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THE DESIGN OF LOW-NOISE BROAD-BAND MICROWAVE FET AMPLIFIERS*

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Abstract

A computer-aided design procedure applicable to low-noise and broad-band MMIC FET amplifiers is presented. The method takes into account the non-unilateral behavior of the FET, losses in the matching networks and complex termination mismatch.

Transducer Gain

A general formula for the transducer gain of an amplifier equalized with lossy matching networks when the source and load admittances are both complex as in Figure 1 can be derived as below: (See "Note" at end.)

$$G_T = \frac{(1-|\rho_g|^2)}{(1-|S_{I11}|^2)} \frac{|S_{I21}|^2}{(1-|S'_{I22'}|^2)} \frac{(1-|\rho_1|^2)}{(1-|S_{T11}|^2)} |S_{T21}|^2 \frac{(1-|\rho_2|^2)}{(1-|S'_{T22'}|^2)} \frac{|S_{021}|^2}{(1-|S_{011}|^2)} \frac{(1-|\rho_\ell|^2)}{(1-|S'_{022'}|^2} \qquad (1)$$

In (1) ρ_g, ρ_1, ρ_2, ρ_ℓ are complex normalized reflection factors measured at ports I_1, T_1, T_2, 0_2 of Fig. 1 as follows: ρ_g measured with NI terminated in unit resistance; ρ_1 measured with NI in place and FET terminated in unit resistance; ρ_2 with NI, FET in place, NO resistively terminated; ρ_ℓ measured with the entire system in place. The complex normalized ρ_k, typically ρ_2, is

$$\rho_2 = \frac{\dot{Y}'^*_{T2} - \dot{Y}_{01}}{\dot{Y}'_{T2} + \dot{Y}_{01}} \qquad (2)$$

where Y'_{T2} is the port 2 impedance (fig. 1) of FET with NI in place and $\dot{Y}_{01}$ is the port 1 impedance of NO when it is terminated in 1 ohm.

Equation (1) is a general formula for the transducer gain calculation of a solid-state amplifier. It can be simplified to calculate the transducer gain for various particular cases. For example with unit conductance source and load, and with lossless matching networks (1) becomes

$$G_T = (1-|\rho_1|^2) \frac{|S_{T21}|^2}{(1-|S_{T11}|^2)} \frac{(1-|\rho_2|^2)}{(1-|S'_{T22}|^2)} \qquad (3)$$

This is the same equation as in Carlin and Komiak,[1,2] and is a non-unilateral design formula. Further if $|S_{12}| \ll 1$, it can be neglected, and we get the unilateral design formula:

$$G_T = (1-|\rho_1|^2) \frac{|S_{T21}|^2}{(1-|S_{T11}|^2)} \frac{(1-|\rho_2|^2)}{(1-|S_{T22}|^2)} \qquad (4)$$

Noise Measure

The noise figure of a FET amplifier[4,5] can be expressed as:

$$F_N = F_{min} + 4R_F \frac{|S'_{I22} - S_F|^2}{|1+S_F|^2(1-|S'_{I22}|^2)} \qquad (5)$$

where F_{min} is the minimum noise figure of the FET,

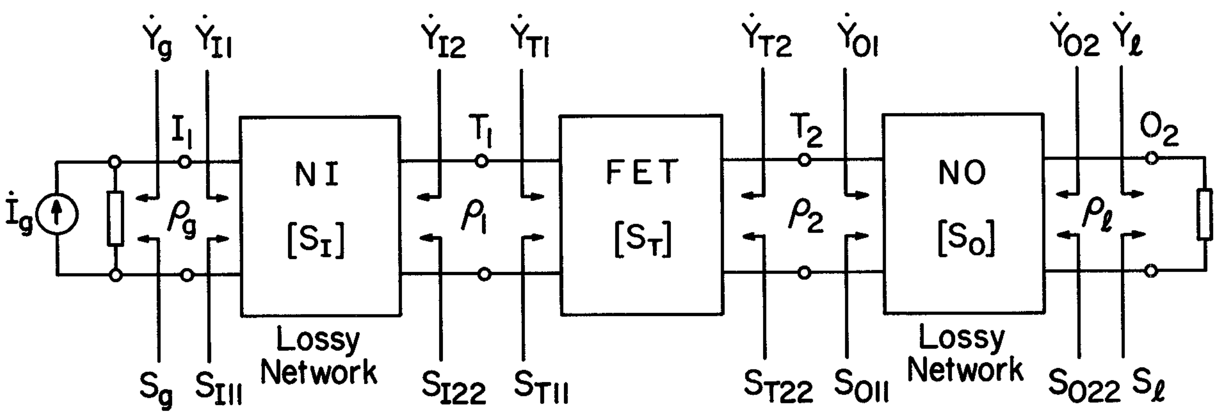


Fig. 1. FET Amplifier with lossy matching networks and complex terminal admittances

*Sponsored under Joint Services Contract F49620-81-C-0082 and NSF Grant ECS 8117875.

R_F is the unit normalized noise resistance of the FET

S_F is the unit normalized optimal noise reflection factor of the FET,

$$S_F = \frac{1 - \dot{Y}_F}{1 + \dot{Y}_F} \quad (6)$$

where $\dot{Y}_F$ is the unit normalized optimal noise admittance of the FET.

It is generally preferable for the design of a first stage low-noise amplifier to take the noise measure as a design criterion so as to include the effect of both noise figure and transducer gain. Thus we can use noise measure

$$M_N = \frac{F_N - 1}{1 - 1/G_T} \quad (7)$$

For a two stage amplifier, the total noise figure is

$$F_{Nt} = F_{N1} + \frac{F_{N2} - 1}{G_{T1}} \quad (8)$$

where F_{N1} and F_{N2} are the noise figures of the first and second stages, respectively; G_{T1} is the transducer gain of the first stage. The total noise figure F_{Nt} can be a minimum, when the first stage is designed for minimum noise measure.

Computer Aided Design Procedure

We have developed a computer aided design procedure for the non-unilateral design of MMIC FET amplifiers equalized with matching networks whose L, C elements have finite frequency dependent Q's to take into account substrate loss and skin effect. Complex admittances at both terminals can also be included. A different CAD procedure is given in [3].

The main program is a multivariable constrained search program. After one chooses a suitable topology for the matching network and the initial guess for the element values, this program can compute the transducer gain (1), the noise figure (5) and noise measure (7) of the amplifier, and taking the min-max noise measure or max-min transducer gain in the passband as the objective function, find the optimal values of the lossy elements (inductors or capacitors).

To arrive at an initial guess, we have found it useful to start with Eq. (4) and employ a modified real frequency technique similar to [1], [2]. The main procedure of this technique is: choose the inverse of a polynomial to represent the real part of the network impedance function, take straight line segments to then approximate the real part, use the Hilbert transform to calculate the imaginary part of the minimum susceptance network function from the straight line segments, connect a susceptance in parallel with the minimum susceptance to form a non-minimum susceptance function, and then use optimization techniques to find the optimal coefficients of the polynomial and the parallel susceptance and finally get the elements of the initialized matching network.

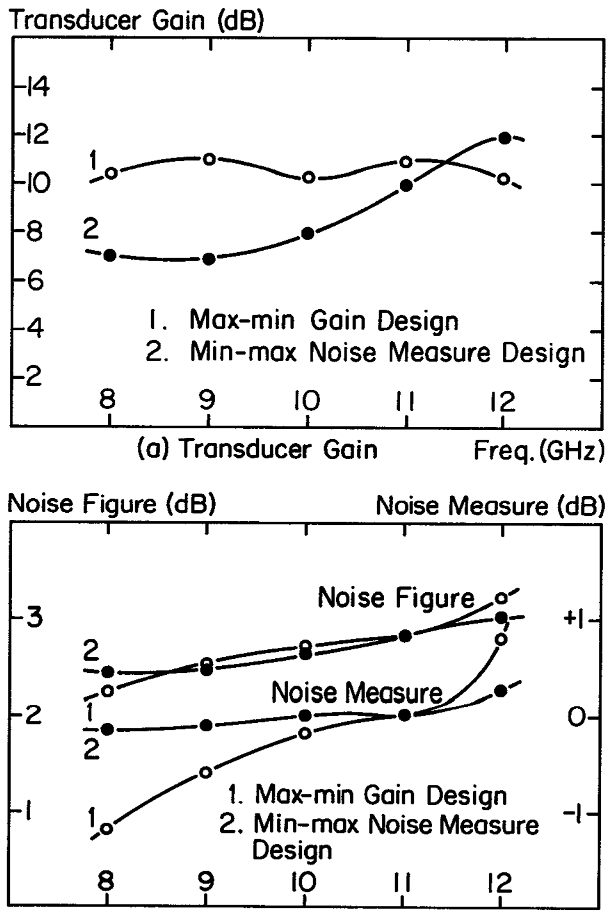
Examples

The design approach is applicable to optimizing a variety of objective functions. Thus it can be used for maximizing the minimum passband gain, or for minimizing maximum noise measure, or for high gain flat noise figure design.

Two design examples are given to illustrate the applications of the design technique.

An 8-12 GHz TRW 0.5 μ FET MMIC equalized amplifier was designed and resulted in a max-min optimized passband transducer gain of 10.56 ± 0.38 dB. Designed for noise measure the result is 0.16 ± 0.23 dB min-max noise measure. A second example is the 6-15 GHz NE388 FET MMIC amplifier. For this case the procedure yields a max-min pass-band transducer gain of 5.74 ± 0.41 dB or a min-max noise measure performance of 1.19 ± 0.25 dB. In both cases the amplifiers are designed using lossy lumped matching networks ($Q_L = 30$, $Q_C = 50$, at 12 GHz) and complex source and load admittances consisting of 0.05 pF. parasitic capacitance in parallel with 50 Ω terminal resistances. The FET device gain taper is also taken into account in the equalization. In the figures performance curves labeled (1) are for the case where max-min transducer gain is optimized. Curves labeled (2) are gain and noise response when min-max noise measure is optimized.

In working out these design problems the program is first initialized (as above described) by assuming resistive terminations, a unilateral FET, and lossless equalizers. The topology and element values of the initialized matching network are then obtained. The final design optimizes the initialized element values using the complete system equation (1) with finite element Q's. The equalizers are four or five element band-pass ladder structures.



(b) Noise Figure and Noise Measure Freq.(GHz)

Fig. 2. Transducer Gain, Noise Figure and Noise Measure of Amplifier #1 (TRW 0.5μ FET)

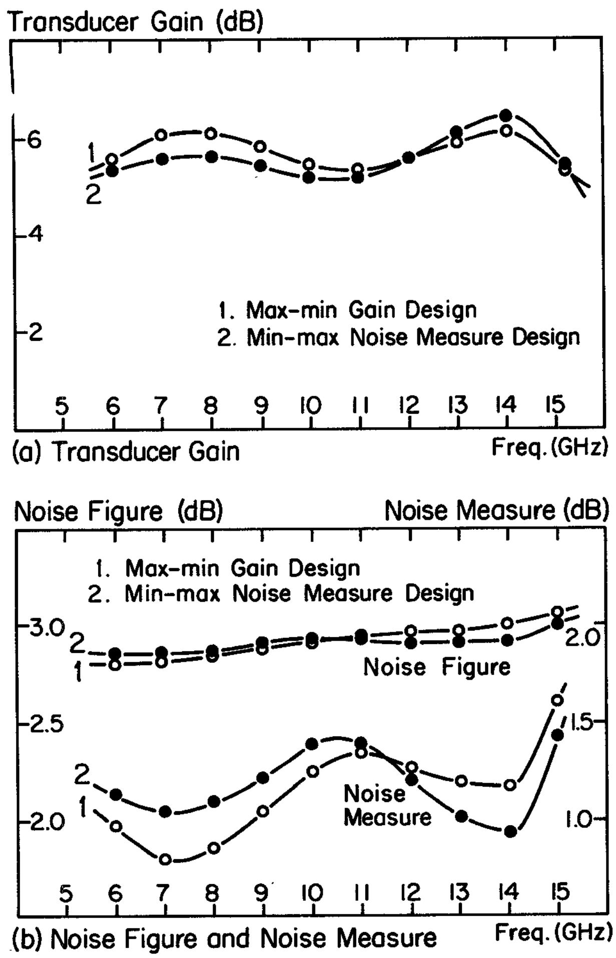


Fig. 3. Transducer Gain, Noise Figure and Noise Measure of Amplifier #2 (NE 38800 FET)

Note: In eq. (1), the unprimed quantities S_{Iij}, S_{Tij}, S_{0ij} refer to unit normalized scattering parameters of NI, FET, NO. The primed quantities are unit normalized reflection factors with the entire system in place.

Conclusion

The design procedure outlined here is extremely flexible and can be modified to optimize a variety of objective functions. Circuit models of the device are not required. In addition the method permits the determination of an excellent initialization of element values by simple methods so the final optimization is rapidly convergent. Furthermore, in view of reference [6], even if a simple amplifier device model were available to permit the use of analytic techniques with Chebyshev gain functions the CAD real frequency method described here would in general yield simpler equalizers with superior performance characteristics than the results obtained from optimized equal ripple gain functions.

Acknowledgement

Helpful discussions with Dr. Siddik Yarman are gratefully acknowledged.

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