HIGH-EFFICIENCY X-BAND POWER AMPLIFIERS AND SPATIAL COMBINERS WITH IMPEDANCE TUNERS USING MEM INDUCTORS AND VARIABLE CAPACITORS

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Abstract

This paper presents work towards heterogeneous integration of high-efficiency power amplifiers (PAs) with tuner and biasing circuits implemented with micro-electro-machined elements. The PAs operate in switched mode with over 70% efficiency at X-band. Many such switched-mode amplifiers are used as the active portion of spatial power combining antenna arrays, with 2.3kW ERP at 8.4GHz at 65% drain efficiency, and 10kW ERP at 10GHz with over 60% efficiency.

The switched-mode PAs are sensitive to the load impedance and small device variations can degrade efficiency. An output tuner for post-production efficiency tuning is developed with varactor diodes as a demonstration. MEM tuners have advantages of linearity, low power consumption, and low loss. For MEM tuners, variable capacitors are developed with 3:1 tuning range and with Q factor above 200. Lumped element bias lines for these amplifier circuits have been developed with MEM inductors that are suspended in air and have very low parasitic capacitance, allowing for high resonant frequencies. The capacitors and inductors can be assembled on any substrate for true heterogeneous integration.

1. INTRODUCTION

In this paper, we present work in high-efficiency power amplifiers, tuners for amplifier load impedance and micro-electro-machined components for biasing and tuning elements. Class-E switched mode of operation has recently gained a lot of attention at different frequency ranges. It was developed for lower frequencies and extended to microwave frequencies in a transmission-line circuit by Mader and Popovic in 1995 [1]. 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, resulting in a theoretical 100% efficient amplifying. Typical class-E transistor voltage and current waveforms for a 50% switching duty-cycle are shown on Figure 1.

The first step in class-E amplifier design is determination of the device output capacitance, necessary for the optimal output impedance calculation. 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 "π" linear model for the device, the output capacitance for the selected MESFET is found to be C_{OUT} = 0.11pF. The optimal class-E impedance is therefore found to be Z_E = (27.3 + j31.5)Ω. The impedance range for the load impedance due to device variations can be tuned with a single-stub tuner with two degrees of freedom. The tuner can be implemented using varactor diodes, which suffer from loss, or MEM capacitors, which are typically fabricated on different substrates than optimal for the PAs. Here we present some MEM variable capacitors that can be integrated on standard microwave substrates. Such optimized PAs can be integrated in a spatial power combiner with good combining efficiency (>75%). In this paper, we present all the individual components necessary for this type of optimized amplifier integration.

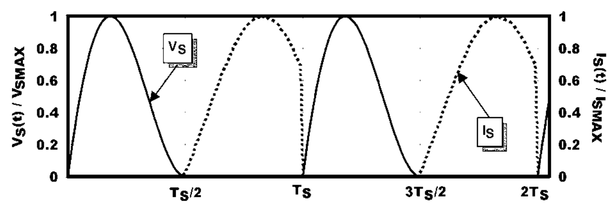

Figure 1. Transistor output voltage and current waveforms in class-E mode of operation.

2. X-BAND SWITCHED-MODE POWER AMPLIFIERS AND SPATIAL COMBINERS

For the X-band class-E power amplifier design used in the spatial power combiner, general purpose GaAs MESFETs produced by Alpha Industries Inc. were selected. In class-A at 18GHz this device is capable of delivering 21dBm of output power with 9dB of power gain at the 1dB compression point. The circuit is fabricated on a Rogers TMM6 substrate (ε_r = 6; thickness = 0.635μm), shown in Figure 2. The active device and RF decoupling capacitor is mounted on a machined copper base connected to the ground plane with conductive epoxy. In the characterization, the optimal bias point is found to be V_{DS}=4.2V, V_{GS}=-1.4V, I_{DS0}=20mA. Measured output power, gain and efficiency are shown in Figure 3.

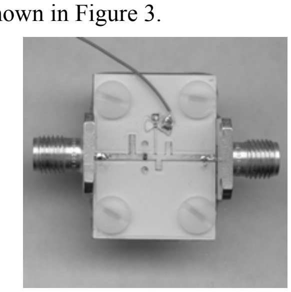

Figure 2. Photograph of 10GHz class-E power amplifier.

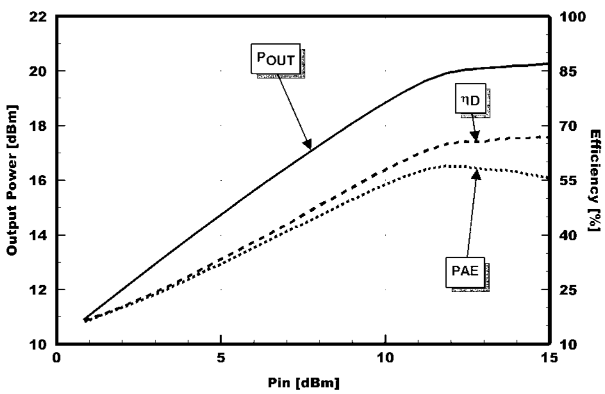

Figure 3. Measured characteristics of the class-E PA element for V_{DS}=4.2V, V_{GS}=-1.4V, I_{DS0}=20mA, showing output power and efficiency as a function of input power.

With the devices available for this combiner, a maximum of 1.8W (20.3dBm average measured PA power) from a 16-element combiner is expected at 10GHz 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. The amplifiers are connected with a corporate fed one-to-four Wilkinson divider, providing good isolation between amplifiers and designed for the selected radiating element geometry. Based on measurements on a back-to-back divider/combiner circuit, insertion losses of the 4-element feed are estimated to 0.7dB. A schematic of the 4-element subarray is shown on Figure 4.

Measurements on the 4-element subarray show 460mW of output power delivered to the antenna, with average drain efficiency of 70% and average PAE of 57%. Radiated power is 400mW and the power combining efficiency is 81%. The measured power, gain and dissipation are shown in Figure 5.

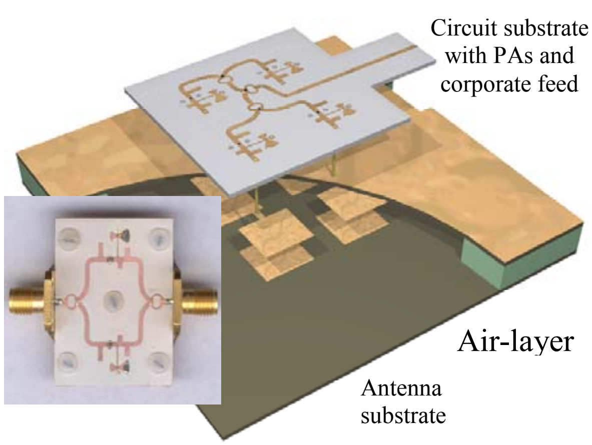

Figure 4. Schematic of the 4-element active subarray showing multiple layers. A Wilkinson combiner is used in the array, with two class-E amplifiers in a corporate configuration shown in the corner inset.

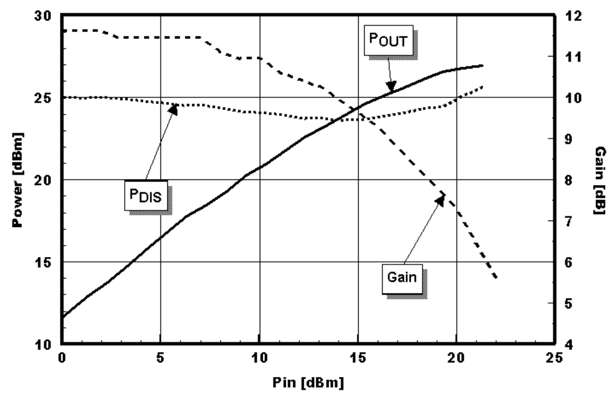

Figure 5. Power sweep characteristics of the amplifier stage in the 4-element active subarray.

3. TUNER FOR POWER AMPLIFIER LOAD IMPEDANCE OPTIMIZATION

Electronic tuners were first developed using monolithic-microwave integrated-circuit (MMIC) techniques for on-wafer noise-parameter measurements [2]-[3]. Both tuners in [2] and [3] use multiple pseudomorphic high electron-mobility transistors (pHEMTs) distributed along a transmission line to create effective short or open-circuit stubs at varying distances to produce a constellation of discrete impedances at the source of the transistor under test [4]. Other tuners use varactor diodes to create a changing capacitance in a transmission line to change the characteristic impedance. Varactor diode and transistor tuning elements are inherently lossy, limiting their tuning range. The nonlinear properties of these semiconductor devices also limit their use in high-power applications.

As discussed above, high-efficiency switched-mode amplifiers require specific input and output impedances. Small device variations in the transistors result in a range of required impedances for post-production tuning. Electronic impedance tuners would allow compensation for these device variations for high-efficiency operation of these amplifiers.

As a demonstration, a single-stub tuner with two varactor diode tuning elements was developed and is shown in Figure 6. The two diodes change the effective electrical length of the stub and the distance from the stub to the load, allowing fine-tuning of the impedance.

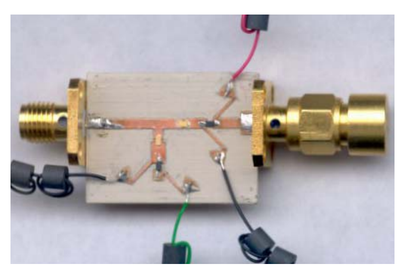

Figure 6. Photograph of an electronic single-stub tuner with two varactor diode tuning elements.

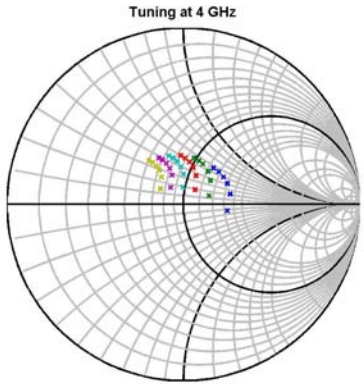

Figure 7. Measured tuning at 4GHz. Discrete points are shown, however, tuning is continuous.

Measurements of this tuner at 4GHz are shown in Figure 7. This approach can be extended to 10GHz to tune the load impedance of the amplifier discussed in this paper for maximum efficiency.

Using capacitance tuning instead of switches allows continuous tuning within the range shown in Figure 7. However, varactor diodes have limitations in high-power applications and would not be sufficient for high-efficiency amplifier applications. The following section describes MEMS variable capacitors and inductors are alternative tuning elements.

4. MEMS VARIABLE CAPACITORS AND HIGH-FREQUENCY INDUCTORS FOR AMPLIFIER TUNER APPLICATIONS

MEMS variable capacitors can be designed with similar capacitance ranges to varactor diodes with the additional advantages of linearity, low power consumption, and low loss.

To obtain a large capacitance tuning range, the device in Figure 8 uses an array of 30 individual capacitors in parallel, suspended by a single central bond pad with support beams of varying widths. The changing spring constant in the support beams actuates the capacitors in a cascading manner as voltage increases, resulting in a linear capacitance response to voltage [5]. Figure 9 shows the capacitance response with increasing voltage, which is linear above a 30V threshold.

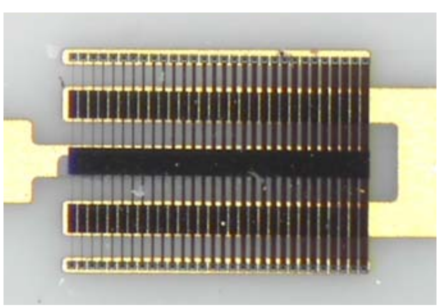

Figure 8. A top-view photograph of a MEM variable capacitor array. Support beams of varying widths create a cascading snap-down effect and a linear 3:1 increase in capacitance with applied voltage.

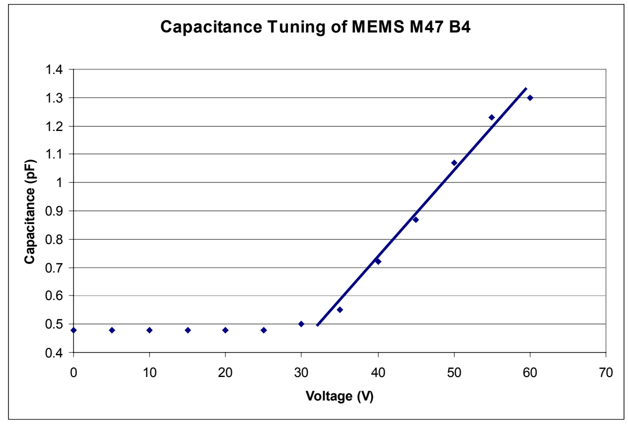

Figure 9. Above a threshold of 30V, the capacitance tuning is linear for the device shown in Figure 8.

The MEM variable capacitor in Figure 8 has a 3:1 capacitance range from 0.5 to 1.5pF, a suitable range for capacitance tuning at X-band. Measured Q-factor of this capacitor exceeds 200.

A suspended micromachined inductor is developed to decrease the complexity and reduce the size of the biasing circuitry required for independent control of multiple tuning elements. This 18nH inductor is suspended 60μm above the substrate, greatly reducing parasitic capacitances. The measured self-resonant frequency is 18GHz. The inductor shown in Figure 10 is approximately 650μm^2. Measured and simulated s-parameters are shown in Figure 11.

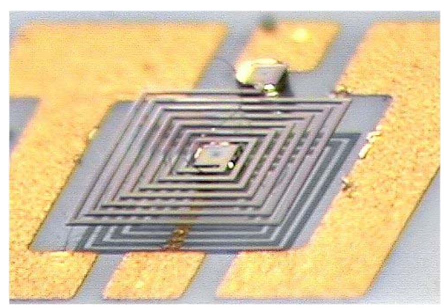

Figure 10. A photograph of an 18nH micromachined inductor suspended 60 µm above the substrate. This inductor has a measured self-resonant frequency of 18GHz.

Both the variable capacitor and inductor, shown in Figures 8 and 10 respectively, are fabricated using an inexpensive and commercially available polysilicon micromachining process provided by the JDS/Cronos Multi-User MEMS Process (MUMPs). These devices flip-chip transferred to a microwave substrate for heterogeneous integration. Both photographs in Figures 8 and 10 show the device on an alumina substrate. The low-resistivity silicon host substrate is removed and gold metal layers are added to reduce losses in these devices. Ordinarily, MEM micromachining occurs on substrates that are not suitable for microwave circuits. The flip-chip process allows fabrication of the MEM device on a low-cost substrate and then the integration of a MEM device with any microwave substrate. Using these MEM capacitors and inductors in amplifier tuner applications will allow post-production tuning for efficiency with a small and low-loss tuner circuit.

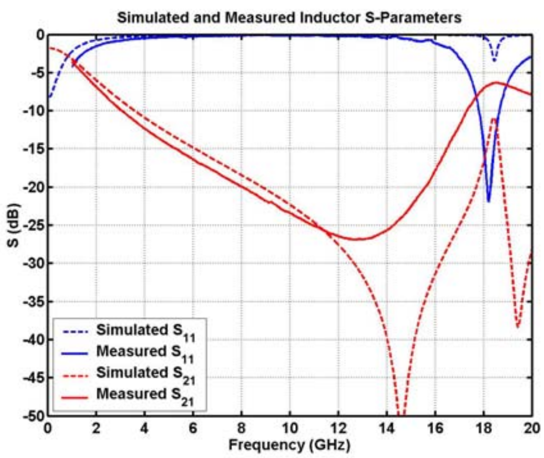

Figure 11. Measured and theoretical s-parameters of the suspended micromachined inductor. Theory accurately predicts the 18GHz self-resonant frequency of the inductor.

5. CONCLUSION

In this paper, we present all the individual components necessary for optimized amplifier integration. High-efficiency switched-mode amplifiers with over 70% efficiency at X-band are developed and applied in a spatial power-combining array. To compensate for small device variations in the amplifiers that degrade efficiency, electronic impedance tuners are developed using varactor diodes for demonstration. Nonlinearity and loss in the diodes are undesirable for high-efficiency amplifier applications, so low-loss low-power MEM variable capacitors are developed as an alternative capacitance-tuning element. Micromachined suspended MEM inductors with a high resonant frequency are also developed to decrease the size of biasing circuitry required for multiple tuning elements. A flip-chip assembly technique allows the integration of these MEM components on a microwave substrate suitable for the amplifier. Integrating these MEM devices, tuners and amplifiers together will allow development of ultrahigh-efficiency X-band power amplifiers.

ACKNOWLEDGEMENTS

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