COPLANAR BALUN CIRCUITS FOR GaAs FET HIGH-POWER PUSH-PULL AMPLIFIERS#

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Abstract

Three-strip coplanar balun circuits have been designed and fabricated for the push-pull operation of high-power amplifiers using GaAs Schottky-barrier FETs. Theoretical and measured properties of the balun and amplifier results are presented.

Introduction

A program has been initiated to make high-power microwave amplifiers using recently developed GaAs Schottky-barrier field effect transistors.[1] Push-pull operation was chosen in anticipation of the low device impedances that result from paralleling high frequency transistor units to achieve a high-power output, since push-pull operation increases the matching impedances by a factor of four over parallel, single-ended operation.

Baluns were chosen for the input and output circuits of the amplifier. The balun transforms a "hot"-conductor/ground transmission line, such as a coaxial line, to a two conductor transmission line where both conductors are isolated from ground and currents flow equally in each conductor but 180° out of phase. The unique feature of the balun circuit reported here is that it is made from three coplanar conductors supported by a dielectric substrate. Since the ground plane can also be on the same side of the substrate, there is no necessity of severing the substrate or cutting a hole in it to bring the ground plane through as exists with microstrip circuits. The coplanar balun has the advantage over a microstrip balun in that no top-to-bottom registration of metal patterns is required.

Balun Operation

Figure 1 illustrates, in top and cross-sectional views, the coplanar balun showing the three quarter-wave-long conductors and a ground plane on the top surface of a dielectric supporting material. At the unbalanced end currents of equal magnitudes but opposite in direction flow in the center or "hot" conductor and in the ground planes. At the balanced end, similar currents flow from two conductors, both of which are isolated from rf ground. In this transformation, conductor 1 is an essential element. The short-circuit between conductors 1 and 2 at the balanced end results in an infinite impedance between the conductors a quarter-wave-length away at the unbalanced end forcing all currents to flow between conductors 2 and 3. Without conductor 1, energy would propagate between conductor 2 and the nearby ground and the current available from conductors 2 and 3 would be reduced. Because conductors 1 and 3 are short-circuited at the unbalanced end, there is an infinite impedance between them at the balanced end and the addition of conductor 1 does not load down the balanced end.

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In addition to transforming the mode of propagation from unbalanced to balanced, a balun also provides an impedance transformation. In the case of the coplanar balun shown in Fig. 1 energy propagates between conductors 2 and 3, and the characteristic impedance between those conductors determines the impedance transformation over the quarter-wave-length section.

For frequency response calculations, the balun can be viewed as a quarter-wave-length transmission line formed by conductors 2 and 3 of Fig. 1, with short-circuited quarter-wave-length stubs connected in parallel at the balanced and unbalanced ends. The characteristic impedances of the stubs - conductors 1 and 2 and conductors 2 and 3 - influence the frequency response of the balun.

Impedance Calculations

The characteristic impedances for the three strip balun have been calculated in terms of even- and odd-mode propagation. Even-mode propagation is obtained by applying equal in-phase potentials to each of the outer conductors with respect to the inner conductor. The even-mode impedance is defined as the impedance between the center conductor and one of the outer conductors with an open-circuit plane cutting through the middle of the center conductor. Odd-mode propagation is obtained by applying equal, 180°-out-of-phase potentials to each of the outer conductors with respect to the inner conductor, and the odd-mode impedance is defined as the impedance between the center conductor and one of the outer conductors with a short-circuit plane cutting through the middle of the center conductor. The even- and odd-mode impedances are sufficient to determine the impedance transformation properties of the balun and the frequency response.

The impedances are found by assuming TEM propagation and applying a conformal transformation to the symmetrical coplanar structure to obtain parallel plate transmission lines, the impedances of which are easily obtained. The exact analysis is a modification and extension of C. P. Wen's work[2] in which he analyzed, among other things, the case of a center strip between two infinitely wide ground planes all on an infinite substrate. In general the analysis is difficult for a finite substrate, but if the dielectric constant is high and the substrate is not too thin, a negligible amount of electric field will exist outside of the dielectric under the substrate, and the bottom side of the substrate can be treated as an open circuit plane. When this is the case there are closed-form solutions for the impedances using conformal mapping techniques.

Figure 2(a) shows curves for the even-mode (Z_{oe}) and odd-mode (Z_{oo}) impedances, respectively, as a function of the width-to-gap ratio (W/G) of the lines for different substrate-thickness-to-line-width ratios

(H/W). The curves are for a material with a dielectric constant of 10 and for a symmetrical structure having equal line widths. For both sets of curves, the line for H/W = 10 is essentially the same line as that for an infinitely thick substrate. For the odd-mode impedance, two of the curves have been terminated because the approximation of an open-circuited dielectric plane is no longer valid.

The validity of the above approximation and analysis is demonstrated in Fig. 3 where theoretical and measured results are shown. The effective dielectric constant (ϵ_{reff}) and even-mode impedance (Z_{oe}) are shown versus a parameter a/b defined in the Figure. The experimental results are plotted for several three-strip transmission lines with varying line and gap widths on a 20-mil-thick alumina substrate (dielectric constant = 10). All line widths are equal, the structure is symmetrical, and the overall width for the three lines and two gaps is constant at 182 mils. The measured results, determined by microwave reflection techniques, have been corrected for a loss-per-unit length of 1/2 dB per inch. As can be seen, the measured data is very close to that predicted by the open-circuit-plane analysis.

Push-Pull Amplifiers

Several push-pull amplifiers have been built using baluns described above as input and output matching circuits for an eight-cell GaAs Schottky-barrier-gate field effect transistor. A photograph of one such balun, giving the 5-GHz performance presented below, is shown in Fig. 4. The input and output three-strip baluns, made by etching gold-evaporated 1/2" x 1" x 20-mil-thick alumina substrates, are shown separated by a copper heat sink on which the transistor is mounted. The effective balun length determines the frequency of operation and in Fig. 4 is shorter than 1/2 inch because of the copper hoods and silver-painted grounds near the connectors. The line and gap widths of the three strips are chosen to provide the proper impedances to the transistor. Other elements which may be seen in the photograph are blocking capacitors near the hoods and gold-strap "shorts." The transistor, similar to that described earlier in the digest[1] with eight independent transistor units on a single chip has an f_T of 3 GHz. Equal numbers of the units are connected in parallel for each of the two "balanced" terminals of the push-pull amplifier.

The small signal gain curves for two amplifiers are shown in Fig. 5. Each has a 1-dB bandwidth of about 28%. The amplifier centered at 2.5 GHz has 300 mW of output power at a 1-dB compression point and has a collector efficiency of 15%. Typical biases are -2 volt on the gate and 10 volts on the drain and the resulting class of operation is A or AB. These results demonstrate that for high-power high-frequency amplifiers, push-pull operation using coplanar baluns is a viable alternative to parallel operation using microstrip circuitry.

Acknowledgements

The push-pull amplifier project was initiated with the aid and direction of L. S. Napoli. J. J. Hughes was responsible for the measurements in Fig. 3 and for the construction of the balun circuits. W. F. Reichert supplied the transistors. Their contributions are greatly appreciated.

References

1. L. S. Napoli and R E. DeBrecht, "Performance and Limitations of FETs as Microwave Power Amplifiers," scheduled to be paper X-1 at this symposium.

2. C. P. Wen, Coplanar Waveguide: "A Surface Strip Transmission Line Suitable for Nonreciprocal Gyromagnetic Device Applications," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-17, No. 12, Dec. 1969.

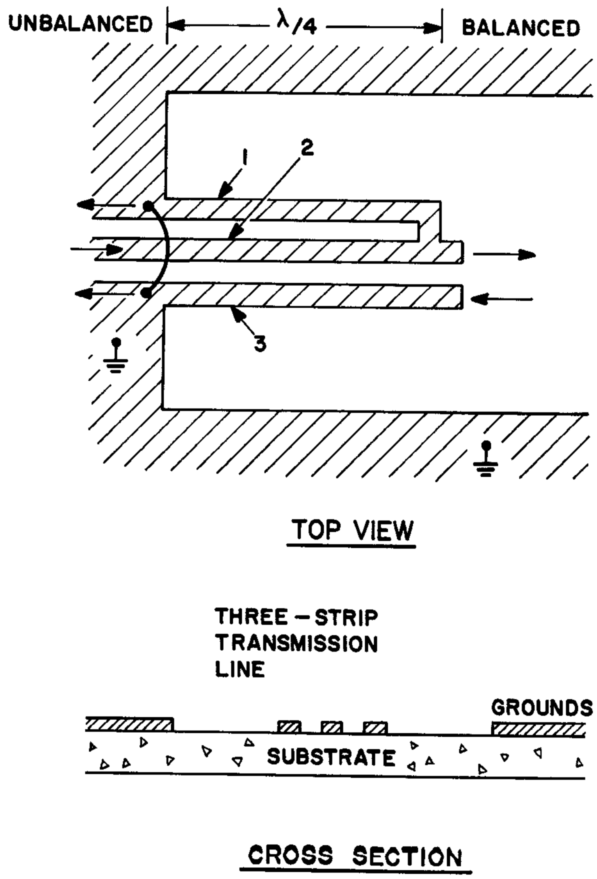
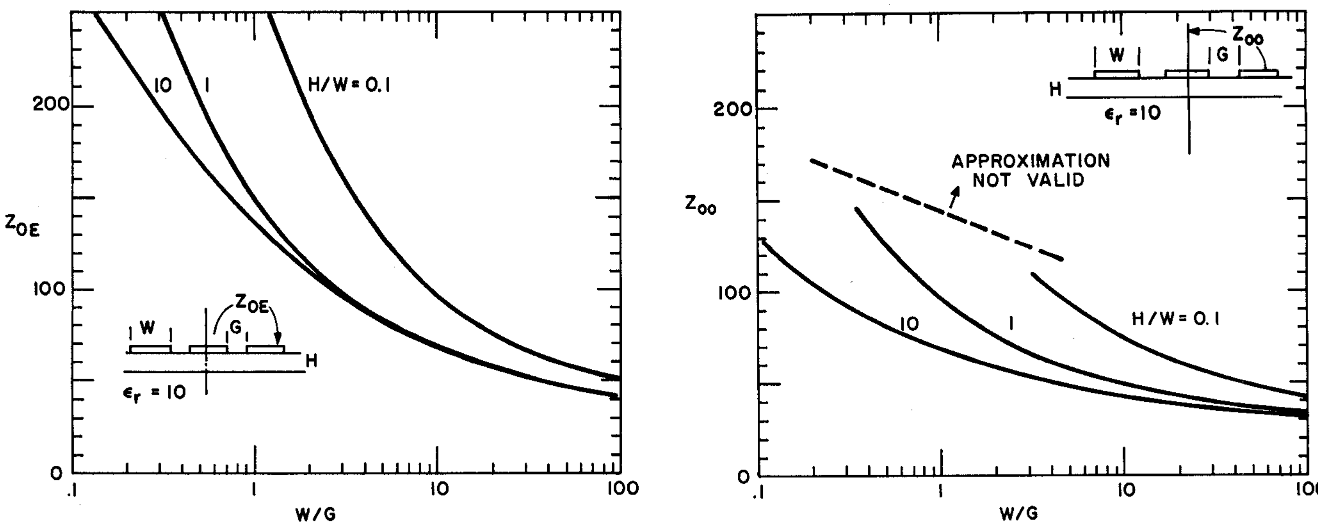


FIG. 1 TOP AND CROSS-SECTIONAL ILLUSTRATIONS OF A THREE-STRIP COPLANAR BALUN



(A) (B)

FIG. 2 EVEN-MODE (A) AND ODD-MODE (B) IMPEDANCE FOR A THREE-STRIP TRANSMISSION LINE VS. THE WIDTH-TO-GAP RATIO (W/G) FOR DIFFERENT SUBSTRATE-THICKNESS-TO-LINE-WIDTH RATIOS (H/W).

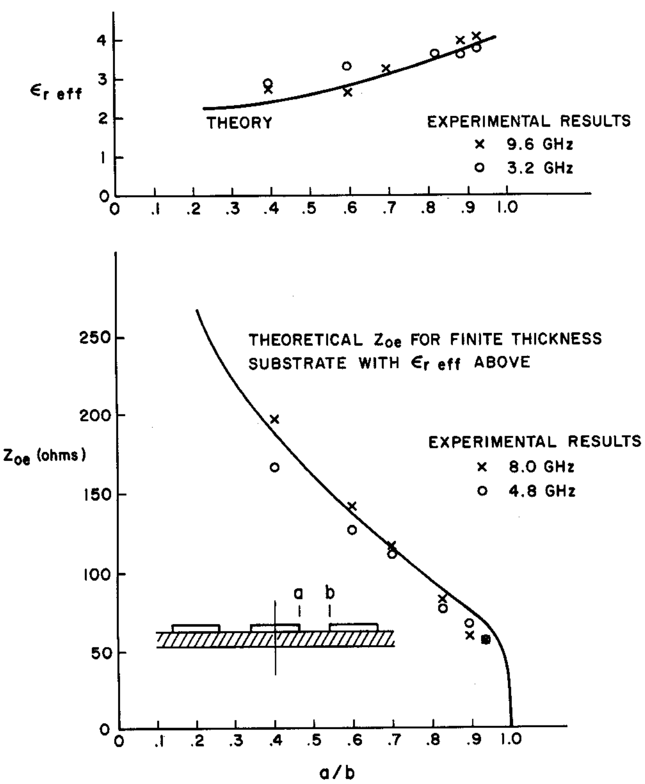


FIG. 3 THEORETICAL AND MEASURED EFFECTIVE DIELECTRIC CONSTANT ($\epsilon_{r\ eff}$) AND EVEN-MODE IMPEDANCE (Z_{oe}) VS. A/B FOR A 20-MIL-THICK ALUMINA SUBSTRATE WITH TOTAL WIDTH OF LINES AND GAPS CONSTANT AT 182 MILS

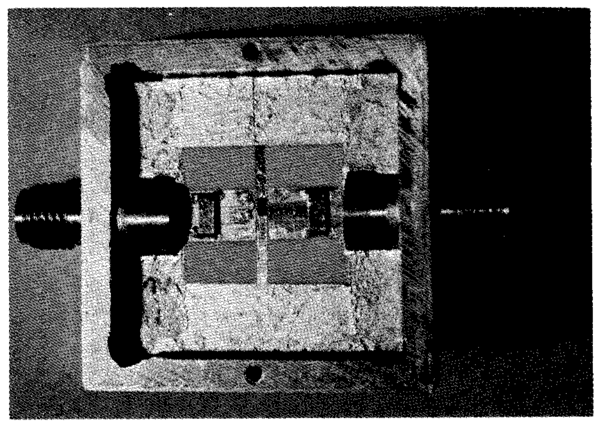


FIG. 4 PHOTOGRAPH OF THE COPLANAR BALUN CIRCUIT, PUSH-PULL AMPLIFIER GIVING THE 5-GHz PERFORMANCE SHOWN IN FIG. 5

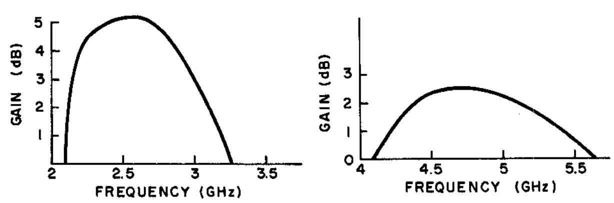


FIG. 5 SMALL-SIGNAL GAIN VS. FREQUENCY CURVES FOR TWO PUSH-PULL AMPLIFIERS USING COPLANAR BALUNS

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