A 10 GHz High-Efficiency Active Antenna

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Abstract—
This work discusses the use of a microstrip-fed slot antenna to directly provide the necessary output match and harmonic tuning for a 10 GHz class-E power amplifier. There is no matching circuit at the output of the amplifier since the slot is designed to provide the correct impedance at the fundamental frequency and to present an open circuit at the second harmonic. This eliminates losses in the matching circuit and decreases circuit area. Since the class-E amplifier requires a complex output load, the designed slot antenna is not a resonant structure. The device used is an Alpha AFM04P2 MESFET, which has a maximum output power of about 21 dBm. The measured performance of the active antenna shows 74% drain efficiency, 62% power-added-efficiency (PAE), and 20 dBm output power at 10 GHz, at 5 dB gain compression. The PAE is greater than 50% in a 400 MHz bandwidth.

I. Introduction

In wireless transmitter or receiver systems, size and efficiency are important factors to take into consideration. High-efficiency circuits are designed for use in portable components in these systems. By integrating matching and tuning functions into the antenna design, the overall size of the circuit is reduced. This can lead to reduced loss in the output part of the transmitter which dominates the overall losses in the system.

In this paper, we discuss switched-mode power amplifiers with high power-added-efficiency (PAE). In these amplifiers, often referred to as class-E and class-F, the transistor is used as a switch and the harmonics of the switched voltage are reflected back towards the transistor before reaching the load [1], [2]. This is usually accomplished by the use of matching circuits and filters, and produces switch current and voltage waveforms which are exactly out of phase with each other. The losses within the switching transistor are thus minimized. A 7% increase in PAE without degrading the radiation properties was achieved by using an integrated antenna which provided harmonic tuning [3].

Previous work on integrated active antennas has included a circular sector patch antenna providing the load to a 2.55 GHz class-F amplifier in which the feed position and sector angle in the circular patch were optimized for the correct load and harmonic tuning. The PAE of this active antenna was 63% with 24.4 dBm output power [4]. Other work has explored broadband harmonic tuning by using a photonic bandgap structure consisting of a microstrip line with a periodically etched ground plane. The radiator was a slot antenna connected to this microstip line. A PAE of over 50% and output power above 22 dBm was obtained from 3.7-4.0 GHz [5].

As the frequency increases, it becomes more difficult to get high PAE because the transistor internal reactances and resistances are larger and cause simultaneously high current and voltage across the switch. This increases power loss in the transistor and reduces efficiency. For example, at 0.5 GHz, a transmission line class-E amplifier was demonstrated with 80% PAE and 27.4 dBm output power [6]. However, at 5 GHz, the same circuit topology resulted in 72% PAE and 27.8 dBm output power. We have extended the class-E topology to 10 GHz, achieving 62% PAE at a reduced output power level of 20 dBm and a 74% corresponding drain efficiency. The class-E performance is achieved by using a microstrip-fed integrated antenna instead of matching and filtering circuits.

In microstrip class-E power amplifiers, the output load at the fundamental frequency is given by:

$$Z_L = \frac{0.28015}{\omega_s C_s} e^{j49.0524^\circ}, \qquad (1)$$

where $\frac{\omega_s}{2\pi}$ is the fundamental frequency, and C_s is the transistor switch output capacitance [7]. At harmonics of the fundamental frequency, the output must be an open circuit. These conditions result in the switch voltage and current waveforms being exactly out of phase with each other, consequently minimizing transistor losses. The theoretical drain efficiency of the class-E circuit is 100%. Although the output must present an open circuit to all harmonics in an ideal class-E circuit, it was demonstrated in [6] that adequate phase offset between the voltage and current waveforms can be obtained by only considering the second harmonic. The gain of the transistor at the third harmonic is usually negligible and therefore the third harmonic content at the output is minimal.

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Above a critical frequency which depends on the device, ideal class-E behaviour is not possible and the efficiency decreases [8]. This critical frequency is proportional to the maximum current handling capability of the device and inversely proportional to the output capacitance [6]. In most commercial X and Ku band devices, however, the output capacitance is proportional to the maximum current. Their ratio therefore stays approximately constant and the critical frequency is about 6 GHz, causing the efficiency to degrade above this value.

In microstrip class-E amplifiers presented in [7], tuned microstrip matching circuits at the output of the transistor provide the proper operating conditions. It is possible to design an antenna with input impedance given by Eq. (1), which removes the need to have a matching circuit and directly couples the amplifier power to the power of a wave in free space. Since a second-resonant slot antenna has a relatively wide bandwidth (compared to eg. a patch antenna), its impedance could provide an approximate class-E match to the transistor over a wide frequency range while maintaining high efficiency. A slot antenna was chosen as the amplifier load instead of a patch antenna due to its larger bandwidth (approximately 20%) at the second resonance. Even though the slot antenna presented here is not a resonant structure, it is close to the second resonance and therefore relatively broadband.

II. Passive Antenna Design and Measurement

An Alpha AFM04P2 power MESFET chip with an output capability of 21 dBm is used as the switch in the class-E amplifier. Since there is no available large signal model for this transistor, the switch capacitance was estimated using small signal s-parameters to be 0.107 pF. This does not take into account the nonlinear nature of this output capacitance which causes it to vary with varying gate-drain and gate-source voltage. For a more precise design, a large signal model for the device is required. According to Eq. (1), the required load impedance for this capacitance is $41.67\,\Omega, \angle 49.0524°$, and s_{11} relative to $50\,\Omega$ is -6.67 dB, $\angle 104°$.

This reflection coefficient is provided by the slot antenna, which is microstrip-fed with a 90° tuning stub and is initially designed to be a second-resonant antenna at 10 GHz. The antenna length and width are then optimized using Boulder Microwave's Ensemble and HP Momentum to obtain the desired class-E reflection coefficient magnitude. A 7 mm long transmission line between the antenna and the amplifier provides the correct phase of the reflection coefficient. At the second harmonic, the tuning stub is 180° long and therefore, the load impedance at the second harmonic is merely the reactance of the line, which has a length of 12 mm from the open end to the transistor. Since this is approximately 360° at 20 GHz, the reactance is close to an open circuit and therefore presents a large impedance at the second harmonic. Although this is not ideal, it is sufficient for approximate class-E operation. The simulated input impedance of the antenna is shown on a Smith chart in Fig. 1. As seen in this figure, the antenna is not a resonant antenna. The slot antenna is 20 mm long, 2 mm wide, and is fed at the center.

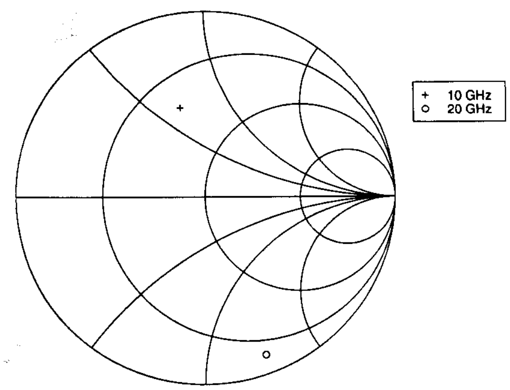

Fig. 1. Input impedance of the passive antenna at 10 GHz (+) and 20 GHz (o).

A passive antenna was fabricated in order to measure the radiation patterns and the impedance as seen by the transistor. The measured reflection coefficient of the passive antenna is $s_{11} = -6.8\,\text{dB}, \angle 106°$. This value is in good agreement with the simulation shown in Fig. 1. The antenna gain was measured between 9 and 11 GHz and ranged from about -3 dB to 4 dB. These measured values agreed well with the simulations at 10 GHz and above, but the gain below 10 GHz was lower than expected. The crosspolarization ratio is approximately 19 dB. The gain of the antenna is approximately 2.3 dB at 10 GHz.

III. Active Antenna Design and Measurement

The active antenna circuit is fabricated on a RT Duroid substrate with $\epsilon_r = 2.2$. The circuit outline is shown in Fig. 2. The Alpha AFM04P2 MESFET has a 0.25 μm gate length and a 400 μm gate periphery, which allows a maximum current of approximately 150 mA and a maximum output power of 21 dBm upto 18 GHz. The DC drain-source series resistance, R_s, is approximately $4.55\,\Omega$. As stated above, the output capacitance, C_s, is 0.107 pF. In [6] the expected drain efficiency is given by

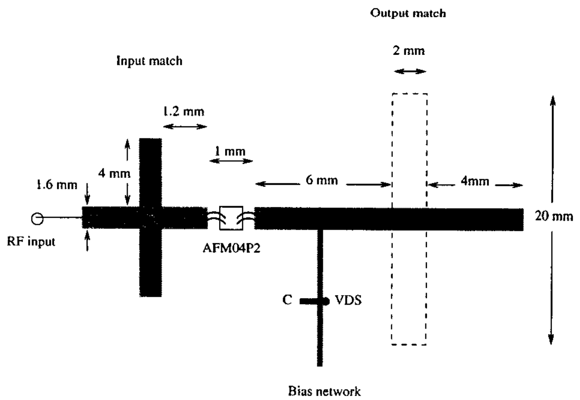

Fig. 2. Circuit layout of the 10 GHz active antenna. The capacitor C is part of the bias network and provides an RF short.

$$\eta_D = \frac{1 + (\frac{\pi}{2} + \omega_s C_s R_s)^2}{(1 + \frac{\pi^2}{4})(1 + \Pi \omega_s C_s R_s)^2}. \qquad (2)$$

This equation predicts a drain-efficiency of 85% for the AFM04P2.

The MESFET is mounted on a brass platform which is epoxied to the ground plane. The gate and drain are wire-bonded onto the microstrip lines. DC biasing is supplied 45° away from the transistor output so as to present an open to the transistor at the second harmonic. The overall size of the active antenna is about $0.4\lambda^2$ where λ is the wavelength in free space.

The performance of the final integrated antenna is measured using the Friis transmission formula, since the output of the circuit couples directly to free space. The gain of the active antenna is the product of the amplifier gain and the passive antenna gain. However, it is necessary to determine if the directivity of the active antenna is equal to that of the passive antenna. This was accomplished by comparing the radiation patterns of the active and passive antennas as shown in Fig. 3 and Fig. 4. The active antenna pattern is similar in shape to that of the passive antenna. Therefore, the directivities of the active and passive antennas were assumed to be equal. In simulations with varying length of the feed line, leaving the stub length and the antenna dimensions constant, the position and magnitude of the nulls varied from 0.5 to 2 dB. The measured nulls occur at approximately the same angles as in the simulation, but they are deeper. This is believed to be in part due to the feed line connector. The cross-polarization in the two antennas are the same.

The input power is varied from -5 dBm to 18 dBm and the transmitted power is received by a standard gain horn antenna in the far field. Using the Friis formula and the measured directivity of the passive antenna, the transmitted power was calculated as shown in Fig. 5. The maximum measured power is 20.5 dBm. The efficiency of the amplifier with varying input power is shown in Fig. 6. As seen here, the peak PAE of 62% is obtained At 12 dBm, or approximately 5 dB gain compression. The corresponding drain efficiency is 74%, with approximately 20 dBm output power. The maximum drain efficiency is 79%, obtained at 18 dBm input power. This is 6% lower than predicted by Eq. (2). This discrepancy indicates that the estimates of the output capacitance and/or series resistance used in the design are slightly lower than the realistic values. This reiterates the need for large signal models in the design of high-efficiency power amplifiers.

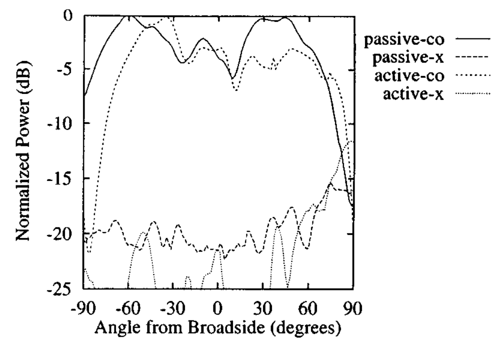

Fig. 3. Copolar (co) and crosspolar (x) radiation patterns in the E-plane of the passive and active antennas.

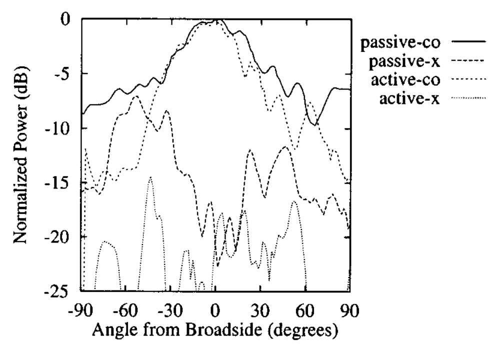

Fig. 4. Copolar (co) and crosspolar (x) radiation patterns in the H-plane of the passive and active antenna.

The frequency dependance of the output power and efficiency is shown in figures 7 and 8 for 12 dBm input power. From 9.7 GHz to 10.1 GHz, the PAE is above 50% and the output power is above 19 dBm.

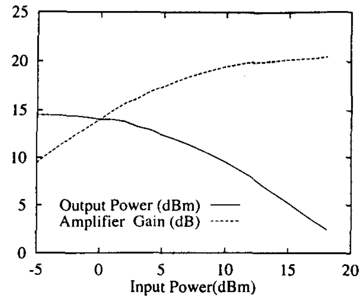

Fig. 5. Output power and gain of the active antenna for varying input power. V_{gs}=-1.2 V, V_{ds}=4.0 V, I_{ds} varies slightly around 35 mA.

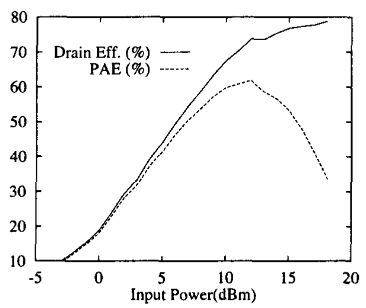

Fig. 6. Drain efficiency and PAE of the active antenna for varying input power. V_{gs}=-1.2 V, V_{ds}=4.0 V, I_{ds} varies slightly around 35 mA.

IV. Conclusions

A 10 GHz high-efficiency power amplifer is integrated with a slot antenna which provides the correct output load to the transistor without the use of a matching circuit. The antenna is also designed to provide harmonic tuning at the second harmonic. This results in a smaller circuit and lower output losses, which affect the efficiency much more than input losses. The radiation patterns of the antenna are similar for both passive and active antennas. The maximum drain efficiency is 74% with 62% PAE and an EIRP of 22.3 dBm. The PAE and power remain above 50% and 19 dBm, respectively, over a relatively broad bandwidth of 400 MHz. The size of the active antenna is approximately $0.4\lambda^2$. These results show that this active antenna is suitable for spatial power combining in a high efficiency transmitter array.

V. Acknowledgements

This work is supported by Caltech through an ARO MURI program on quasi-optical power combining, grant number DAAH04-98-10001.

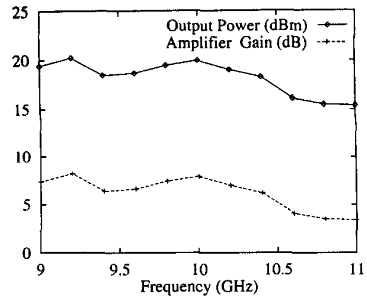

Fig. 7. Output power and gain of the active antenna from 9 to 11 GHz for 12 dBm input power.

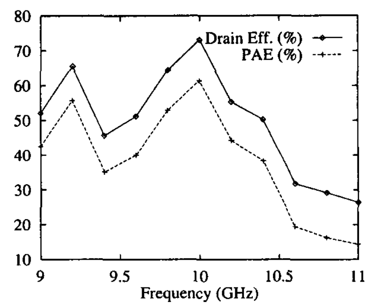

Fig. 8. Drain efficiency and PAE of the active antenna from 9 to 11 GHz for 12 dBm input power.

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