OPTIMAL DESIGN OF LOW CROSSTALK, WIDEBAND, BIDIRECTIONAL DISTRIBUTED AMPLIFIERS

S. N. Prasad* and Z. M. Li**

* Department of Electrical and Computer Engineering, Bradley University, Peoria, Illinois
**Megahertz Division, U.S. Robotics Corporation, Salt Lake City, Utah

ABSTRACT

An optimal approach to the design of low crosstalk, wideband, bidirectional, distributed amplifiers is proposed. The new technique based on Chebyshev scaling of device transconductances, gives considerably greater directivity bandwidth than the previously published approach using binomial scaling, for specified number of devices and minimum directivity. The theory and design guidelines, as well as simulated and measured results are presented.

I. INTRODUCTION

A distributed amplifier is inherently bidirectional because of symmetry in its architecture. The signal paths in a bidirectional distributed amplifier are shown in Fig. 1.

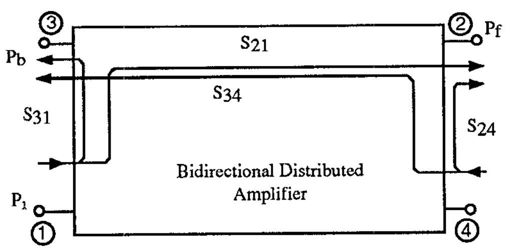

Fig. 1. Signal Paths in a Bidirectional Distributed Amplifier

The cross-talk between the isolated ports, represented by S_{31} and S_{24} is considerably low at discrete frequencies in the passband.

Therefore a distributed amplifier is well suited for application as a duplexer [1] in transceivers for wireless communications. The gain (G) and directivity (D) of a bidirectional distributed amplifier can be expressed as

$$G = 10\ell og \frac{P_f}{P_i} = 20\ell og|S_{21}| \tag{1}$$

$$D = 10\ell og \frac{P_f}{P_b} = 20\ell og\left|\frac{S_{21}}{S_{31}}\right| \tag{2}$$

A distributed amplifier circuit can be tuned to obtain a low S_{31} characteristic over a narrowband [1]. The bandwidth of S_{31} response can be increased by binomial scaling of device transconductances as shown by computer simulations in [2].

In this paper, a new design technique using Chebyshev scaling is proposed. It is shown that Chebyshev scaling of device transconductances gives considerably greater directivity bandwidth than binomial scaling. Further, this design approach is considered optimal because, in contrast to binomial scaling approach [2], for a given number of devices, and specified values of minimum directivity and gain, maximum bandwidth is obtained. Also, for specified minimum directivity and gain over a passband, minimum number of devices are required. The objective of this paper is to present the Chebyshev design approach and illustrate the design technique by means of an example, as well as present simulated and measured results.

II. OPTIMAL DESIGN

The schematic of a FET distributed amplifier is shown in Fig. 2.

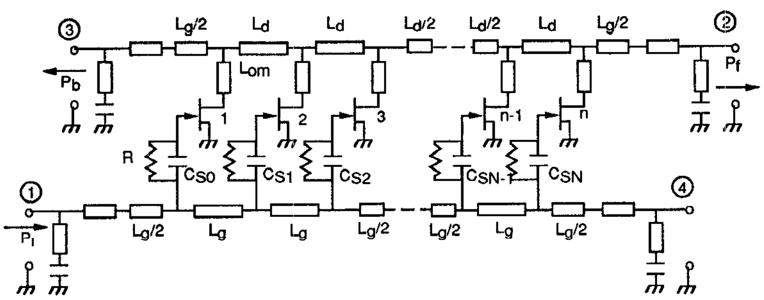

Fig. 2 Schematic of a Bidirectional Distributed Amplifier

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From multielement directional coupler theory [3], for this circuit, S_{21} is given by,

$$S_{21} = -\frac{1}{2} Z_\pi e^{-j\beta N} \left[\sum_{i=0}^{N} g_{mi} \right] \quad (3)$$

From (1) and (3) the gain of the amplifier is

$$G = 20 \ell og \left| -1/2 \ Z_\pi e^{-j\beta N} \left[\sum_{i=0}^{N} g_{mi} \right] \right| \quad (4)$$

Where, Z_π is the π-section image impedance of the drain line, β is the phase shift per π-section along the lines, g_{mi} is the transconductance of the i-th device, N = n-1 and n represents the number of devices in the amplifier.

S_{31} for the amplifier is given by,

$$S_{31} = -\frac{1}{2} Z_\pi \sum_{i=0}^{N} g_{mi} e^{-j\beta 2i} \quad (5)$$

From (2), (3) and (5) directivity of the amplifier is

$$D = 20 \ell og \frac{\left| -\frac{1}{2} Z_\pi e^{-j\beta N} \sum_{i=0}^{N} g_{mi} \right|}{\left| -\frac{1}{2} Z_\pi \sum_{i=0}^{N} g_{mi} e^{-j\beta 2i} \right|} \quad (6)$$

using (4) directivity can be expressed in the form

$$D = G - 20 \ell og \left| -\frac{1}{2} Z_\pi \right| - 20 \ell og \left| \sum_{i=0}^{N} g_{mi} e^{-j\beta 2i} \right| \quad (7)$$

If we are to achieve a wideband directivity design, we must make the array factor

$$F = \left| \sum_{i=0}^{N} g_{mi} e^{-j\beta 2i} \right|$$

to give a high directivity over the passband. In order to obtain an optimal design the array factor in (7) must be made proportional to a Chebyshev polynomial.

If we choose a symmetrical array, with $g_{m0} = g_{mN}$, $g_{m1} = g_{mN-1}$ etc., we obtain

$$F = \left| \sum_{i=0}^{M} 2 g_{mi} \cos(N-2i)\beta \right| = K \left| T_N(\sec\beta_m \cos\beta) \right| \quad (8)$$

where M = (N-1)/2 for N odd and N/2 for N even, β_m is the phase shift per section at the upper and lower edges of the passband, T_N ($\sec\beta_m \cos\beta$) is the Chebyshev polynomial of the N-th degree and K is a constant.

From (4) and (8) the expression for gain at the center of the band ($\beta = 0$) is

$$G = 20 \ell og \left[1/2 Z_\pi K \left| T_N(\sec\beta_m) \right| \right] \quad (9)$$

From (7), (8) and (9) directivity may be written as

$$D = 20 \ell og \frac{\left| T_N(\sec\beta_m) \right|}{\left| T_N(\sec\beta_m \cos\beta) \right|} \quad (10)$$

The minimum value of directivity, D_m occurs when $\left| T_N(\sec\beta_m \cos\beta) \right| = 1$. Therefore,

$$D_m = 20 \ell og \left| T_N(\sec\beta_m) \right| \quad (11)$$

From (11) it is evident that if D_m is specified, $\sec\beta_m$ is fixed, which in turn fixes the bandwidth and vice versa. Then (9) can be solved for K in terms of the specified value of gain. From (8) the device transconductances can be determined.

If the device transconductances in the array factor are made proportional to binomial coefficients, one achieves a binomial design [2]. In Fig. 3 the frequency responses of $|S_{21}|$ and $|S_{31}|$ for both binomial and Chebyshev designs are shown. It is evident that for the given number of devices (n = 5) and specified minimum directivity (D = 15 dB), Chebyshev design has considerably greater directivity ($|S_{21}|$ - $|S_{31}|$) bandwidth than the binomial design. Hence the Chebyshev design is considered optimal.

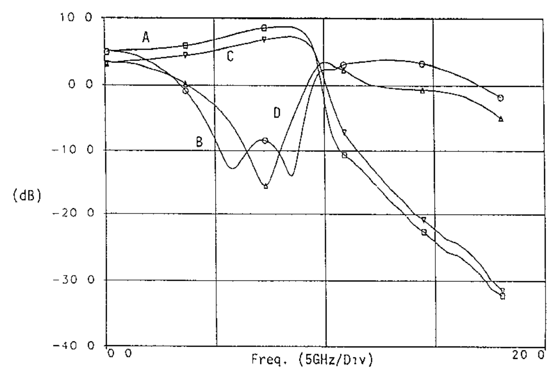

Fig.3. Plots of $|S_{21}|$ and $|S_{31}|$ for both Chebyshev and Binomial scaling
A: $|S_{21}|$ Chebyshev; B: $|S_{31}|$ Chebyshev
C: $|S_{21}|$ Binomial; D: $|S_{31}|$ Binomial

III. DESIGN PROCEDURES

The design procedures will be outlined in this section by means of an example. Consider the design of a distributed amplifier having G = 10 dB, D_m = 30 dB and five FETs (NE76084). Solving (11) for β_m, we get β_m = 51.23°. From (8) the following equations can be obtained [3].

$$2g_{m0} = K\sec^4\beta_m \quad (12)$$

$$2g_{m1} = K\left(4\sec^4\beta_m - 4\sec^2\beta_m\right) \quad (13)$$

$$g_{m2} = K\left(3\sec^4\beta_m - 4\sec^2\beta_m\right) \quad (14)$$

By fixing $g_{m2} = g_m$ (40 mS for NE76084), from (14) the value of K is found to be 4.3 x 10^{-3}. Using this value of K and Z_π = 50Ω in (9) we find G = 10.62 dB. The transconductances of the devices calculated [4] using (12) and (13) are: $g_{m0} = g_{m4}$ = 13.97 mS and $g_{m3} = g_{m1}$ = 33.97 mS. The g_m of the transistor can be scaled using gate-series capacitors [5], to obtain the effective transconductances calculated above. The series capacitors (C_{si}) at the gates are calculated using

$$C_{si} = \frac{g_{mi}C_{in}}{g_m - g_{mi}} \quad i = 0, 1, 2...N \quad (15)$$

where C_{in} is the gate-to-source capacitance of the FET. C_{in} and C_{out} (drain-to-source capacitance) can be determined from the measured S-parameters of the FET [4]. The series capacitor values in this design are: $C_{s0} = C_{s4}$ = 0.041 pF; $C_{s1} = C_{s3}$ = 0.426 pF and $C_{s2} = \infty$.

IV. CIRCUIT IMPLEMENTATION AND MEASURED RESULTS

The amplifier circuit designed in the preceding section was implemented in hybrid MIC form. The gate and drain lines (Z_π = 50Ω) were designed to be constant-k and m-derived lines respectively. The inductors L_g, L_d and L_{om} (Fig. 2) were realized as high impedance (Z_0 = 75Ω) microstriplines. Discrete capacitors were used for scaling the transconductances. Chip resistors (R = 10KΩ) were used for biasing the gates. The computer simulated responses of $|S_{21}|$ and $|S_{31}|$, using HP-EEsof test bench are shown in Fig. 4. In the range 3-5.5 GHz, $|S_{21}|$ is 10 dB and $|S_{31}|$ is less than -20 dB.

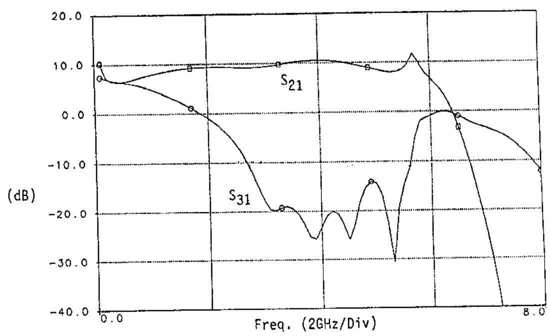

Fig.4. Plots of $|S_{21}|$ and $|S_{31}|$ for the Bidirectional Distributed Amplifier shown in Fig.5.

The amplifier circuit is shown in Fig. 5. The S-parameters were measured using the HP8722C Network Analyzer. The amplifier was biased through external Bias-Tees. The measured $|S_{21}|$ and $|S_{31}|$ frequency responses are shown in Fig. 6 and 7 respectively.

The measured $|S_{21}|$ is lower and $|S_{31}|$ is higher than predicted in the band 3-5.5 GHz. This discrepancy is attributed to non-exact values of gate-series capacitors used in building the circuit. $|S_{11}|$ and $|S_{22}|$ were less than -10 dB in the passband.

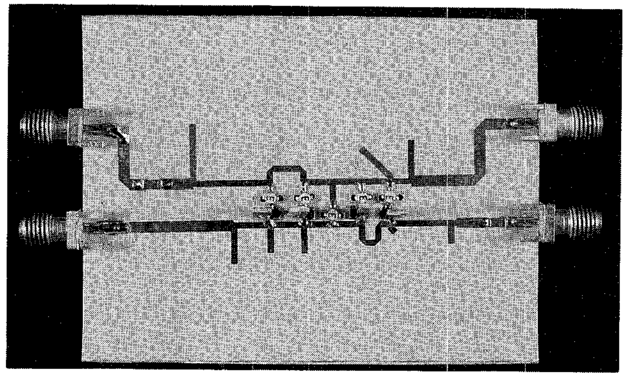

Fig.5. Bidirectional Distributed Amplifier Circuit; n = 5; Circuit borad: ε_r = 3.0; Thickness = 0.030"

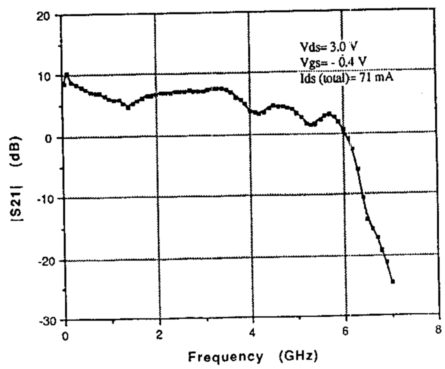

Fig.6. Measured $|S_{21}|$

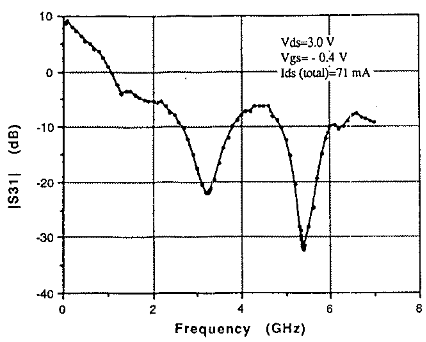

Fig.7. Measured $|S_{31}|$

V. CONCLUSIONS

A technique for optimal design of low crosstalk, wideband, bidirectional distributed amplifiers has been introduced. The design using Chebyshev polynomials to scale device transconductances has been shown to be optimal by computer simulations. The design procedures have been outlined by means of an example, and measured results have been presented.

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