

2W Wideband Microwave PA Design for 824-2170 MHz Band Using Normalized Gain Function Method

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Abstract

In this work, we present the design of a 2W linear wideband microwave PA (power amplifier) targeted to operate in 824-2170 MHz mobile frequency range covering GSM850, EGSM, DCS, PCS and WCDMA. The design is basically based on the NGF (Normalized Gain Function) method which is very recently introduced into the literature. NGF is defined as the ratio of T and $|S_{21}|^2$, i.e. $T_{NGF}=T/|S_{21}|^2$, shape of the gain function of the amplifier to be designed and the shape of the transistor forward gain function, respectively. Synthesis of input/output matching networks (IMN/OMN) of the amplifier requires target gain functions, which are mathematically generated in terms of T_{NGF} . The particular transistor used in the design is FP31QF, a 2W HFET from TriQuint Semiconductor. Theoretical PA performance obtained in Matlab is shown to be in a very high agreement with the simulated performance in MWO (Microwave Office) of AWR Inc.

1. Introduction

Increasing importance of highly functional mobile wireless equipment such as smart mobile phones in daily use requires wideband PA (Power Amplifier) designs based on substantial amplifier design methods. In this manner, a recently developed microwave amplifier design method so-called NGF (Normalized Gain Function) method [1] can be effectively utilized to design a wideband PA. To demonstrate the NGF's capability in wideband microwave PA design, a particular wideband PA design is addressed in this paper: a 2W wideband microwave PA operating in 824-2170 MHz mobile frequency range. Such a wide frequency range can accommodate many mobile communication standards such as GSM850, EGSM, DCS, PCS and WCDMA by using only one single PA at the output stage of the transmitter. Therefore, the use of a this type wideband amplifier decreases the problems such as system complexities, high costs, heavy equipment structure, large circuitry areas, high DC power consumption caused by many separate narrow-band PAs and their accompanying matching elements [1,2]. On the other hand, this PA must be accompanied with a highly digital control unit (DCU, such as an ASIC), in a SDR (Software Defined Radio) sense, that is to generate all the signals to be broadcasted in a very precise manner from the amplitude, phase and frequency band requirements point of view.

Analytic solution of the amplifier equations composed of many unknown variables related to element values of the input and output matching networks (IMN/OMN) is impossible beyond simple cases that may include several elements only. Therefore, it is unavoidable to choose a numerical technique that is highly successful, yielding always convergent and realizable solution and numerically stable. Real Frequency Techniques (RFTs) are very well-known and widely used numerical solvers in the literature [3-5]. Reflectance based version called as "Simplified Real Frequency Technique (SRFT)" [6-10], is one of the most successful RFT technique and preferred as the fundamental numerical design technique in this work.

NGF takes its name from the amplifier gain function T divided by the forward scattering parameter of the transistor $|S_{21}|^2$, a kind of normalization or division operation applied to the amplifier gain function T by the normalization factor $|S_{21}|^2$. We may also use a term NGF-SRFT (NGF assisted SRFT technique) suitably which combines NGF method with SRFT based design technique [1].

A wideband Flat Gain Amplifier (FGA) with a flat gain level $T_0=16\text{dB}$ (see Fig 1.b) along $(f_L-f_H)=(824-2170)$ MHz frequency band is designed using the developed Matlab [11] code. The linear small signal normalized scattering parameters of FP31QF of TriQuint Semiconductor [12], a 2W wideband 50-4000 MHz HFET (Heterostructure FET) in a 6X6 mm 28-pin QFN smd package, is used in the design and the theoretical results are found in 100% agreement with the simulations done in the Microwave Office (MWO) of AWR Corporation [13].

In the following sections; first, amplifier design equations are introduced in Section 2. In Section 3, Normalized Gain Function method is shortly reviewed, although one may be referred to [1] for more detailed information on step-by-step procedure of NGF based amplifier design. Finally, section 4 deals with an example design of an wideband amplifier based on NGF and its performance evaluations.

2. Amplifier Design Equations

For the wideband microwave amplifier seen in Fig. 1.a which is composed of Input Matching Network (IMN), Output Matching Network (OMN), transistor Q, resistive terminations R_G and R_L at the generator (source) and load sides respectively, Transducer Power Gain (TPG or shortly T) is given as [1],

$$T = T_G T_Q T_L \quad (1)$$

where the partial gains are expressed in terms of IMN input reflectance Γ_G , reflectances Γ_{IN} , Γ_{OUT} seen from the input and output of the transistor and OMN input reflectance Γ_L such that [1],

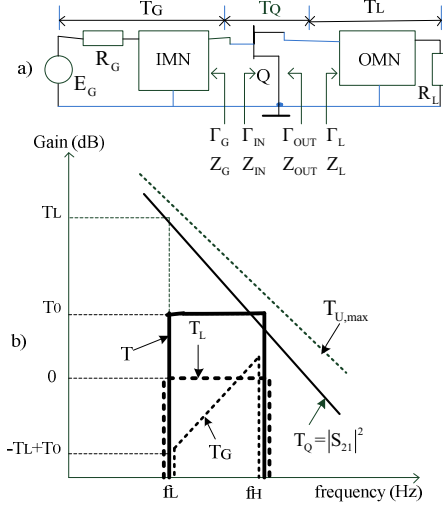


Fig. 1. a) An ultra wideband microwave amplifier composed of IMN, OMN, a single transistor Q, source and load side resistive terminations R_G and R_L . b) Gain curve shape for the amplifier operating in the (f_L-f_H) frequency band: T_G , $T_Q=|S_{21}|^2$, T_L , T , T_{Umax} (Maximum Unilateral Power Gain, i.e.).

$$T_G = \frac{1-|\Gamma_G|^2}{|1-\Gamma_{IN}\Gamma_G|^2}, T_Q = |S_{21}|^2, T_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \quad (2)$$

The reflectances seen from the input and output of the transistor can be written in terms of unit normalized scattering parameters (shortly S-parameters) given for the transistor, input reflectances Γ_G and Γ_L of IMN and OMN matching circuits as [1],

$$\Gamma_{IN} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}, \Gamma_{OUT} = S_{22} + \frac{S_{12}S_{21}\Gamma_G}{1-S_{11}\Gamma_G} \quad (3)$$

Γ_G and Γ_L are both frequency dependent complex quantities that are expressed as rational functions defined by the ratio of two polynomials such that

$$\Gamma_G = \frac{h_G(p)}{g_G(p)}, \Gamma_L = \frac{h_L(p)}{g_L(p)} \quad (4)$$

where $p = j\omega$ is Laplace variable in terms of real frequency ω . Denominator polynomials for both reflectances must be “Strictly Hurwitz” polynomials whose all roots reside in the open LHP (Left Half Plane) and both numerator polynomials are arbitrary polynomials with real coefficients. Numerator and denominator polynomials of both matching networks are expressed in the following forms

$$\begin{aligned} h_M(p) &= h_{1,M}p^n + h_{2,M}p^{n-1} + \dots + h_{n,M}p + h_{n+1,M} \\ g_M(p) &= g_{1,M}p^n + g_{2,M}p^{n-1} + \dots + g_{n,M}p + g_{n+1,M} \end{aligned} \quad (5)$$

for $M = \{G \text{ or } L\}$

where M denotes generator (G) or load (L) side matching networks, i.e. IMN or OMN, respectively. n is the total number of L and C (inductors and capacitors) lumped elements in each matching network which has $(n+1)$ number of total elements including one resistive termination [1]. Once either reflectance function is obtained in the form of (4), its corresponding Darlington driving point input impedance function is obtained as

$$\begin{aligned} z_M(p) &= \frac{1+\Gamma_M(p)}{1-\Gamma_M(p)} = \frac{g_M(p)+h_M(p)}{g_M(p)-h_M(p)} = \frac{a_M(p)}{b_M(p)} \\ &= \frac{a_{1,M}p^n + a_{2,M}p^{n-1} + \dots + a_{n,M}p + a_{n+1,M}}{b_{1,M}p^n + b_{2,M}p^{n-1} + \dots + b_{n,M}p + b_{n+1,M}}, \text{ for } M = \{G \text{ or } L\} \end{aligned} \quad (6)$$

which must be a rational PRF (Positive Real Function) from the realizability point of view [1].

The sole meaning of amplifier design is basically to determine the topology and circuit parameter values of IMN and OMN matching circuits, that is to realize them using LC lossless components either in lumped, distributed or mixed fashion so that the resulting overall amplifier gain function T satisfy the prescribed gain curve shape such as seen in Fig. 1.b. Any PRF, thus “realizable”, input impedance function $z(p)$ in the form of (6) can be synthesized in such a way that it always yields an LC network with resistive termination, which completes the design. This is known as “Darlington Synthesis” and it could be achieved via a procedure known as *Long-Division* or *Continued Fractional Expansion* using the following form [1]

$$z(p) = z_1 + \frac{1}{y_2 + \frac{1}{z_3 + \frac{1}{y_4 + \frac{1}{\dots + \frac{1}{z_n \text{ (or } y_n)} + \xi_{n+1}}}}} \quad (7)$$

where z_i and y_i designate the series arm impedances and the shunt arm admittances in a reciprocal lossless two-port ladder topology, respectively. ξ is the constant resistive termination (resistance or conductance) of the lossless two-port which can be omitted with a transformer loaded by unit resistance and

$$\{z_i \text{ and } y_i\} = \begin{cases} a_i p \\ \frac{1}{b_i p} \\ \frac{c_i p}{c_i d_i p^2 + 1} \end{cases} \quad (8)$$

where coefficients a_i , b_i and “c;-d; pair” could be realized by inductor in series branch (capacitor in shunt branch), capacitor in series branch (inductor in shunt branch), “capacitor-shunt-

inductor in series branch (capacitor-series-inductor in shunt branch)" if we deal with impedance z_i (or admittance y_i) function. The term related "c_i-d_i pair" represents a resonant circuit composed of serial or parallel connected L and C components [1].

3. Summary of the NGF Method

Since the amplifier gain function $T_{data}(\omega)$ in (1) and the transistor forward gain function $|S_{21}(\omega)|^2$ have known shapes along the design or operating frequency band ($f_b \dots f_c$), their ratio is a function whose shape is known as well. We define this ratio as "Normalized Gain Function (NGF)" [1] and write it as

$$T_{NGF-data}(\omega) = \frac{T_{data}(\omega)}{|S_{21}(\omega)|^2} = T_{G-data}(\omega)T_{L-data}(\omega) \quad (9.a)$$

For a flat gain amplifier whose gain $T_{data}(\omega) = T_0$ as seen in Fig. 1.b, (9.a) becomes

$$T_{NGF-data}(\omega) = \frac{T_0}{|S_{21}(\omega)|^2}, \quad \omega_b \leq \omega \leq \omega_c \quad (9.b)$$

which has a "tapered" gain shape due to reciprocal of $|S_{21}(\omega)|^2$ function [1]. A good candidate for OMN target gain function can be a bandpass gain function modeled by Chebyshev or Butterworth template function denoted by $T_{Ch}(\omega)$ or $T_{Bw}(\omega)$ of degree $2n$ and ripple factor \mathcal{E} with a maximum gain amplitude of unity within $\omega_b \leq \omega \leq \omega_c$ band which is known as LRA (Least Reflection Approach in the Output) [1]. Therefore, using bandpass Chebyshev or Butterworth template function, the shapes of both IMN and OMN target gain functions are mathematically generated using NGF given in (9) as,

$$T_{L-data-temp}(\omega) = T_{temp}(\omega), \quad \omega_b \leq \omega \leq \omega_c \quad (10)$$

$$T_{G-data-temp}(\omega) = T_{NGF-data}(\omega) \times T_{temp}(\omega) = \left(\frac{T_0}{|S_{21}(\omega)|^2} \right) \times T_{temp}(\omega), \quad \omega_b \leq \omega \leq \omega_c \quad (11)$$

where T_{temp} denotes designer's choice of bandpass Chebyshev or Butterworth template function as follows

$$T_{temp}(\omega) = \begin{cases} T_{Ch}(\omega) \\ T_{Bw}(\omega) \end{cases} \quad (12.i)$$

$$\max\{T_{temp}(\omega)\} = 1, \quad \omega_b \leq \omega \leq \omega_c$$

Bandpass Chebyshev or Butterworth template function $T_{temp}(\omega)$ is generated using bandpass to lowpass transformation

$p \leftarrow (p^2 + \omega_0^2) / Bp = j(\omega^2 - \omega_0^2) / B\omega$ into the lowpass prototype function $T_L(p)$ as

$$T_L(p) = \begin{cases} T_{ChL}(p) = \frac{1}{1 + \mathcal{E}^2 T_m^2(x)} \Big|_{x=p/j} \\ T_{BwL}(p) = \frac{1}{1 + x^{2m}} \Big|_{x=p/j} \end{cases} \quad (12.ii)$$

$$T_{temp}(\omega) = T_L(p) \Big|_{p \leftarrow j \frac{\omega^2 - \omega_0^2}{\omega B}}$$

where $T_L(p)$ is chosen by the designer as either a Chebyshev lowpass prototype function $T_{ChL}(p)$ built by m th order Chebyshev polynomials and ripple factor epsilon or a m th order Butterworth lowpass prototype function $T_{BwL}(p)$. The target gain functions in (10) and (11) are used in OMN and IMN optimization functions in a two sequential execution in a least square sense error minimization as given in the error (or distance) functions computed by

$$d_{OMN}(i) = T_L(p_i) - T_{L-data}(\omega_i), \quad "i = 1, 2, \dots, nd" \quad (13)$$

$$d_{IMN}(i) = T_G(p_i) - T_{G-data}(\omega_i), \quad "i = 1, 2, \dots, nd" \quad (14)$$

where $T_L(p)$ and $T_G(p)$ are partial gain functions given with the forms

$$T_L(p) = \frac{1 - |\Gamma_L(p)|^2}{|1 - S_{22}(\omega)\Gamma_L(p)|^2} \quad (15)$$

$$T_G(p) = \frac{1 - |\Gamma_G(p)|^2}{|1 - \Gamma_{IN}(\omega)\Gamma_G(p)|^2} \quad (16)$$

At the end of a successful optimization, $z_L(p) = a_L(p)/b_L(p)$ is computed from the optimized $\Gamma_L(p) = h_L(p)/g_L(p)$ and synthesized in the form of (7) to get the topology and the element values of the OMN network, which completes the OMN phase of the design [1]. A similar procedure applies also to the IMN optimization sequences, i.e., at the end of a successful optimization, $z_G(p) = a_G(p)/b_G(p)$ is synthesized in the form of (7) to get the topology and the element values of the IMN network, which completes the IMN phase of the design [1].

4. 2W Wideband Microwave PA Design and Its Performance Evaluations

A flat gain amplifier (FGA) is to be designed with the following specifications: Flat gain level $T_{data}(\omega) = T_0 = 16$ dB lower corner frequency $f_L = 824$ MHz, upper corner frequency $f_H = 2170$ MHz, Chebyshev template function $T_{temp}(\omega) = T_{Ch}(\omega)$, passband ripple factor $\mathcal{E} = 0.0962$, total number of L and C elements $n = 8$ (excluding termination resistance) for IMN and OMN, $ndc = n/2 = 4$ transmission zeros at

DC, lower and upper optimization frequency bounds $f_b=0.1$ GHz and $f_c=6$ GHz, active device FP31QF of TriQuint Semiconductor, a 2W wideband 50-4000 MHz HFET (Heterostructure FET) in a 6X6 mm 28-pin QFN smd package.

Solution: Using the developed Matlab code “Main_NGF.m”, starting with initial polynomials $h_L, f_L, h_G, f_G, OptOMN.m$ and $OptIMN.m$ optimization codes yields the following optimized results:

$$h_L(p) = 3.2104p^8 - 1.8926p^7 + 2.4162p^6 - 2.6523p^5 + 1.4342p^4 - 0.4985p^3 + 0.6019p^2 + 0.0054p + 0.0630$$

$$f_L(p) = 1.0540p^4$$

$$g_L(p) = 3.2104p^8 + 8.4585p^7 + 13.0013p^6 + 13.2809p^5 + 9.4454p^4 + 4.6034p^3 + 1.6395p^2 + 0.3617p + 0.0630$$

$$h_G(p) = 14.3146p^8 - 27.4051p^7 - 28.8165p^6 - 94.8209p^5 - 48.6720p^4 - 36.7765p^3 - 1.2433p^2 - 1.9351p + 0.8649$$

$$f_G(p) = 28.8730p^4$$

$$g_G(p) = 14.3146p^8 + 75.0711p^7 + 141.8004p^6 + 203.3106p^5 + 162.6985p^4 + 92.6018p^3 + 30.0384p^2 + 7.6064p + 0.8649$$

then, numerator and denominator polynomials of Darlington input impedance functions $z_L(p)=a_L(p)/b_L(p)$ and $z_G(p)=a_G(p)/b_G(p)$ for the corresponding OMN and IMN networks are

$$a_L(p) = 6.4208p^8 + 6.5659p^7 + 15.4174p^6 + 10.6285p^5 + 10.8796p^4 + 4.1050p^3 + 2.2414p^2 + 0.3671p + 0.1261$$

$$b_L(p) = 10.3512p^7 + 10.5851p^6 + 15.9332p^5 + 8.0112p^4 + 5.1019p^3 + 1.0376p^2 + 0.3564p$$

$$a_G(p) = 28.6292p^8 + 47.6660p^7 + 112.9839p^6 + 108.4897p^5 + 114.0265p^4 + 55.8253p^3 + 28.7951p^2 + 5.6713p + 1.7299$$

$$b_G(p) = 102.4762p^7 + 170.6170p^6 + 298.1315p^5 + 211.3705p^4 + 129.3782p^3 + 31.2817p^2 + 9.5415p$$

And finally, optimized partial gain functions in p-domain for OMN and IMN networks are

$$T_L(p) = \frac{F_L(p)}{G_L(p)} = \frac{F_{L,0}p^{2nk}}{G_{L,1}p^{2n} + G_{L,2}p^{2(n-1)} + \dots + G_{L,n}p^2 + G_{L,2n+1}} = \frac{1.111p^8}{G_L(p)}$$

$$G_L(p) = 10.3066p^{16} + 11.9315p^{14} + 5.0066p^{12} + 1.8734p^{10} + 3.8574p^8 + 1.8112p^6 + 0.5485p^4 + 0.0759p^2 + 0.0040$$

$$T_G(p) = \frac{F_G(p)}{G_G(p)} = \frac{F_{G,0}p^{2nk}}{G_{G,1}p^{2n} + G_{G,2}p^{2(n-1)} + \dots + G_{G,n}p^2 + G_{G,2n+1}} = \frac{8.3365p^8}{G_G(p)}$$

$$G_G(p) = 20.49p^{16} - 157.60p^{14} - 576.02p^{12} - 823.72p^{10} - 378.14p^8 - 164.83p^6 - 225p^4 - 0.59p^2 + 0.07$$

which constructs the overall amplifier gain function as $T(\omega) = T_G(\omega)|S_{21}(\omega)|^2 T_L(\omega)$ by substituting $p = j\omega$. Typical gain functions of the designed FGA amplifier via Matlab code and via MWO simulation, the amplifier schematic and the element values are given in Fig. 2.a, Fig. 2.b, Fig. 3, and Tab. 1, respectively.

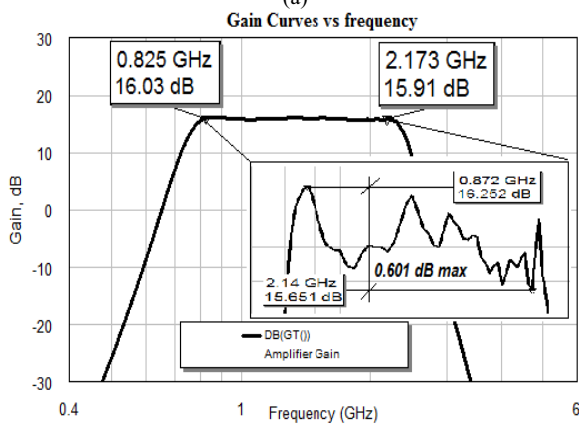
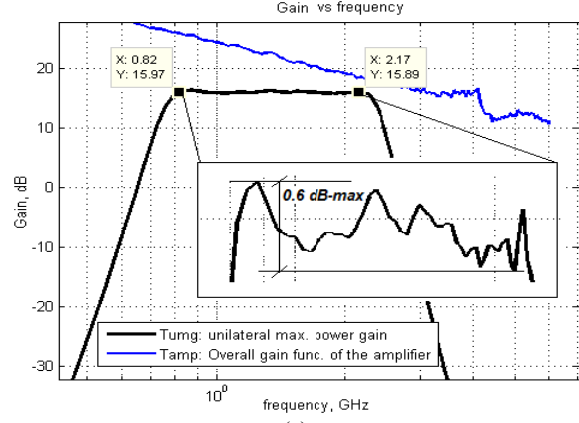


Fig. 2. a) Matlab design: gain performance of the designed FGA. b) MWO: Simulated gain performance of the designed FGA.

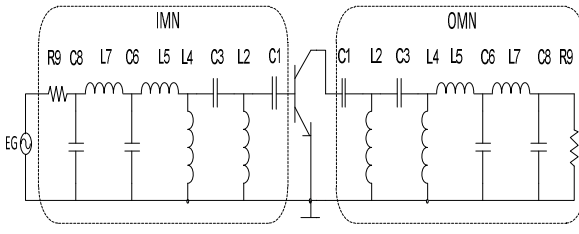


Fig. 3. Matlab design: schematic of the designed FGA amplifier.

Table 1. Matlab design: element values of the designed amplifier by Matlab

Element Values: pF, nH, Ohm	Matching Network		Element Values: pF, nH, Ohm	Matching Network	
	IMN	OMN		IMN	OMN
C1	8.091	4.146	L5	3.585	10.249
L2	2.052	4.491	C6	2.488	1.406
C3	6.098	2.759	L7	3.648	15.170
L4	4.766	8.378	C8	0.883	0.453
			R9	49.900	158.26

5. Conclusions

In this work, Normalized Gain Function (NGF) method, which has been very recently introduced into the literature [1], is used in the design of a wideband (824-2170 MHz) 2W microwave PA. The theoretical results generated by the Matlab code are found in %100 agreement with the results obtained from the simulations done in MWO environment. The practical implementation of this (824-2170) MHz wideband amplifier based on NGF methodology is currently under investigation.

7. References

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