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The Bias Smith Tube: Simultaneous Optimization of Bias Voltage and Load Impedance in Power Amplifier Design

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***Abstract* — Multiple factors must be considered in power-amplifier design for wireless communications and radar, including bias voltage, input power, and load impedance. The Bias Smith Tube is presented as a three-dimensional extension of the Smith Chart with bias voltage as the vertical axis. It allows simultaneous visualization of nonlinear output characteristic behaviors over transistor bias voltage and load reflection coefficient. Simulated and measured three-dimensional surfaces of constant power-added efficiency (PAE), adjacent channel power ratio (ACPR), and delivered power are shown in the Bias Smith Tube, and a design approach is illustrated that finds the combination of load impedance and bias voltage providing maximum PAE under ACPR and/or delivered power constraints.**

***Index Terms* — Power amplifiers, load-pull, nonlinear measurements, design.**

I. INTRODUCTION

Design of nonlinear power amplifiers requires consideration of multiple output criteria variation over several input parameters, including bias voltage, input power, and load impedance. We have previously described the simultaneous optimization of load reflection coefficient and input power for power-added efficiency (PAE) and adjacent-channel power ratio (ACPR) using the Power Smith Tube [1]. In this paper, we introduce the Bias Smith Tube and demonstrate its use to simultaneously optimize bias voltage and load impedance.

The variations of transistor power efficiency and linearity with bias voltage are well described in the literature, including envelope modulation of gate-voltage bias [2], control of drain voltage and current to improve PAE [3], tuning of both input and output bias voltages [4], consideration of both drain voltage and RF input to simultaneously optimize bias and RF power for efficiency [5], and simultaneous optimization of the input waveform and DC voltage using a DC-DC converter [6]. The literature also examines the effect of load resistance on the bias point and power efficiency [7], the variation of optimum load impedance on the Smith Chart and PAE with bias [8, 9], and selection of matching circuit impedance and bias voltage to optimize peaking and carrier amplifier performance in Doherty amplifiers [10].

II. THE BIAS SMITH TUBE

The Bias Smith Tube is shown in Fig. 1. This Smith Tube uses a bias voltage as its vertical axis, and a traditional Smith Chart (the complex plane of the load reflection coefficient Γ_L) as the horizontal plane.

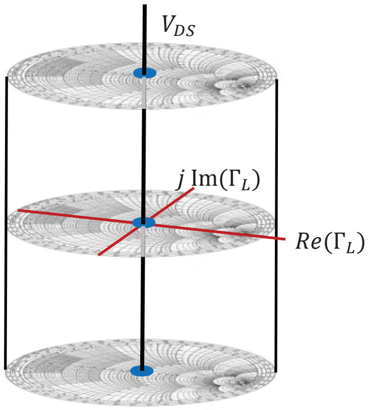

Fig. 1. The Bias Smith Tube. The vertical axis represents a bias voltage (drain-source voltage V_{DS} in this case), while the horizontal cross section of the tube is a conventional Smith chart.

Using the bias tube, variations of device performance metrics such as PAE, ACPR, and delivered power P_d can be plotted versus variations in both Γ_L and bias voltage. These are plotted in the form of three-dimensional "contours," or surfaces: the loci of points in the tube containing the same PAE, ACPR, P_d, or other metric.

II. SIMULATION EXAMPLE

Using a Modelithics nonlinear transistor model for Excelis EFA060BS5 MESFET in Keysight Technologies' Advanced Design System (ADS) simulator, we attempt to maximize the PAE while requiring ACPR ≤ -45 dBc. Simulations were performed at a fixed frequency of 3 GHz and input power $P_{in} = 15$ dBm. This is a typical communications or sensing example where the efficiency must be optimized while the adjacent-channel power is maintained below a threshold.

Figure 2 shows the surface representing ACPR = -45 dBc in the Bias Smith Tube. This data was gathered by performing load-pull simulations from 0.5 V to 12 V in steps of 0.5 V, with gate-source voltage $V_{GS} = -1$ V. As V_{DS} is increased, the optimum load resistance for linear performance is expected to increase as the optimum-linearity load line slope decreases in the I_D-V_{DS} plane. As V_{DS} is lowered, the quiescent point approaches the knee region and the linearity worsens (fewer Γ_L points provide acceptable ACPR).

The goal for the design is to find the point providing maximum PAE while maintaining ACPR ≤ -45 dBc. This constrained optimum point is shown in Fig. 3, along with the equal-PAE surface representing this constrained optimum PAE value. The surface of points in the Smith Tube providing the largest PAE while meeting constraints (35.79 percent) is also plotted. The surface shows that the Smith Chart region of points providing a PAE of 35.79 percent or greater gets smaller as V_{DS} is increased.

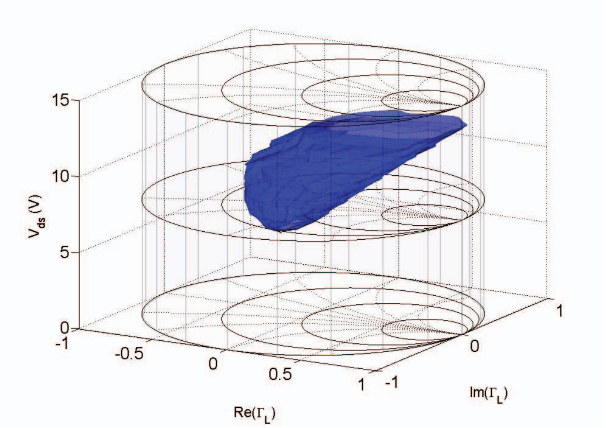

Fig. 2. Simulated constant-ACPR surface for the Excelics EFA060BS5 MESFET model in the V_{DS} Smith Tube representing ACPR = -45 dBc at 3 GHz for $P_{in} = 15$ dBm.

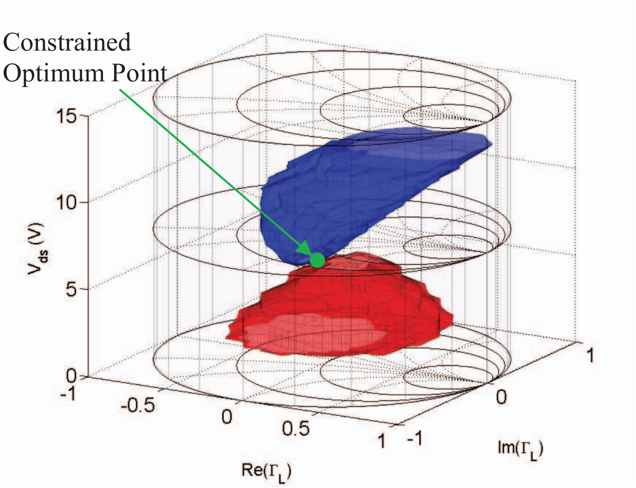

Fig. 3. Surface for ACPR = -45 dBc and region with PAE ≥ 35.79% from simulations. The constrained optimum point is $\Gamma_L = 0.1\underline{/165^\circ}$, V_{DS} = 5.5 V, and PAE = 35.79%.

III. MEASUREMENT EXAMPLE

To demonstrate the diversity of situations in which the Bias Smith Tube is useful, we now present a measurement example where the bias supply of a fully designed, packaged amplifier is varied. In addition, we demonstrate how more than one design constraint can be applied to the optimization. For this experiment, the bias supply V_{DD} of a Skyworks SKY65017-70LF InGaP amplifier (shown in figure 4) was varied from 3 V to 9.5 V in steps of 0.5 V at a frequency of 3.3 GHz and a constant input power of 2 dBm. The goal is to obtain the largest PAE possible while maintaining ACPR ≤ -27.5 dBc and the delivered power (P_d) above 17.5 dBm. This is a typical design problem: the transmitted power is important to the success of the communication or sensing operation, while low ACPR must be maintained to meet spectrum requirements.

Figure 5 shows the measured surface containing points providing ACPR ≤ -27.5 dBc in the Bias Smith Tube. Figure 6 shows the measured surface containing points providing $P_d \geq 17.5$ dBm. To satisfy both of these objectives the solution must fall within the intersection of the acceptable ACPR and P_d regions, shown in Fig. 7. Figure 8 shows the constrained optimum point: maximum PAE of 12.59% is obtained for $\Gamma_L = 0.44\underline{/-14.8^\circ}$ and $V_{DD} = 7.5$ V. The surface of points possessing this PAE is also shown.

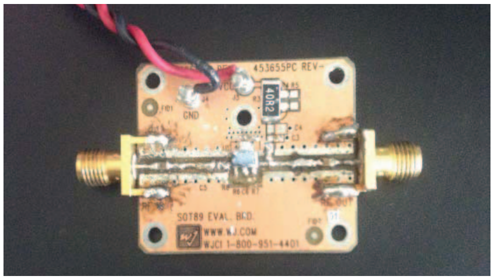

Fig. 4. Skyworks SKY65017-70LF InGaP amplifier

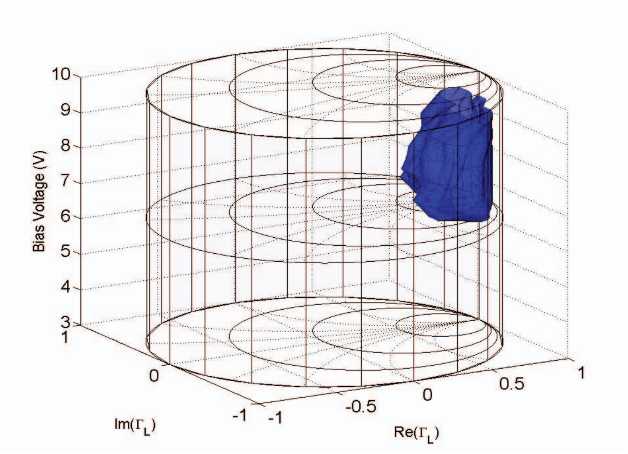

Fig. 5. Measured surface for ACPR = -27.5 dBc

IV. CONCLUSIONS

The Bias Smith Tube is introduced as a visualization tool to allow simultaneous optimization of the load reflection coefficient and bias voltage in nonlinear power amplifier design. This approach is expected to find usefulness in CAD- and measurement-based power amplifier design, as well as providing visualization for fast real-time reconfiguration algorithms in communication and radar systems. Note that while the Bias Smith Tube is a useful visualization tool, it still requires hundreds of measurements to fully examine the tube. Design of a fast algorithm to quickly find the constrained optimum solution is the next step toward fast, accurate, simultaneous optimization of multiple design parameters for multiple objectives.

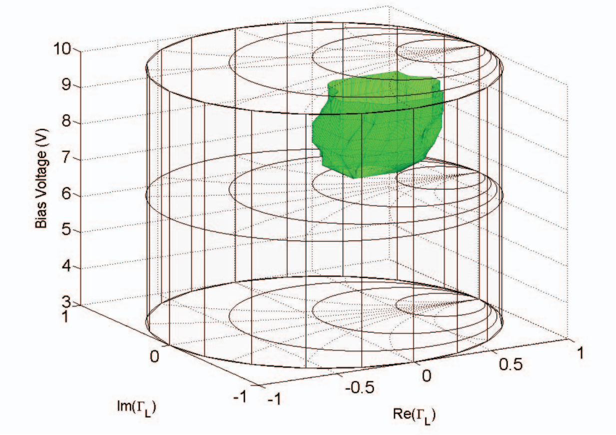

Fig. 6. Measured surface for $P_d = 17.5$ dBm

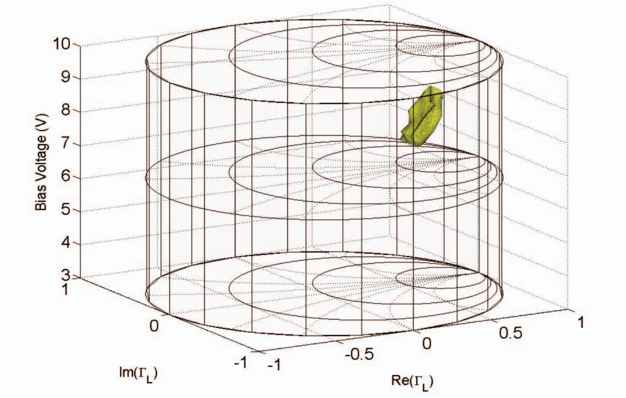

Fig. 7. Combined acceptable region providing ACPR ≤ -27.5 dBc and $P_d \geq 17.5$ dBm

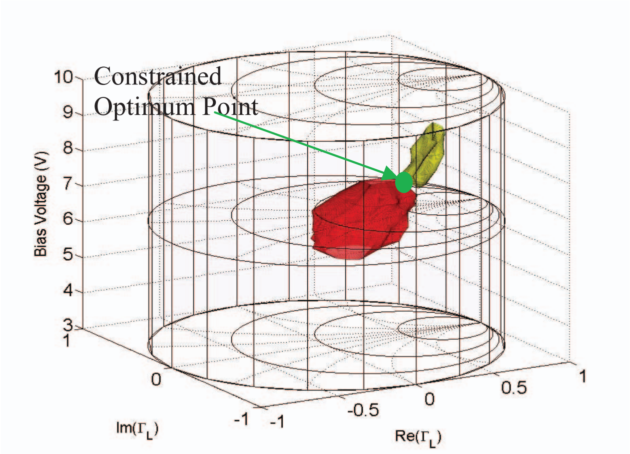

Fig. 8. Constrained optimum point providing maximum PAE with ACPR ≤ -27.5 dBc and $P_d \geq 17.5$ dBm. The constrained optimum PAE is 12.59% at $\Gamma_L = 0.44\underline{/-14.8°}$, $V_{DD} = 7.5$ V. The surface of points possessing PAE = 12.59% is also shown with the combined P_d and ACPR acceptable region.

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