Abstract—This paper describes the design, implementation and characterization of a high efficiency 10-GHz amplifier antenna array for spatial power combining. An average drain efficiency of 70% at 162 W EIRP, or about 1.5 W of transmitted power, is measured for an array of 16 amplifiers consisting of four 4-element subarrays. The power combining efficiency of the 16-element array is above 79%. The active device is a low-cost GaAs MESFET with a maximum available power in class-A of 21 dBm. The single class-E power amplifier delivers 20.3 dBm with 67% drain efficiency and 58% power added efficiency.

Index Terms—power amplifiers, high-efficiency, spatial power combining, active antenna arrays

I. INTRODUCTION

Spatial power combining of transistor amplifiers has been a topic of research in the past decade [1]. In this approach, the powers of a large number of amplifiers are combined in free space upon radiation from an antenna array. Grid amplifiers have been demonstrated up to 35 GHz with 5 W output power, at 21% efficiency [2]. Small tray arrays in waveguide have demonstrated very high power levels over X-band of 120 W [3]. Standard antenna arrays loaded with amplifiers have also been demonstrated up to V-band [4], [5], [6]. Most of these arrays are planar transmission amplifiers and therefore cannot have heat sinks. This results in temperature gradients across the arrays, which degrade the gain and power [7]. The problem addressed in this paper is reduction of heat dissipation and improvement of DC-power usage by increasing the power-added efficiency (PAE) and drain efficiency (ηD) of the power amplifiers (PAs). These efficiencies are maximized by operating the devices in switched mode [8] and using a low-loss corporate input network, while maintaining the spatial output power combining as in [9]. The design of a high-efficiency active array is performed in several stages presented in the following sections:

1. Section II describes the class-E PA design and characterization, along with repeatability issues.
2. Section III describes the antenna element design. The antenna chosen in this approach is a broadband multi-layer patch.
3. Section IV describes the 4-element subarray design, including corporate feed and bias network. Measurements of the subarray are also presented and serve as a baseline for assessing the power combining efficiency (PCE).

II. CLASS-E AMPLIFIER DESIGN

Class-E switched mode of operation has recently gained a lot of attention at different frequency ranges [10], [11]. Switched mode amplifier operation was developed by Artym [12], Gruzdev [13], Popov [14], Kozyrev [15] and Sokal [16] independently for HF amplifiers, and extended to microwave frequencies in a transmission-line circuit by Mader and Popović [8], [17], [18]. In this class of operation, the transistor is operated as a switch in such a way that the current and voltage time waveforms overlap minimally during a period. The load for this mode of operation needs to be a particular complex impedance at the design frequency, and an open circuit at all harmonics [19], resulting in theoretically 100% efficient amplification. Typical class-E transistor voltage and current waveforms normalized to the peak values for a 50% switching duty-cycle are shown in Fig. 1.

![Fig. 1. Transistor normalized output voltage and current waveforms in class-E mode of operation.](image)

The optimal class-E load impedance [8], [17] for the transistor with the given output capacitance $C_{OUT}$ and the operating (switching) frequency $\omega_S$ can be calculated as

$$Z_E = \frac{0.28}{C_{OUT} \cdot \omega_S} e^{j49^\circ}.$$  (1)

However, because the microwave transistor has finite resistance during the ON state, and finite switching time, ideal 100% efficiency cannot be achieved. In this case, class-E waveshaping minimizes voltage and current overlapping, providing minimal losses in the active device, compared to linear classes of operation (A, AB, etc.).

For the X-band class-E power amplifier design used in the spatial power combiner, the low-cost general purpose GaAs...
MESFET produced by Alpha Industries Inc. was available. In class-A at 18 GHz this device is capable of delivering 21 dBm of output power with 9 dB of power gain at the 1 dB compression point. The device has useful gain up to 40 GHz. In class-E mode of operation, voltage and current stresses on the device are higher than in linear modes of operation [17]. Taking into account the maximum device current and voltage ratings, an amplifier designed with such a MESFET is capable of operating in sub-optimal class-E mode [20], but still with high expected drain efficiency, on the order of 60-70%. However, due to the relatively low linear gain of the device, and the fact that it will operate deep in compression (more than 3 dB), lower PAE, on the order of 50-60%, is expected.

The first step in class-E amplifier design is determination of the device output capacitance, necessary for the optimal output impedance calculation, Eq.(1). If the nonlinear model of the active device is not known, manipulating given s-parameters can give a good initial estimate for the output capacitance. Converting S- to Y-parameters and using a simple "$\pi$" linear model for the device, the output capacitance for the selected MESFET is found to be $C_{OUT} = 0.11 \text{ pF}$. The optimal class-E impedance is found to be $Z_E = (27.3 + j31.5) \Omega$ at 10 GHz. The input of the PA is matched starting with a conjugate match using small-signal parameters, followed by post-production tuning. This is necessary because an acceptable nonlinear model for this device does not exist at present [21]. The circuit is fabricated on a Rogers® TMM6 substrate ($\varepsilon_r = 6, h = 0.635 \text{ mm}, t = 35 \mu\text{m}$), Fig. 2.

The active device and RF-decoupling capacitor are mounted on a machined copper base connected to the ground plane with conductive epoxy. The gate bias is provided through a bias tee, since in the array it is provided through the feed. In the characterization, performing the automated bias-sweep, the optimal bias point is found to be $V_{DS} = 4.2 \text{ V}, V_{GS} = -1.4 \text{ V}, I_{DS0} = 20 \text{ mA}$. Measured output power, gain and efficiency for the selected bias point are shown in Fig. 3.

The class-E power amplifier shows an output power flatness of 0.5 dB and drain efficiency above 60% over a 14% frequency bandwidth, as shown in Fig. 4.

In order to determine amplifier repeatability and robustness of the fabrication process, about 20 amplifiers were made and measured. Table I shows the range of amplifier parameters, measured at 10 GHz. Relatively narrow amplifier parameter spreading is important to achieve high power combining efficiency in the spatial combiner.
TABLE I

<table>
<thead>
<tr>
<th>$P_{\text{OUT}}$ [dBm]</th>
<th>$G$ [dB]</th>
<th>$\eta_D$ [%]</th>
<th>PAE [%]</th>
<th>$\rho$ [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-20.5</td>
<td>7-7.5</td>
<td>60-70</td>
<td>48-57</td>
<td>&lt;-13</td>
</tr>
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</table>

$P_{\text{OUT}}$ - output power, $G$ - gain, $\eta_D$ - drain efficiency, PAE - power added efficiency and $\rho$ - input reflection coefficient

III. RADIATING ELEMENT DESIGN

In an active antenna element fed by a high-efficiency amplifier, variations of the optimal impedance presented to the active device can lead to performance degradation. In the case of an ordinary patch antenna, with 1-2% frequency bandwidth, the input impedance is highly sensitive to the fabrication tolerances and material property variations. In order to provide a robust 50-Ω load to the amplifier output, a broadband patch antenna with 2:1 VSWR bandwidth of 11.6% is used. The antenna element is shown in Fig. 5.

The antenna consists of a directly fed and parasitic patch, separated by an air layer. The parasitic patch is inverted and its substrate serves as a radome. Two inserted FR4 frames are used as spacers. The directly-fed patch is fed by a 50-Ω microstrip line through a via hole. The feed is fabricated on the same substrate as the amplifiers (Rogers® TMM6). A common ground plane separates the feed from the radiating side. The antenna design is optimized, using Agilent® Momentum. The multilayer design of the radiating-edge fed patch allows for a 50-Ω input impedance with no impedance transformer, thereby minimizing the surface area occupied by the antenna. This is required in order to have enough area for the amplifier, feeding and biasing networks, while maintaining low mutual coupling. At 10 GHz, the antenna has an input reflection coefficient of -27 dB, with a 2:1 VSWR frequency bandwidth of 11.6%. The radiation pattern of the antenna element was measured in an anechoic chamber, and simulated and measured principal plane cuts are shown in Fig. 6. The simulated gain of the antenna is 8.5 dB and the measured gain, determined using the Friis formula is 7.7 dB. The measured gain includes the loss of the feed network.

IV. 4-ELEMENT ACTIVE SUBARRAY DESIGN

With the devices available for this combiner, a maximum of 1.8 W (20.3 dBm average measured PA power, Table I) from a 16-element combiner is expected at 10 GHz with class-E efficiency. First, a 4-element subarray was designed with an antenna period of 0.6 $\lambda_0$. This period is chosen as a compromise between sidelobe levels and mutual coupling between elements that could affect the impedance presented to the amplifiers in array.

A corporate feed is used at the input, and a more detailed discussion on feeds for these types of power combiners is given in Section IV. The corporate feed is a one-to-four Wilkinson divider, providing good isolation between amplifiers. Based on measurements on a back-to-back divider/combiner circuit, insertion loss of the 4-element feed is estimated to be 0.7 dB [22]. A schematic of the 4-element subarray is shown in Fig. 7.

An additional FR4 layer (not shown in Fig. 7), connected with each amplifier bias line provides drain voltage for the active elements. This approach avoids the problem of non-uniform drain biasing addressed in [7], and eliminates potential bias-line instabilities.
In order to calculate amplifier efficiency it is necessary to measure output power delivered to the radiating element. In the case of an active antenna array this is a difficult measurement, since the outputs of the amplifiers are not directly accessible. Accurate measurement of the 3-D co- and cross-polarized radiation pattern, along with an estimate of antenna efficiency, can be used to calculate the output power by integration. Another approach, used in this work, is a comparative measurement. A passive antenna array, with exactly the same geometry as the active one and with the amplifiers replaced by 50-Ω thru lines, is designed and characterized in an anechoic chamber. The gain of the passive antenna, with the feed loss correction, can be found from the Friis formula for the measured input and received powers:

$$G_{PASS} = \left(\frac{4\pi R}{\lambda}\right)^2 \cdot \frac{P_{REC}}{P_{IN}} \cdot \frac{1}{G_R} \cdot \frac{1}{L_F},$$

where $R$ is the distance between passive sub-array and receiving standard antenna with antenna gain $G_R$, $\lambda$ is the free-space wavelength, $P_{REC}$ is the measured power received by a standard-gain antenna, $P_{IN}$ is the power delivered to the sub-array, and $L_F$ is the subarray feed loss. If the passive and active antenna have the same gain, by measuring the received power from the active subarray, the output power generated by the amplifiers in the array can be calculated as

$$P_{OUT} = \left(\frac{4\pi R}{\lambda}\right)^2 \cdot \frac{P_{REC}}{G_R} \cdot \frac{G_{PASS}}{1},$$

where $P_{REC}$ is now the measured power received by a standard-gain antenna, and $G_{PASS}$ is the previously determined passive subarray gain. The assumption that the radiation gains of the passive and active subarrays are equal (or very similar) can be justified by comparing measured radiation patterns, with the assumption that the efficiencies of both antennas are the same. The simulated and measured radiation patterns of the 4-element subarray are shown in Fig. 8.

Simulated radiation gain of the passive 4-element subarray at 10 GHz is 13.2 dB, while the measured gain of the subarray is 12.8 dB. Based on a 0.7-dB estimated feed loss, the resulting gain of the passive antenna array, calculated from Eq.(2), is 13.5 dB. This value is used for active subarray output power calculations. The measured radiation patterns of the passive and active subarrays are shown in Fig. 9. The very similar radiation patterns measured for the active and passive subarrays justify using passive antenna data for estimating gain, and therefore, output power. The power sweep characteristics are shown in Fig. 10.
values for the output power is given. It corresponds to a possible 0.5-dB deviation in estimated output power.

Finally, the power combining efficiency (PCE) is calculated as

$$PCE = \frac{P_{RAD}}{N \cdot P_{AMP}} \cdot 100\%,$$  \hspace{1cm} (4)

where $P_{RAD}$ is radiated power from the array, $N$ is the number of array elements, and $P_{AMP}$ is the power available from a single amplifier circuit. The power combining efficiency of the 4-element subarray is 81%, with a possible error margin of ±5%.

V. 16-ELEMENT ACTIVE ARRAY DESIGN

Based on the subarray design, a 16-element active antenna array was designed, with a similar 16-way Wilkinson divider as the feed, and the same broadband antenna elements. A photograph of the assembled 16-element array is given in Fig. 11. To estimate output power in the active array, a passive 16-element array was designed and simulated and measured patterns are shown in Fig. 12.

The feed loss is measured on a 16-element back-to-back Wilkinson combiner with the amplifiers replaced by 50-Ω through-lines. The simulated antenna gain and radiation efficiency of the 16-element antenna array at 10.2 GHz are 18.8 dB, and 90%, respectively, not including feed loss. When the measured feed-loss of 1.4 dB is added to the measured antenna gain (18.4 dB), a higher 19.8 dB antenna gain is obtained. It is evident from the measurement in Fig. 12 that the measured pattern is narrower than the simulated one, confirming this loss calibration. The active antenna array radiation patterns are shown in Fig. 13 and compared to the passive array patterns. Power sweep characteristics are shown in Fig. 14.

![Photograph of the 16-element active antenna array, front side (left) and back side (right). Metalized FR4 board covers the active feed, providing uniform drain bias to the active devices.](image_url)

![Simulated and measured radiation patterns of the passive 16-element antenna array at 10.2 GHz.](image_url)

![Power sweep characteristics of the amplifier stage in the 16-element active array at 10.2 GHz. The bounds on performance correspond to an estimated 0.5-dB uncertainty in output power measurement.](image_url)

The measured EIRP of the 16-element active array at 10.2 GHz is 52.1 dBm (162 W). As before, due to the uncertainty in determination of the antenna array gain, a range of
possible values is shown, corresponding to an error in PA output power determination of \( \pm 0.25 \) dB. The corresponding cross-polarized radiation is shown in Fig. 15.

![Fig. 15. Cross-polarized (solid line) patterns of the active 16-element antenna array at 10.2 GHz](image)

The second and third harmonic radiation patterns of the active array operating at 10.2 GHz are shown in Fig. 16, relative to the fundamental frequency power. Harmonic power in the signal generated by the amplifiers is significantly suppressed, due to the antenna input mismatch at harmonic frequencies. The second harmonic is also suppressed by the harmonic trap in the amplifier output matching circuit, resulting in a maximal harmonic power level that is more than 45 dB below the maximum in the fundamental radiated power, for both the second and third harmonics.

![Fig. 16. Second harmonic (solid line) and third harmonic (dotted line) radiation patterns of the active 16-element array, operating at 10.2 GHz.](image)

The measured frequency dependence of the active 16-element array EIRP, radiating gain and feed loss are shown in Fig. 17. Based on measured EIRP and radiating gain of the active antenna, the frequency dependence of the maximal output power, corresponding drain efficiency and PAE of the amplifier stage in the array are calculated and shown in Fig. 18. The maximum output power is measured at 10.2 GHz, and the 2% increase in optimal operating frequency is attributed to mutual coupling of elements in the array. The power-combining efficiency of the 16-element active array is calculated based on a simulated radiation efficiency of the antenna array, and its frequency dependence is shown in Fig. 19. The maximum EIRP of 52.1 dBm (162 W) is observed at 10.2 GHz. At this frequency, estimated radiated power is 31.7 dBm, amplifier output power is 32.3 dBm and the drain efficiency is 70%.

![Fig. 17. Measured EIRP (solid line), feed loss (dashed line) and extracted radiation gain of the active 16-element antenna array (dotted line). Active antenna gain is calculated from the measured passive antenna gain and measured feed loss.](image)

![Fig. 18. Measured frequency dependence of the output power, drain efficiency and PAE of the active 16-element array, corresponding to the maximal power-added efficiency. An estimated range of values is given, because directly measured output power of the amplifiers is not available.](image)

![Fig. 19. Frequency dependence of the power combining efficiency for the 16-element active antenna array, based on measured output power and gain.](image)
Estimation of the array parameters beyond the frequency range of 9.9-10.3 GHz becomes inaccurate, due to the deviation from the initial assumption that passive and active antenna gains are equal. The average PA efficiency is very close to the highest achieved in a microstrip amplifier. When the antenna becomes mismatched due to its limited bandwidth and mutual coupling, the amplifier performance degrades. Parameter variations between individual amplifiers in the array (from Table I) also contribute to the degradation of the combiner characteristic. A summary of the 16-element spatial array at 10.2 GHz is shown in Table V.

VI. CONCLUSION

This paper describes the design, fabrication and characterization of an X-band spatial power combiner of switched-mode power amplifiers. The 16 active antenna elements exhibit an output EIRP of 162 W with a 70% average drain efficiency at 10.2 GHz. The power combining efficiency is estimated from measured power and gain to be above 79% at the same frequency. The 4-element subarrays and the 16-element array have power combining efficiencies around 80%, demonstrating that the array size can further be increased by arraying 16-element subarrays without significant penalty. The loss in input combining efficiency can be compensated by a driver amplifier in the feed.

The main achievement of the applied approach can be illustrated by comparison of the power-loss budgets of the designed class-E combiner with the equivalent combiner realized with the same active device operating in linear class-A mode. For this comparison the assumed gain of the active device in class-A is 11 dB, and average drain efficiency is 25%. The output power is assumed to be the same as in class-E mode. The result of a power-loss budget calculation is shown in Fig. 20. For the same output power, the dissipation in the active devices is reduced by a factor of 4.4.

In this combiner, the feed is chosen to be a corporate one, since a well-known input power distribution is necessary to understand and measure the efficiency. In most other spatial combiners the feed is spatial [5], and the argument is that feed loss remains constant for large array size. However, a spatial feed often involves non-uniform input amplitude and phase across the array. This in turn leads to degraded combining efficiency where the RF power is the most expensive - at the output. This problem is even more critical in a deeply saturated class-E power amplifier, where different input power levels lead to different compression levels. This affects both output signal amplitude and phase (AM-PM conversion), significantly degrading power combining efficiency. In the combiner presented here, all PAs saturate simultaneously as the input power is raised, and the drain efficiency across the array remains constant, maintaining the main benefit of switched-mode high-efficiency power amplifiers.

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REFERENCES


