205.1mW), translating to a 0.35-dB coupler loss after the connector loss in the measurement is calibrated out. The measured properties of the Wilkinson "curly-brace" combiner are given in Fig.4b. The Wilkinsons were optimized for space constraints, and the array feed network consists of 3 such combiners, with a total estimated loss of 0.7dB (based on two back-to-back coupler measurements, and consistent with the measured 2-PA combiner efficiency).



(a)

(b)

Fig. 4. (a) Photograph of a 2-PA combiner. (b) Measured characteristics of the Wilkinson combiner.

IV. Array

Four of the 7.7-dB gain patch antennas are spaced in a $0.6\lambda_0$ square lattice in the array in Fig.1. The measured return loss for the passive (no amplifiers) and active subarray, with an HP8510 network analyzer, are shown in Fig.5. For the active array measurement, the PAs were first biased at the nominal 4.2V and 20mA per amplifier (dashed line) in Fig.5). Since the mean current changes with input power required for class-E operation, we also measured the return loss at the full DC power consumption operating point (solid line in Fig.5). The plots show that the amplifiers are well matched to the feed at full bias.

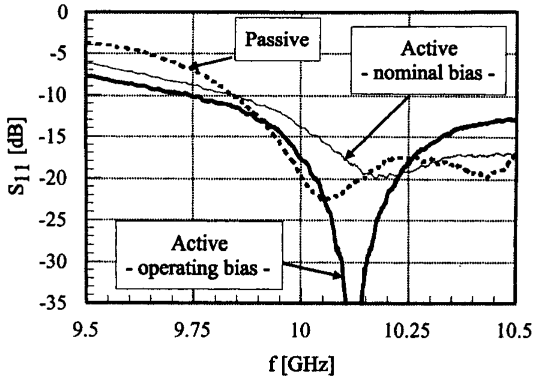
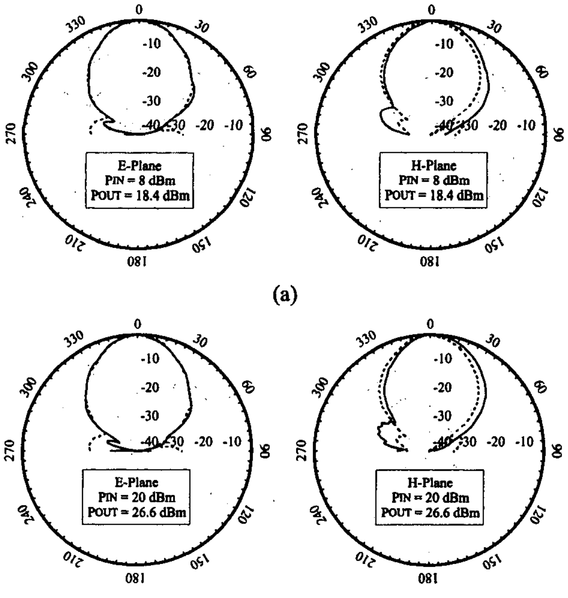


Fig.5. Measured return loss of the passive array (dashed) and active array for the nominal bias point (solid, thin) and full-DC consumption bias point (solid, tick).



(a)

(b)

Fig.6. Measured E and H-plane far-field radiation patterns for the passive (dashed line) and active (solid line) 4-element sub-arrays under (a) small-signal and (b) saturated operation.

In order to estimate the efficiency of the PAs in the active array, the E and H-plane radiation patterns of the passive and active array (both small-signal and saturated) are measured and are shown in Fig.6. From the measurements, we conclude that the amplifiers are exciting the antennas equally in both small and large signal modes, since the radiation patterns do not change much. This fact allows us to use the gain of the passive array, which is easily determined by the Friis formula, for estimating the array output power and efficiency.

The output power and efficiency of the array, Fig.7 are estimated from a free-space measurement using the measured passive array gain of 12.8dB in the Friis transmission formula. This measurement includes the losses in the Wilkinson feed network. When calculating the array output power, this 0.7-dB loss was added to the antenna gain of the array. The PAE can be calculated only for the four amplifiers, giving 57%, or including the feed network, amounting to 55%. The input power delivered to each amplifier (feed loss taken into account) is:

$$P_{in}' = 20dBm-6dB-0.7dB=13.3dBm$$

For this input power, single microstrip amplifiers give on average 20.9dBm (the SMA connector loss is subtracted from the value in Table 1), while the array output from Fig.7 is 26.6dBm. To estimate the power combining efficiency, we take into account the antenna efficiency (93%), the loss in the via holes, and the total measured output power of the array and four single amplifiers. A power combining efficiency of 81% is obtained.

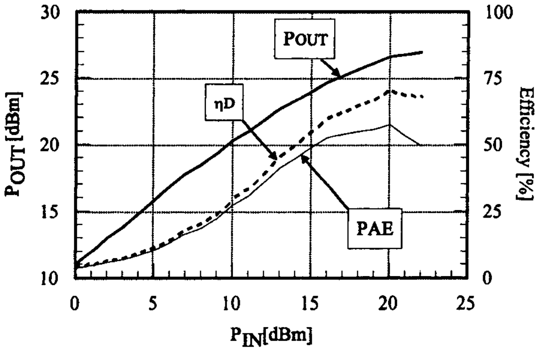


Fig.7. Measured output power, drain and power added efficiency of the 4-element active array.

The output power, gain contributed by the amplifiers, along with the total dissipated power is shown in Fig.8. The dissipated power is calculated by subtracting the output power from the sum of the DC and input powers. The efficiency remains above 50% when the output power is larger than the dissipated power, for input power greater than 15dBm (9dBm per element).

The bandwidth of a single amplifier over which the drain efficiency is larger than 60% is around 1.3 GHz (13%), similar as the individual antenna element bandwidth. We expect the array bandwidth to be slightly reduced. These measurements are in progress and will be added to the final version of the paper.

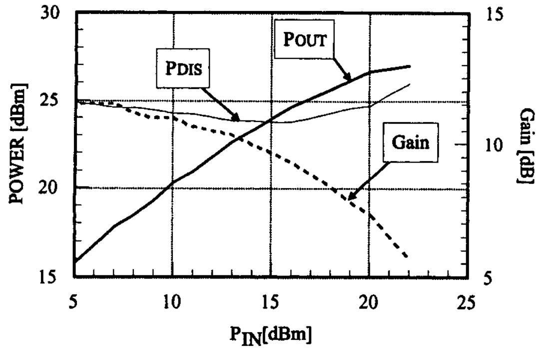


Fig. 8. Measured output power, active gain contributed by amplifiers, and total power dissipation of the 4-element active array.

V. SUMMARY

In summary, this paper describes the performance of a high-efficiency 10-GHz 4-element spatial power amplifier combiner. The PAs operate in sub-optimal class-E mode with an average drain efficiency 70%, PAE of 57%, and output power only a fraction of a dB lower than the 1-dB compressed power given in the device specifications. The total loss in the input feed circuit is 0.7dB. The 4-element array is designed to be a sub-array of a larger active array in which the input is a hybrid between spatial and network combining, while the outputs of the PAs are spatially combined. It was therefore important to ensure that all elements of the subarray are fed equally, as confirmed by radiation pattern measurements of the passive and active arrays. It was also important to quantify the range of efficiencies, output power and gain for variations in the transistors and circuit fabrication parameters, as given in Table 1. From the results presented in this paper, we estimate that with the same devices, an array with 2W output can be designed to have over 50% total power added efficiency at 150$/Watt.

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