A HIGHLY DIRECTIVE, BROADBAND, BIDIRECTIONAL DISTRIBUTED AMPLIFIER

Joseph W. Byrne and James B. Beyer, Senior Member IEEE

Department of Electrical and Computer Engineering
University of Wisconsin-Madison
1415 Johnson Drive, Madison, WI 53706-1691

ABSTRACT

Design considerations for developing a highly directive broadband bidirectional distributed amplifier are discussed. Directivities on the order of -25 to -35 dB over as much as an octave in frequency are demonstrated using computer simulation with measured s-parameter data for an NEC 9000 transistor.

I. INTRODUCTION

The idea of distributed amplification has been thoroughly analyzed and studied ever since its introduction by Percival [1] in 1937. The conventional distributed amplifier circuit is shown in Fig. 1. Renewed interest in this circuit has been shown in recent years because of its realization as a planar microwave circuit utilizing GaAs FETs.

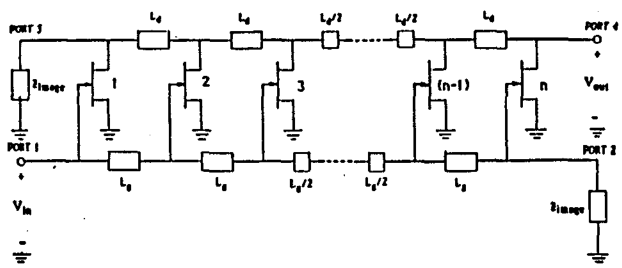


Figure 1. Conventional distibuted amplifier circuit ($f_c \approx 12.732$ GHz, $L_d = L_g = 1.25$ nH)

Due to the symmetry of the circuit, half of the current from each device propagates in the forward direction (toward port 4) and half in the reverse direction (toward port 3). Unlike the "in phase" currents traveling in the forward direction, those traveling in the reverse direction are "out of phase" with each other and thus destructively interfere to some extent. Because of this cancellation, the conventional distributed amplifier is inherently a directional circuit. In fact, Leisten [2] compares the directional properties of a conventional distributed amplifier to that of an ideal circulator.

We can define directivity for the distributed amplifier as the ratio of the reverse output power (P^-_{out}) at port 3 to the forward output power (P^+_{out}) at port 4. In dB, this is given as

$$D \equiv -10\log[P^-_{out}/P^+_{out}] = -20\log[|s_{31}/s_{41}|] \quad (1)$$

The conventional distributed amplifier typically has a directivity of between -10 to -20 dB over most of the frequency range of interest. It has been shown that these values can be considerably improved through the minimization of s_{31} [3], thus yiedling a broadband, highly directive distributed amplifier. It is the objective of this paper to outline this technique and present computer simulated results.

II. BINOMIAL SCALING

From directional coupler theory, a minimized and maximally flat (broadband) characteristic for s_{31} will be obtained about a center frequency $\omega = \omega_0$ if s_{31} and its first N-1 derivatives with respect to frequency are identically zero at $\omega = \omega_0$. One such function which exhibits this behavior is

$$f(\beta) = A(1 + e^{-j2\beta})^N = A\sum_{i=0}^{N} c_i^N e^{-j2i\beta} \quad (2)$$

where A is a constant and the coefficients c_i^N are binomial coefficients given by

$$c_i^N = \frac{N!}{(N-i)!\,i!} \qquad i = 0,1,2,\ldots,N \quad (3)$$

The significance of (2) is that the expression for s_{31} for the conventional distributed amplifier is similar in form as will be shown next.

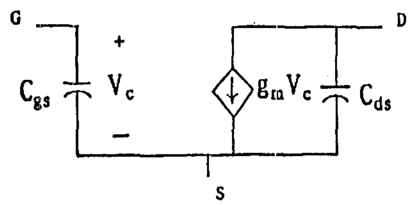


Figure 2. FET lossless small signal model (typical values - C_{gs} = .50 pF, C_{ds} = .09 pF).

1989 IEEE MTT-S Digest

III. IDEAL DISTRIBUTED AMPLIFIER CIRCUIT

In the case of the ideal distributed amplifier, we assume no losses and model each device as in Fig. 2 using typical capacitance values for a 400 μm FET. It is assumed here that the transconductances of the FETs may differ from one another. For this circuit, s_{31} and s_{41} are given as

$$s_{31} = -1/2\, Z_{image} \left[\sum_{i=1}^{n} g_{mi} e^{-j2(i-1)\beta}\right] \quad (4)$$

$$s_{41} = -1/2\, Z_{image}\, e^{-j(n-1)\beta} \left[\sum_{i=1}^{n} g_{mi}\right] \quad (5)$$

where β is the phase shift per π-section along the lines and n represents the number of devices in the amplifier. Comparing (2) and (4), it can be seen that they are essentially the same expression if $A = -1/2\, Z_{image}$ and $C_i^N = g_{mi}$. Therefore, by binomially scaling the FET transconductances, we should obtain a minimized maximally flat signal at port 3, thus improving the directivity.

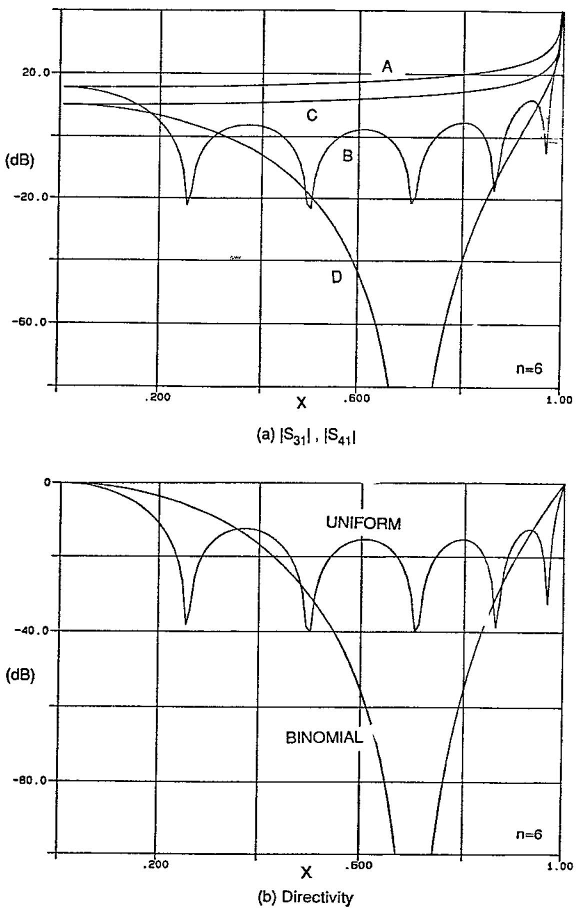


Figure 3. Plots of $|s_{31}|$, $|s_{41}|$, and directivity for the ideal distributed amplifier for both unifor and binomial scaling. (A = $|s_{41}|$ uniform, B = $|s_{31}|$ uniform, C = $|s_{41}|$ binomial, D = $|s_{31}|$ binomial).

Figure 3 compares s_{31}, s_{41}, and the directivity for both uniform scaling (g_{mi} = constant = 1) and binomial scaling. In this case, the circuit contains 6 devices (n=6). These curves are plotted as a function of the normalized frequency, X, which is given as

$$X = \omega/\omega_c \quad (6)$$

where ω_c is the cutoff frequency of the lines

$$\omega_c = 2/\sqrt{LC} \quad (7)$$

From Fig. 3a, it is quite clear that binomial scaling has minimized s_{31}. In the process however, Fig. 3a also illustrates the undesirable reduction in s_{41} due to the smaller values of transconductance used in the binomial case. Regardless of this reduction, Fig. 3b clearly shows the greatly improved directivity obtained using binomial scaling. Although we have chosen to illustrate our results using 6 devices, it should be noted that the directivity bandwidth increases with an increase in the number of devices.

IV. A DISTRIBUTED AMPLIFIER CIRCUIT WITH LOSSES AND M-DERIVED TERMINATIONS

Figure 4 shows a more realistic FET small signal model in which device losses have been included. This model will replace the earlier lossless model in the circuit of Fig. 1. We will also terminate each port with m-derived impedance transforming sections. These sections match the lines image impedance to conventional 50 Ω systems.

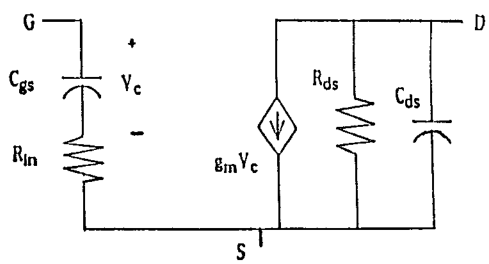


Figure 4. FET small signal model with losses (typical values - C_{gs} = .50 pF, C_{ds} = .09 pF, R_{ds} = 375 ohms, R_i = 7.5 ohms, g_m = .04 mhos).

Obtaining discrete FETs with scaled transconductances is impractical and thus an alternative method of realizing the binomial scaling must be utilized. One such method is to incorporate a series capacitor (C_s) in the gate lead of each device. The voltage divider established between C_{gs} and C_s yields an effective transconductance given by

$$g'_{mi} = g_{mi} \frac{C_{si}}{(C_{si} + C_{gs})} \quad (8)$$

Therefore, by simply adjusting the values of the individual series capacitors, the desired binomial scaling can be achieved. A padding capacitor (C_p) is also added at each gate to keep the total shunt capacitance at each node along the gate line constant.

Now, it can easily be shown that approximate expressions for s_{31} and s_{41} are very similar in form to those obtained for the ideal circuit. Therefore binomial scaling can again be used to increase the directivity of the amplifier. The results are shown in Fig. 5 where again both the uniform and binomial cases are compared (again n=6). These results are very similar to those obtained for the ideal circuit, with the directivity improved from between -10 to -20 dB in the uniform case to between -25 to -35 dB in the binomial case.

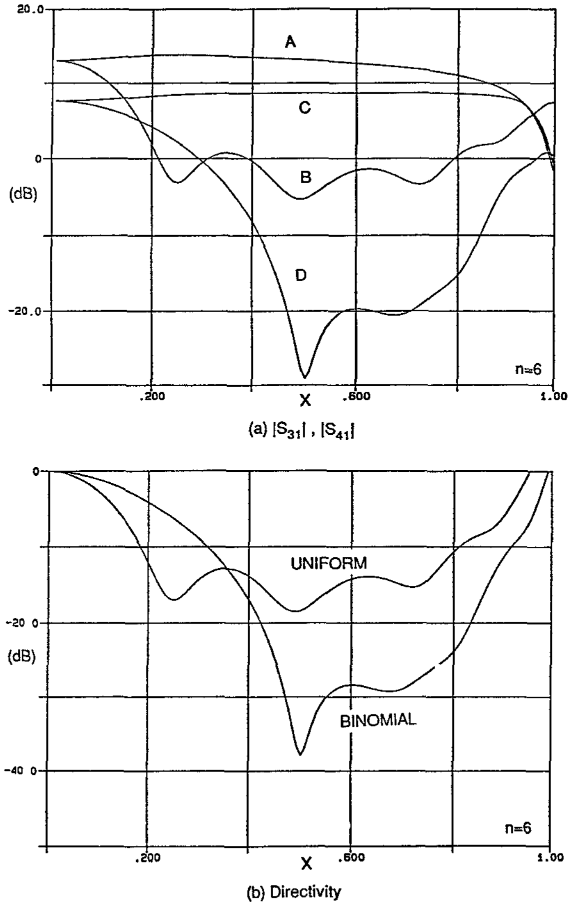


Figure 5. Plots of $|s_{31}|$, $|s_{41}|$, and directivity for the distributed amplifier with losses and m-derived terminations for both uniform and binomial scaling.

V. DIRECTIVITY BANDWIDTH SHIFTING

The minimization of s_{31} is inherently centered about a frequency $\omega = \omega_0$ at which the phase shift per π-section is $\beta = \beta_0 = 90°$. This frequency is fixed at $X_c = .707$ and thus a large portion of the minimization bandwidth falls above $.707\ \omega_c$. Unfortunately, this is also the frequency above which the magnitude of s_{41} begins to roll off quite rapidly. For this reason, and also for added flexibility, it would be desirable to shift the minimization bandwidth to lower frequencies.

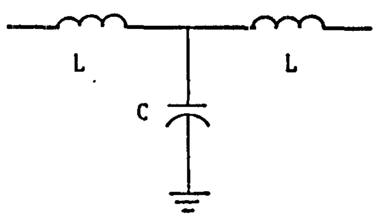


Figure 6. T-section inserts used to shift the minimization bandwidth to lower frequencies.

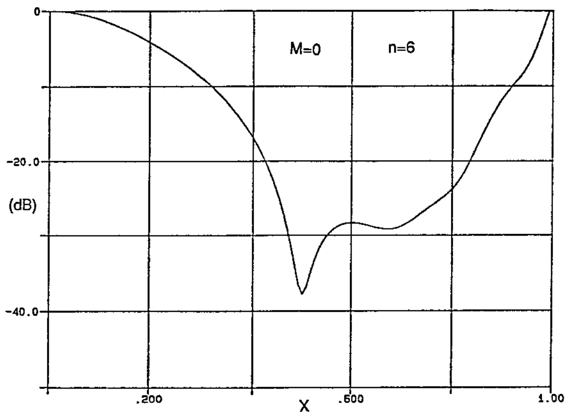
This can easily be done by inserting the passive T-section of Fig. 6 between devices in both the gate and drain lines. This will in turn lower the minimization bandwidth center frequency ω_0 to a frequency at which $\beta_0 = 90°/(M+1)$ where M is the number of T-sections inserted between devices. Figure 7 shows the results of using this technique in the circuit of Figure 1. It is quite easy to see the desired shift in the minimization bandwith to lower frequencies.

VI. COMPUTER SIMULATION USING MEASURED S-PARAMETER DATA FOR THE NEC 9000 TRANSISTOR

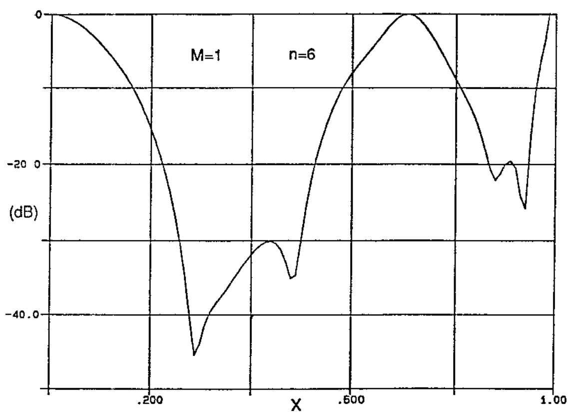
To obtain even more meaningful results, the FET small signal equivalent circuit of Fig. 4 was replaced with the actual measured s-parameter data of an NEC 9000 transistor obtained using an HP 8510 network analyzer. The circuit, utilizing lumped elements between devices, was optimized with the results shown in Fig. 8.

Figure 8a shows directivities on the order of -30 dB over as much as an octave in frequency (5 GHz - 10 GHz). Figure 8b illustrates the results obtained for the same circuit utilizing the T-section inserts of Fig. 6. The minimization bandwidth has clearly been shifted to lower frequencies with directivities on the order of -30 dB obtained over the frequency range from 2.5 GHz to 6.5 GHz. For both circuits, the input and output insertion losses were better than -15 dB over the frequency range of interest.

As one final note, it should be pointed out that this circuit and all of the previous circuits are bidirectional and can be excited from either port 1 or port 2 with the same high directivity

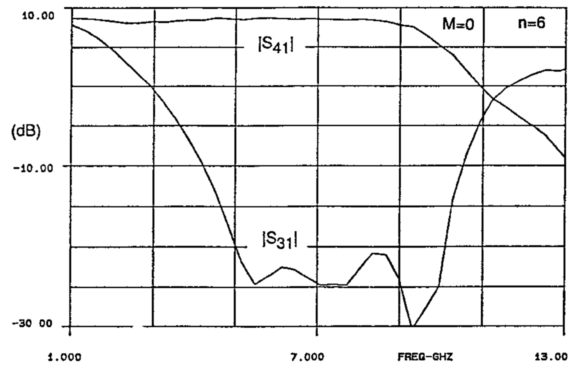


(a) No T-section inserts

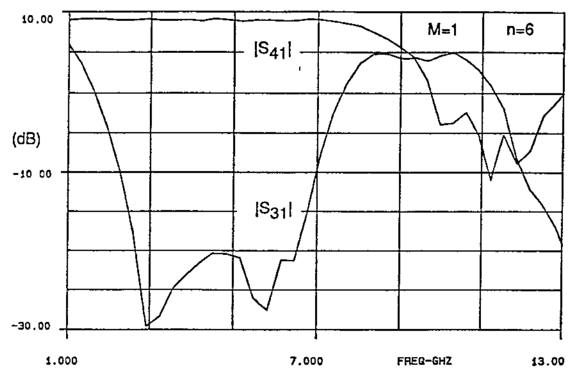


(b) One T-section insert

Figure 7. Plots of directivity for the binomially scaled distributed amplifier with losses and m-derived terminations comparing the cases for which M=0 (no T-section inserts) and M=1 (one T-section insert).



(a) No T-section inserts



(b) One T-section insert

Figure 8. Plots of $|s_{31}|$ and $|s_{41}|$ for the binomially scaled distributed amplifier utilizing measured s-parameter data for the NEC 9000 transistor. (Note: Directivity = $|s_{41}|-|s_{31}|$).

obtained at the respective output ports on the drain line.

VII. CONCLUSION

A technique to increase the directivity of the conventional distributed amplifier has been introduced. Through effective binomial scaling of the individual device transconductances, directivities on the order of -25 to -35 dB have been exhibited using computer simulation and measured s-parameter data for the NEC 9000 transistor. The circuit is broadband with the potential for operation over an octave or more in frequency. Finally, it should be noted that the circuit is bidirectional in that it may be driven from both ends of the gate line simultaneously with high directivity exhibited at each respective port on the drain line.

REFERENCES

[1] W. S. Percival, "Thermionic Valve Circuits," British Patent 460562, Jan. 1937.

[2] O. P. Leisten, R. J. Collier and R. N. Bates, "Distributed Amplifiers as Duplexer/Low Crosstalk Bidirectional Elements in S-Band," Electronics Letters, vol. 24, no. 5, pp. 264-265, March 3, 1988.

[3] Joseph W. Byrne, "A Study of the Basic Concepts Involved in the Design of a Highly Directive, Broadband, Bidirectional Distributed Amplifier," MSEE Thesis, University of Wisconsin, 1989.