A High-Efficiency Traveling-Wave Power Amplifier Topology Using Improved Power-Combining Techniques

Eric S. Shapiro, Jian Xu, Amit S. Nagra, Freddy Williams, Jr., U. K. Mishra, and Robert A. York

***Abstract*— Traditional distributed amplification techniques have allowed for high gain and bandwidth at the expense of low efficiency. The decreased efficiency is primarily due to the existence of an actively loaded artificial transmission line as the output, resulting in backward wave propagation. Using the same traditional input line distributed techniques to achieve high bandwidth, this research has explored a delay line and corporate combining output topology which improves the travelling-wave amplifier's (TWA's) efficiency at large signal by elimination of the backward waves. The broad-band output combiner transforms the amplifier load impedance to that of an optimum load for each device, thus realizing a traveling-wave power amplifier. The results for a 1–9-GHz hybrid circuit are presented.**

I. Introduction

THE conventional traveling-wave amplifier (TWA) circuit was originally intended for broad-band small-signal applications. Such a broad-band response is also desirable in large-signal applications such as radar and satellite communications. The conventional TWA at large-signal output levels presents significant limitations with regards to efficiency. The forward wave constructive interference through the distributed output network results in nonuniform voltage swing across each unit cell. Additionally, power is lost to backward wave excitation on the artificial output line. A goal of this research was to develop a modified output topology that eliminated the backward wave propagation and uniformly loaded each of the class-A gain blocks with an impedance closer to the optimum load for power, while still maintaining broad-band response provided by the distributed input line matching technique.

Fig. 1 shows the proposed modified topology. The modified version of the traditional TWA employed the same distributed circuit matching techniques to achieve broad-band matching. The output artificial line was replaced by delay lines of characteristic impedance $R_{\rm opt}$ which phase matched the device output signals at the power combiner inputs. An efficient broad-band output combiner transformed the amplifier load impedance to that of an optimum load for each port, thus realizing a traveling wave power amplifier (TWPA). A 1–9-GHz coplanar waveguide (CPW) hybrid circuit was successfully designed in HPEEsof and fabricated on Aluminum Nitride. The measured TWPA results are presented and compared to measured results for a conventional TWA with the same device and input periphery.

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II. Broad-Band Combiner Design

For an N device input periphery we essentially require a broad-band match between $R_{\rm opt}$ and NZ_o. The NZ_o term results from N devices output signals sharing the Z_o amplifier load under even mode excitation of the combiner. In our case of $N = 4$ devices and $R_{\rm opt} = 100\,\Omega$, we observe that a tapered line would have to be of characteristic impedance 100 Ω on one end and 200 Ω on the other side. The unrealizable 200-Ω transmission line section necessitated a different approach. In fact, it was observed that the even-mode excitation of the combiner could be used to effectively realize the higher impedance lines by sharing arms of binary corporate combiner network. In a traditional Wilkinson power combiner, a three-port simultaneous match is achieved by introducing isolation resistors across the transmission line networks. In the TWPA output combiner, these isolation resistors were eliminated since we were realizing a large-signal load line output match, and were under the assumption of a uniform excitation of all input ports. A Cohn combiner [1] is a redesigned Wilkinson combiner with additional quarter-wave transmission line sections for increased bandwidth. This same approach was used in the TWA's corporate combiner to effectively approximate the necessary broad-band taper. The center frequency of the combiner was determined by that of the quarter-wave sections.

III. Results

To avoid thermal management issues for this proof-of-concept circuit, we used small-signal nec76000 MESFETS biased for Class-A with an optimum load close to 100 Ω. $C_{\rm gs}$ was about 0.4 pF, and the series gate resistance was about 9 Ω. HPEEsof simulations confirmed an increase in gain, and thus efficiency, over the conventional TWA for the $N = 4$ device periphery. Element values and a simulation for the combiner are available in Fig. 2. Efficiency simulations are available in Fig. 3. The amplifier, shown in Fig. 4, was constructed in 2.54-μm-thick gold CPW on Aluminum Nitride ($\varepsilon_r = 8.5$) with ground plane. The board dimensions were 1 in × 0.5 in. Thermal conducting epoxy was used to secure the devices and 1-mil bond wires were used for device

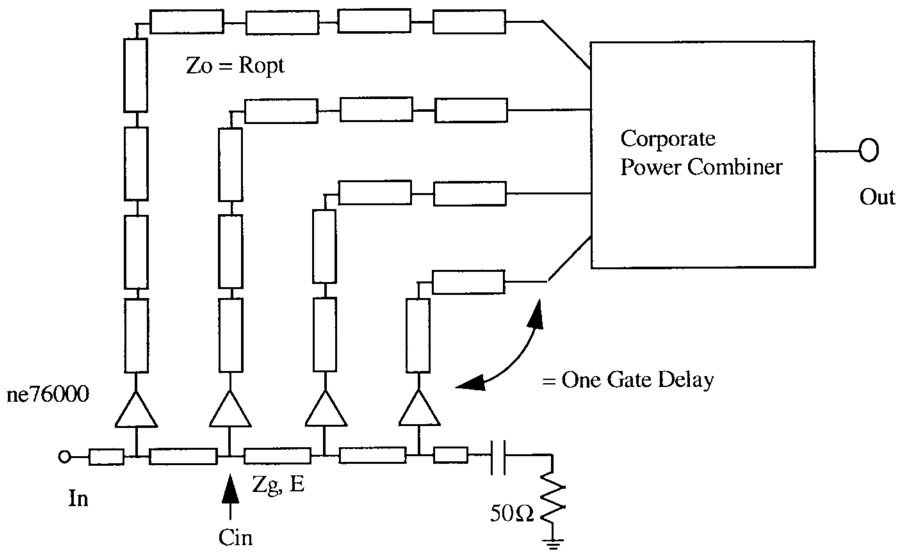

Fig. 1. Modified TWPA for eliminating backward wave and improving efficiency.

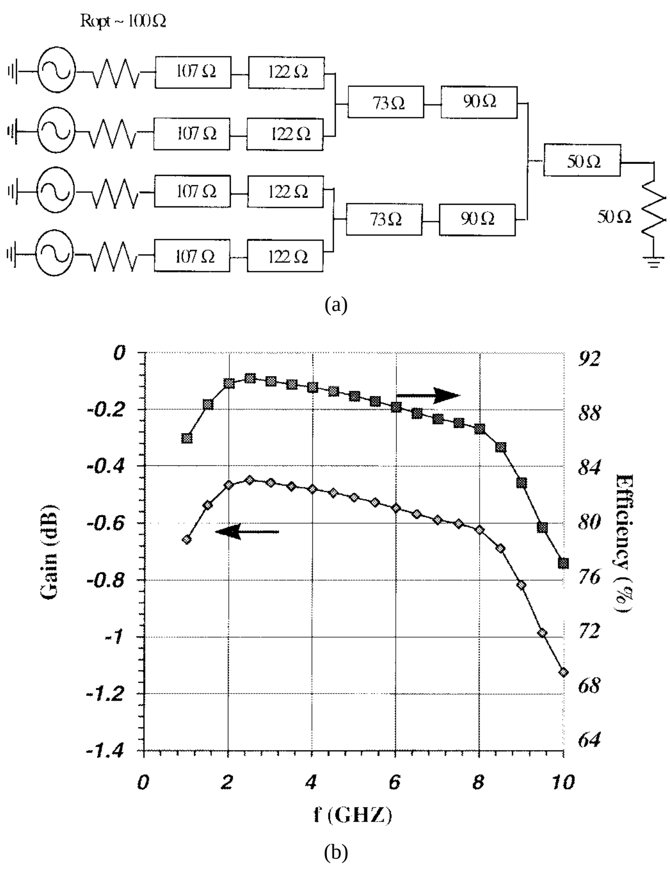

Fig. 2. HPEEsof simulation of the corporate power combiner. (a) Corporate power combiner circuit. (b) Simulation results.

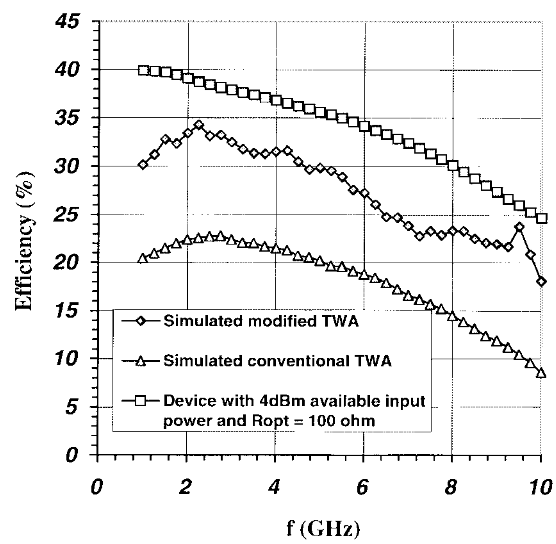

Fig. 3. HPEEsof simulation of the output efficiency for the individual device, conventional TWA, and modified TWPA.

ports and CPW air bridges. The results in Fig. 5 show the measured TWPA gain versus the measured conventional TWA gain. The HPEEsof TWPA simulation is also shown for comparison. The improvement in gain, and thus efficiency, was demonstrated. We see that output network of the TWPA exhibited a frequency roll-off starting at 5.5 GHz. This may be attributed to CPW gap radiation from the high-impedance lines of the combiner, a need for better characterization of the substrate, and parasitics associated with the CPW corners and wire bonding. Future work will continue to explore these details as well as incorporating high-power devices into the design.

IV. Conclusion

A TWPA circuit was developed by using improved power-combining techniques for the output network of a distributed amplifier. The output network design appropriately phase aligned the device output signals and then utilized an efficient broad-band combiner to transform the amplifier load to $R_{\rm opt}$ for each input port. The combiner was designed to take advantage of the even excitation at its inputs. Measurements demonstrated the improvement in efficiency and durability under higher power levels, desirable in a power amplifier configuration. Combining more than four devices is predicted

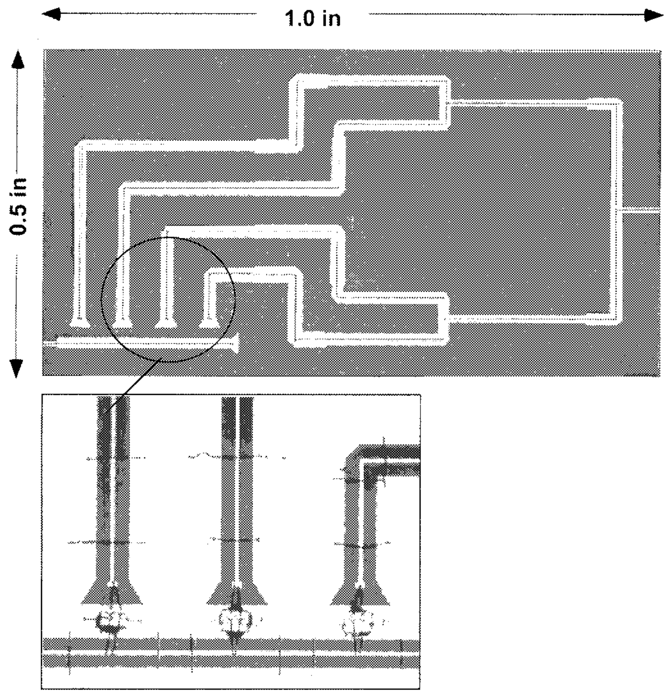

Fig. 4. Modified TWPA layout (∼0.5 in × ∼1.0 in) and close-up view of wire-bonded devices.

to result in lower combining efficiency since the artificial input line attenuation begins to adversely affect the excitation of the power combiner inputs. Also, one must be aware of practicalities when designing for extremely high-impedance transmission lines and a greater than four input power combiner. As mentioned previously, future efforts will continue to explore the radiation effects from wider CPW gaps, and aim for a more detailed model of the substrate in resolving the frequency roll-off issues, as well as incorporating high-efficiency power gain blocks.

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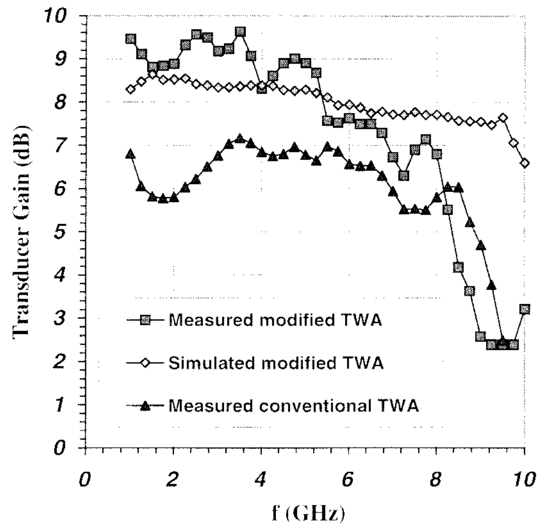

Fig. 5. Simulated and measured results for the prototype circuit shown in Fig. 4.

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