NEW RESULTS ON THE DESIGN OF BROADBAND MICROWAVE BIPOLAR AND FET AMPLIFIERS*

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Abstract

New results on the design of broadband microwave transistor amplifiers are presented. These results include analytical design and computer-aided optimization techniques for microwave bipolar and FET amplifiers with prescribed transistor gain roll-off characteristics and practical realizations of broadband input and output matching networks. Several designs of octave-band microwave bipolar and GaAs FET amplifiers are presented to illustrate the general design techniques.

Introduction

The current state-of-the-art on the design of broadband microwave bipolar and FET amplifiers relies heavily on computer-aided optimization and experimental cut-and-try techniques which are often inadequate especially for high- and medium-power bipolar and GaAs FET amplifiers with bandwidths covering octave bands or above. There exists no definitive analytical design techniques which are applicable to really broadband amplifier design. Most of the design techniques using Smith charts are limited to single-frequency or narrow-band amplifiers. The difficulties involved in choosing the configurations of the matching networks and in providing broadband impedance matching consistent with the intrinsic reactive constraints and gain slopes are largely left to be solved by computer-aided optimization and/or experimental techniques which can only lead to suboptimal solutions. The basic analytical design problem has not been solved at present and the broadband amplifier designer must make a number of restrictive and gross approximations and ideal assumptions, such as no gain taper and matching at a single frequency, and rely completely on some computer-aided or experimental techniques to optimize the design. The configuration of the matching networks is usually restricted to low-pass ladder structures and the fundamental gain-bandwidth limitations are all but ignored.

This paper presents in summary form a new and recently derived analytical design technique which is applicable to the design of broadband amplifiers operating under either high-power Class-C or linear small-signal conditions. Several designs of octave-band microwave bipolar and GaAs FET amplifiers are presented to illustrate the general design technique.

Analytical Design Techniques

For the broadband matching of the high-power bipolar transistor amplifiers, the designer is faced with the dual problem of matching into extremely low input impedance and broadband matching the reactive components at both the input and the output. The basic design problem is shown in Fig. 1 in which the large-signal bipolar transistor is represented by equivalent circuits derived from large-signal measured impedances. In the derivation of our analytical design, the equivalent circuit element values are assumed to be constant and we assume that the large-signal model is unilateral. The first assumption is taken care of by the final computer-aided optimization step in which the actual transistor impedance variations with frequency are incorporated. The more basic assumption of an unilateral model is accounted for in our analytical design by using tapered-magnitude gain characteristics in the matching network design to compensate for the intrisic transistor gain roll-off with frequency. The basic broadband FET amplifier design problem is shown schematically in Fig. 2. The dual requirements of broadband impedance matching into the high impedance levels of the FET and reactive constraints associated with high Q's at both the input and the output pose opposite but equally difficult design problems. In the analytical design of small-signal linear transistor amplifiers, we impose the basic assumption that the transistor is unilateral, or $s_{12}=0$, and accounted for this approximately by using the appropriate gain slopes in our analytical design of the matching networks. In the final optimized design, the complete measures scattering parameters of the transistor are used.

The analytically derived broadband amplifier design technique is based on an exact synthesis of low- and band-pass matching networks with prescribed gain taper characteristics. The more important band-pass characteristics are illustrated in Fig. 3 and Fig. 4. These results can be considered as generalizations of the previous and significant contributions by Matthaei[1], Cristal[2], and Levy[3,4], on broadband impedance-transforming filters, and the more recent contributions by Pitzalis and Gilson on tapered-magnitude low-pass matching networks[5] and Class-C trasistor output matching network design[6].

Broadband Transistor Amplifiers[7]

To illustrate the analytical and the final computer-aided design techniques, four representative microwave transistor amplifiers have been designed and the results are presented in Fig. 5-8 and Tables 1-4. In Fig. 5 and Table 1(a) and 1(b), the results are for an octave-band (1-2GHz) high-power bipolar transistor amplifier using a CTC E10-28 10W L-band transistor. In the analytical design, the exact synthesis of the band-pass matching networks are based on a gain slope of 4.39dB/oct and impedance ratios of r_i=50 and r_o=22.2. Similar designs for MSC, RCA, TRW, and PHI high-power transistors have been made. Fig. 6 shows the design of a bipolar transistor amplifier for a HP 35831E transistor covering a 1GHz-2.5GHz band. The gain slope used is 6.22dB/oct. Fig. 7 and Fig. 8 present the final designs of two GaAs FET octave-band amplifiers using the Fairchild FMT-940 and the experimental HP B-045 MESFET chips.[7]

Acknowledgment

The authors wish to acknowledge the encouragement and support by Dr. W. W. Everett, Jr., of RADC and Mr. L. Bosin of FAA, and useful discussions with O. Pitzalis, Jr., and W. Gelnovatch, both of ECOM.

*Portion of this work was supported by the NSF Grant GK-31012X and jointly by Federal Aviation Administration (FAA) under the RADC Post-Doctoral Program, Contract F30602-72-0497.

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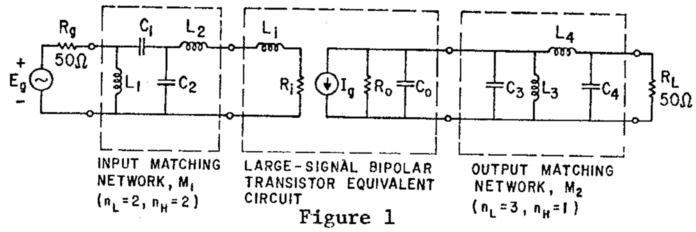


Figure 1

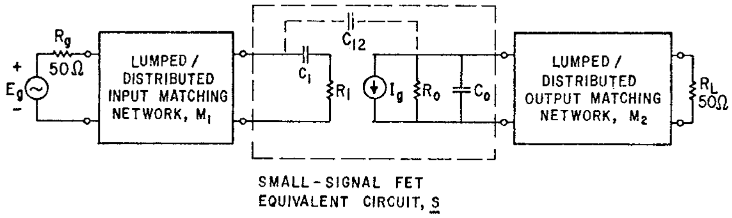
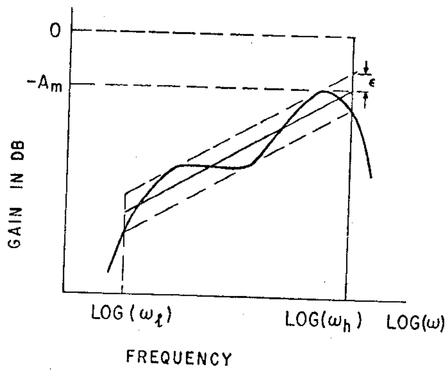


Figure 2



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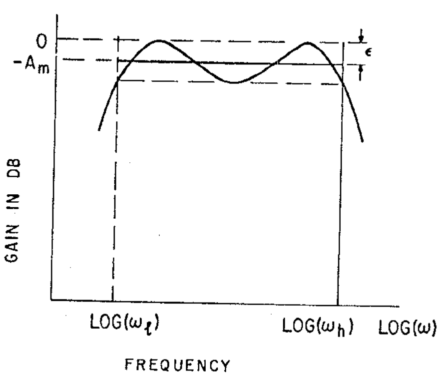

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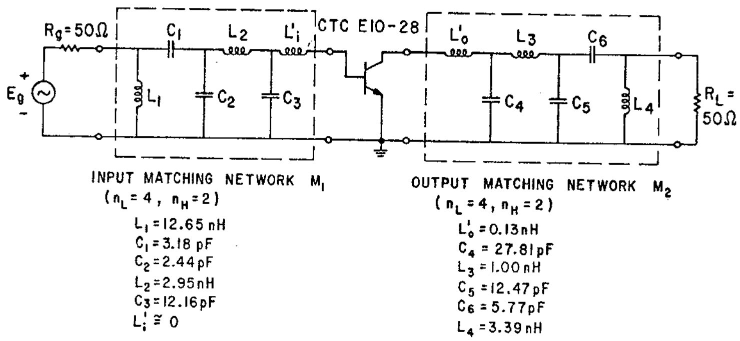

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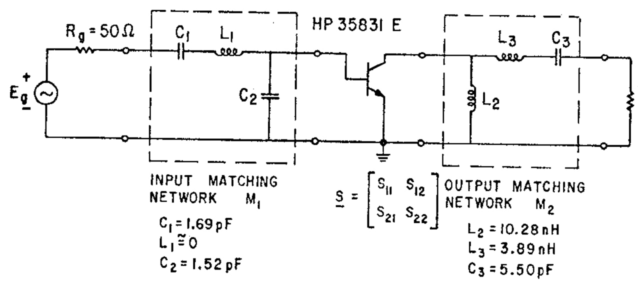

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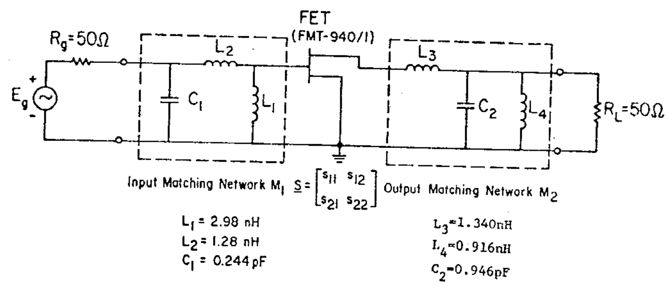

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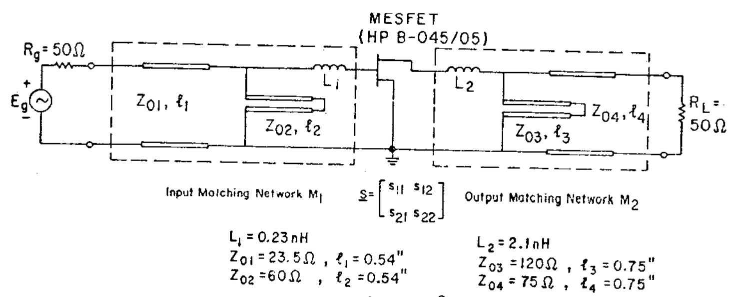

Figure 8

TABLE 1(a)

EQUIVALENT LARGE-SIGNAL IMPEDANCE OF A HIGH-POWER BIPOLAR TRANSISTOR(CTC E10-28)

F(GHz)	R_i (Ω)	L_i (nH)	R_o (Ω)	L_o (nH)
1.0	0.70	0.64	3.00	-0.207*
1.1	0.76	0.65	2.85	-0.130*
1.2	0.82	0.68	2.70	-0.053*
1.3	0.88	0.67	2.55	0.012
1.4	0.94	0.69	2.40	0.068
1.5	1.00	0.71	2.25	0.117
1.6	1.06	0.73	2.10	0.169
1.7	1.12	0.75	1.95	0.206
1.8	1.18	0.76	1.80	0.256
1.9	1.24	0.77	1.65	0.276
2.0	1.30	0.79	1.50	0.318

*Capacitive output modeled by a negative inductance.

TABLE 1(b)

OPTIMIZED GAIN RESPONSE OF AN OCTAVE-BAND HIGH-POWER BIPOLAR TRANSISTOR AMPLIFIER

F(GHz)	GAIN(dB)	INPUT VSWR	OUTPUT VSWR
1.0	4.84	10.74	1.92
1.1	5.38	8.49	1.43
1.2	5.17	7.05	1.87
1.3	4.98	6.29	1.93
1.4	5.07	5.58	1.65
1.5	5.14	4.99	1.35
1.6	5.04	4.39	1.46
1.7	4.87	3.69	1.82
1.8	4.91	2.99	1.95
1.9	5.24	2.48	1.50
2.0	4.42	2.91	1.79

TABLE 2(a)

SCATTERING PARAMETERS OF A MICROWAVE BIPOLAR TRANSISTOR(HP 35831E)

F(GHz)	$\|s_{11}\|$	$<s_{11}$	$\|s_{12}\|$	$<s_{12}$	$\|s_{21}\|$	$<s_{21}$	$\|s_{22}\|$	$<s_{22}$	K	MAG(dB)
1.00	0.670	160	0.06	62	3.20	72	0.35	-78	1.211	14.5
1.25	0.675	154	0.08	63	2.70	66	0.35	-81	1.082	13.5
1.50	0.680	147	0.10	63	2.20	60	0.35	-85	1.067	11.8
1.75	0.680	140	0.12	63	1.88	54	0.35	-89	1.062	10.4
2.00	0.680	134	0.13	63	1.57	48	0.35	-93	1.176	8.3
2.25	0.685	128	0.14	62	1.49	45	0.35	-98	1.162	7.8
2.50	0.690	122	0.15	61	1.26	41	0.36	-103	1.271	6.1

TABLE 2(b)

OPTIMIZED GAIN RESPONSE OF A BROADBAND BIPOLAR TRANSISTOR AMPLIFIER(1-2.5GHz)

F(GHz)	GAIN(dB)	INPUT VSWR	OUTPUT VSWR
1.00	5.88	19.39	1.65
1.25	6.19	12.33	1.95
1.50	5.96	8.40	2.20
1.75	6.02	5.75	2.43
2.00	5.75	3.81	2.32
2.25	6.39	2.60	2.13
2.50	5.74	1.56	1.61

TABLE 3(a)

SCATTERING PARAMETERS OF FAIRCHILD GaAs MICROWAVE FET(FMT-940/1)

F(GHz)	$\|s_{11}\|$	$<s_{11}$	$\|s_{12}\|$	$<s_{12}$	$\|s_{21}\|$	$<s_{21}$	$\|s_{22}\|$	$<s_{22}$	K	MAG(dB)
4	0.908	-70.3	0.018	44.5	0.906	95.7	0.897	-59.6	1.058	15.54
5	0.888	-88.8	0.017	54.6	0.928	86.3	0.894	-67.7	0.988	UNDEF
6	0.856	-100.8	0.021	61.4	0.944	63.3	0.880	-77.6	1.119	14.43
7	0.827	-111.5	0.022	51.9	0.865	46.1	0.878	-90.2	1.553	11.57
8	0.777	-129.9	0.028	48.5	0.938	30.0	0.864	-111.1	1.456	11.25

TABLE 3(b)

OPTIMIZED GAIN RESPONSE OF AN OCTAVE-BAND GaAs MICROWAVE FET AMPLIFIER(4-8GHz)

F(GHz)	GAIN(dB)	INPUT VSWR	OUTPUT VSWR
4	4.93	17.20	5.81
5	6.03	7.95	6.97
6	5.71	4.65	8.40
7	5.75	3.56	6.03
8	5.02	4.50	4.71

TABLE 4(a)

SCATTERING PARAMETERS OF A HEWLETT-PACKARD X-BAND GaAs MICROWAVE MESFET(HP B-045/05 CHIP)

F(GHz)	$\|s_{11}\|$	$<s_{11}$	$\|s_{12}\|$	$<s_{12}$	$\|s_{21}\|$	$<s_{21}$	$\|s_{22}\|$	$<s_{22}$	K	MAG(dB)
7	0.824	-89.1	0.035	37.1	1.67	100.2	0.836	-19.2	1.132	14.55
8	0.803	-96.7	0.037	33.0	1.54	92.3	0.832	-21.3	1.285	12.98
9	0.785	-103.4	0.038	29.4	1.43	84.9	0.830	-23.5	1.435	11.78
10	0.770	-109.2	0.039	26.3	1.32	78.0	0.828	-25.6	1.581	10.78
11	0.757	-114.3	0.040	23.6	1.23	71.5	0.828	-27.7	1.726	9.91
12	0.746	-118.8	0.041	21.3	1.15	65.3	0.828	-29.7	1.866	9.15
13	0.737	-122.9	0.041	19.2	1.08	59.4	0.829	-31.8	2.001	8.47
14	0.729	-126.5	0.041	17.3	1.01	53.8	0.831	-33.9	2.132	7.85

TABLE 4(b)

OPTIMIZED GAIN RESPONSE OF AN OCTAVE-BAND GaAs MICROWAVE FET AMPLIFIER(7-14GHz)

F(GHz)	GAIN(dB)	INPUT VSWR	OUTPUT VSWR
7	8.10	14.50	3.35
8	8.17	9.81	2.18
9	7.94	7.10	1.96
10	7.61	5.43	2.27
11	7.54	4.09	2.50
12	7.74	2.81	2.23
13	8.13	1.71	1.56
14	7.95	1.02	1.18

References

1. G. L. Matthaei,"Tables of Chebyshev Impedance-Transforming Networks of Low-Pass Filter Form," Proc.IEEE-Vol. 52, pp. 939-963, August 1964.
2. E. G. Cristal, "Tables of Maximally Flat Impedance-Transforming Networks of Low-Pass-Filter Form," IEEE Trans. MTT, Vol. MTT-13, pp. 693-695, September 1964.
3. R. Levy, "A New Class of Distributed Prototype Filters With Applications to Mixed Lumped/Distributed Component Design," IEEE Trans. MTT, Vol. MTT-18, pp. 1064-1071, December 1970.
4. R. Levy, "Synthesis of Mixed Lumped and Distributed Impedance-Transforming Filters," IEEE Trans. MTT, Vol. MTT-20, pp. 223-233, March 1972.
5. O. Pitzalis, Jr., and R. A. Gilson, IEEE Trans. MTT, Vol. MTT-19, pp. 381-386, April 1971.
6. Pitzalis and Gilson, IEEE Trans, MTT, Nevember 1973.
7. W. Ku, A. Podell, and W. Petersen, to be published.