An Eclectic Approach To Design Tunable Amplifiers

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Abstract—**Coverage of commercial communication standards such as GSM, UMTS, Wi-Fi and Wi-Max within a single transceiver chip is one of the most desired properties by wireless communication manufacturers. In this regard, communication companies are keenly interested in the design of high power amplifiers for broadband cellular communications to achieve this coverage. In this work, design of broadband tunable matching networks is investigated using Real Frequency Techniques. In practical applications, tunability is needed to compensate for the load impedance variations with environmental effects. In order to be able to work on sample structures, impedance transforming filters with proper topology are chosen and a broadband tunable matching network with a tunability strategy is developed. Eventually a broadband amplifier has been designed using the tunable inductor concept.**

Keywords- broadband matching networks; simplified real frequency technique (SRFT); impedance transforming filter; frequency dependent tunable inductors (FDTI); broadband amplifier; tunable matching network

I. INTRODUCTION

In recent years, Software Defined Radio (SDR) [1, 2] concept has attracted considerable interest from industry, military, and scientific community. The objective of SDR technology is to realize reconfigurable radios that may be used for various communication systems without the need of modifying or replacing any hardware components. Therefore, this concept is very important to facilitate the design of low cost and compact commercial mobile equipment. The design of programmable and tunable radio frequency (RF) front-end components carries extreme importance for the realization of a high frequency SDR terminal.

A SDR-based wireless communication device is prospected to have the coverage of standards like, GSM, DCS1800, PCS1900, UMTS, Bluetooth and WLAN. The operation frequency range of the standards above ($0.8 - 5.2\ GHz$) is extremely broad and coverage of this range of frequency cannot be achieved by traditional power efficient amplifiers [3-6]. Therefore, conventional multimode mobile equipment uses up to 6 amplifiers connected in parallel to accommodate these standards. Such amplifier architectures increase cost, size and weight of the mobile equipment. The objective of this work is to design matching networks that may facilitate to accommodate the standards mentioned above by using a single amplifier.

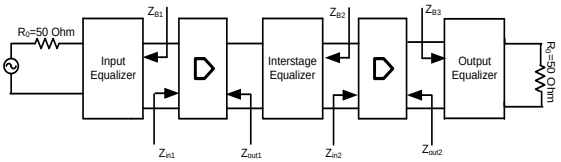


Fig. 1. Power stage of a cellular communication transmitter base station

In this work, first we have investigated the impedance transforming problem employing the filter prototype circuits over $800\ MHz$ to $5.2\ GHz$. In the course of amplifier designs, 'Simplified Real Frequency Technique (SRFT)' [7,8] is employed. As far as design of amplifiers are concerned, it may be appropriate to suppress the third harmonic of the upper edge frequency band within the matching network and subsequently, by choosing a proper matching network topology, tuning ability of the selected circuit is investigated to compensate the parasitic effects on the gain performance.

Secondly, we derived the "almost-equivalence" between the inductive impedance $Z(j\omega) = j\omega L = jX(\omega)$ and impedance $Z_x(j\omega) = jX_x(\omega)$ which is specified as a parallel resonance circuit $C_x \,//\, L_x$ in series configuration. In this context, we assumed that L is an idealized tunable inductor which is approximated by means of a tunable capacitor C_x in parallel with a fixed inductor L_x . This configuration acts like a frequency dependent tunable inductor $L_t(\omega)$ over a normalized angular frequency band of $0 \leq \omega \leq \omega_0 = 1$. In this paper, behaviour of $L_t(\omega)$ was also investigated as a function of normalized angular frequency ω, L_x and C_x.

Lastly, after the filter design and tuning strategy procedure was constructed, a broadband amplifier was designed with tunable broadband input and output matching networks.

II. TUNABLE INDUCTORS AND IMPLEMENTATION

As far as VLSI implementation of the proposed circuit is concerned, capacitors can be implemented using varactor diodes. For the case study under consideration, we can use Metal Oxide Semiconductor (MOS) varactor diode forms provided by Taiwan Semiconductor Manufacturing Company (TSMC). Furthermore, we propose the tunable inductor configuration to be placed on the VLSI layout as described below.

Referring to Fig. 2, reactance X(ω) of an inductor L is expressed as,

$$X(\omega) = \omega L \tag{1}$$

On the other hand, admittance of a parallel resonance circuit $C_x \,//\, L_x$ is given by,

$$\begin{aligned} Y_x(j\omega) = jB_x(\omega) &= j\left[\omega C_x - \frac{1}{\omega L_x}\right] \\ &= j\left[\frac{\omega^2 L_x C_x - 1}{\omega L_x}\right] \end{aligned} \tag{2}$$

where elestance $B_x(\omega)$ is,

$$B_x(\omega) = \frac{\omega^2 L_x C_x - 1}{\omega L_x} = \frac{\left(\frac{\omega}{\omega_r}\right)^2 - 1}{\omega L_x}$$

and angular resonance frequency ω_r is given by,

$$\omega_r^2 = \frac{1}{L_x C_x} \tag{3}$$

Using (2) and (3),

$$Z_x(j\omega) = jX_x(\omega) = \frac{1}{Y_x(j\omega)} = -j\frac{1}{B_x} \tag{4}$$

or

$$X_x(\omega) = -\frac{1}{B_x} = \omega \frac{L_x}{1 - \left(\frac{\omega}{\omega_r}\right)^2} = \omega L_t(\omega)$$

In (4) frequency dependent-tunable inductor (FDTI), L_t is specified by,

$$L_t(\omega) = \frac{L_x}{1 - \left(\frac{\omega}{\omega_r}\right)^2} \tag{5}$$

In (5), inductor L_x is fixed. However, resonance frequency ω_r is varied as the value of the tunable capacitor changes. Thus, effective value of the tunable inductor $L_t(\omega)$ is changed as we change C_x or equivalently as we change resonance frequency ω_r.

Now, let us design a tunable inductor L_t. At $\omega = \omega_0$ we demand $X(\omega_0) = X_x(\omega_0)$. Then,

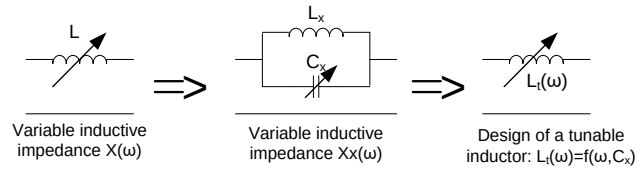


Fig. 2. A tunable inductor in series configuration.

$$\omega_0 L = \omega_0 \frac{L_x}{1 - \left(\frac{\omega_0}{\omega_r}\right)^2} \tag{6}$$

Hence, for a given inductor L, angular frequency ω_0 and resonance frequency ω_r, L_x is determined as,

$$L_x = \left[1 - \left(\frac{\omega_0}{\omega_r}\right)^2\right] L > 0 \quad such\ that\ \ \omega_r > \omega_0 \tag{7}$$

Hence, using (3), C_x is determined as,

$$C_x = \frac{1}{\omega_r^2 L_x} \tag{8}$$

In the above formulation, we prefer to select the normalized angular frequency ω_0 as the high-end of the passband which may be fixed as $\omega_0 = 1$. For a realizable inductor $L_x > 0$, the resonance frequency ω_r must be larger than that of ω_0. On the other hand, we know that at ω_r, series equivalent impedance becomes infinity. Therefore, ω_r must be reasonably away from ω_0. Location of ω_r depends on the practical realization of C_x and L_x.

III. Implementation of Tunable Broadband Amplifier

In this section, design of a tunable amplifier by using tunable inductors and capacitors, is explained step by step below.

Step-1: At first, a broadband flat gain amplifier (FGA) is designed by using SRFT over 800 MHz - 5200 MHz frequency range with 50 Ohm terminations R_G and R_L (Fig.3). A commercially available 63 mW low power NPN wideband silicon germanium RF transistor, BFU760F from NXP Corporation, is used in the design.

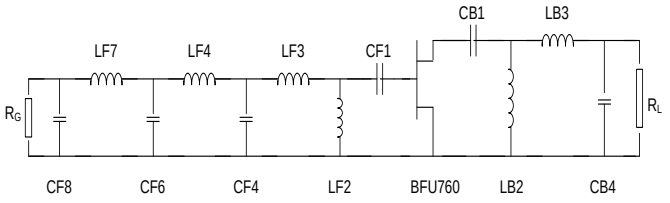


Fig. 3. 800-5200 MHz FGA schematics

TABLE I. ELEMENT VALUES OF FGA

Front-End Elements							
CF1	**LF2**	**LF3**	**CF4**	**LF5**	**CF6**	**LF7**	**CF8**
2.24	25.74	0.34	2.70	0.77	1.06	1.17	0.56
Back-End Elements							
CB1		**LB2**		**LB3**		**CB4**	
1.51		35.02		2.34		0.56	

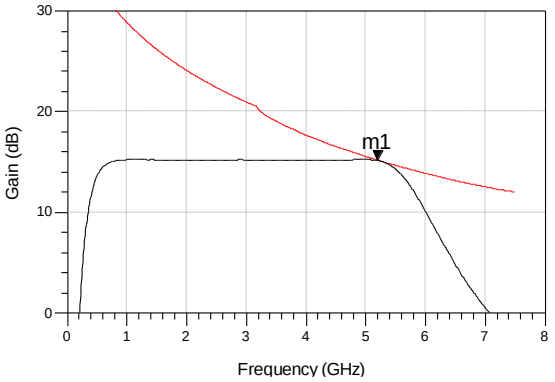


Fig. 4. Red line: MSG of BFU760F, Black line: Gain of the FGA

The element values obtained via SRFT are given in Table 1. According to this table, unit of all capacitances is in pF and unit of all inductances is in nH. The gain of the FGA is depicted in Fig. 4. Furthermore, maximum stable gain (MSG) is also shown in this figure and m1 marks the $15.188\ dB$ flat gain level of the design.

Step-2: In this step, a tunable amplifier is designed by using tunable inductors. For designing tunable amplifier, series inductors in $800-5200\ MHz$ FGA schematic seen in Fig. 3 are replaced with FDTIs as shown in Fig. 5. Therefore, (7) and (8) are used to compute FDTI and capacitor values, except high-pass inductors, where $\omega_0 = 5200\ MHz$ and $\omega_r = 7500\ MHz$. The high-pass inductors in Fig. 3 are substituted with series LC resonance circuits with tunable capacitors to design high-pass tunable inductors.

The gain performance of this amplifier is given in Fig. 6a. Then, "Gradient" and "Minimax" optimizations are run in Advanced Design System (ADS) respectively by employing these initial element values to maximize the gain within the whole design band (Fig. 6b). Instead of computation, high-pass tunable inductors (with series tunable capacitors) are obtained via the optimization. The element values of this amplifier are given in Table II. In this table, capacitance and inductance units are pF and nH, respectively.

Step-3: Eventually, 4 different frequency bands are chosen to design frequency dependent tunable amplifier with the topology given in Fig. 5. These frequency bands and flat gain levels are,

- $850-4200\ MHz;\ 17.212\ dB\ (@\ 4200\ MHz)$
- $850-5200\ MHz;\ 15.188\ dB\ (@\ 5200\ MHz)$
- $850-6200\ MHz;\ 13.585\ dB\ (@\ 6200\ MHz)$
- $850-7500\ MHz;\ 12.006\ dB\ (@\ 7500\ MHz)$

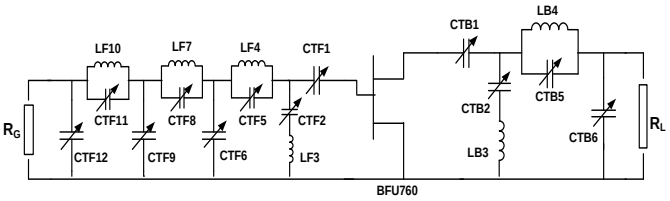
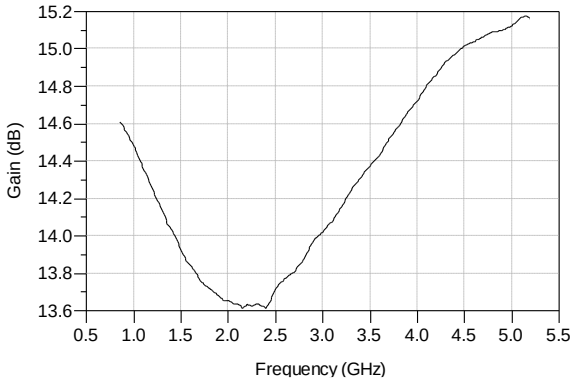
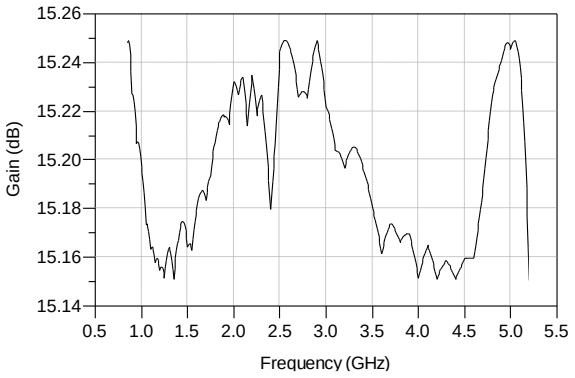


Fig. 5. The proposed tunable amplifier.



(a)



(b)

Fig. 6. Gain performance of the tunable amplifier, (a) Before optimization, (b) After optimization

By initially employing the element values of $850-5200\ MHz$ amplifier, the element values of the other three bands are obtained with ADS optimization which are given in Table II and gain of these amplifiers are depicted in Fig. 7.

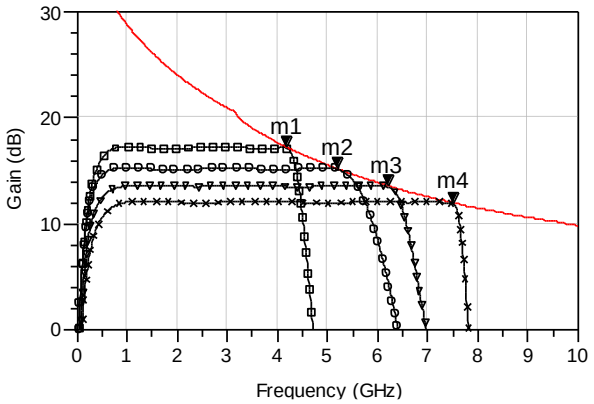


Fig. 7. Red line: MSG of BFU760, Black line: Gain performance of the proposed tunable amplifier according to chosen flat gain levels; $m1 = 17.212\ dB$, $m2 = \mathbf{15.188\ dB}$, $m3 = \mathbf{13.585\ dB}$ and $m4 = \mathbf{12.006\ dB}$

TABLE II. ELEMENT VALUES OF FREQUENCY DEPENDENT TUNABLE AMPLIFIER

	850-4200 MHz	**850-5200 MHz**	**850-6200 MHz**	**850-7500 MHz**
Front-End Elements				
CTF1	3.23655	3.71637	3.14978	2.50298
CTF2	0.1	1.65876	1.18983	1.41862
LF3	**0.1**	**0.1**	**0.1**	**0.1**
LF4	**0.1**	**0.1**	**0.1**	**0.1**
CTF5	3.84915	2.8122	1.60753	3.82582
CTF6	0.1	1.85999	2.61013	2.4434
LF7	**0.6**	**0.6**	**0.6**	**0.6**
CTF8	0.370075	0.278735	0.266685	0.182587
CTF9	2.32326	1.40883	1.41312	1.00531
LF10	**1**	**1**	**1**	**1**
CTF11	0.785767	0.100042	0.276266	0.103576
CTF12	0.55194	0.435151	0.116557	0.1
Back-End Elements				
CTB1	1.84206	1.5825	1.35858	1.26501
CTB2	0.1	0.1	0.1	0.1
LB3	**0.1**	**0.1**	**0.1**	**0.1**
LB4	**1**	**1**	**1**	**1**
CTB5	0.934984	0.490289	0.255443	0.121252
CTB6	0.66478	0.52405	0.372855	0.377848

IV. CONCLUSION

The purpose of this research work is to design tunable RF power amplifier over four frequency bands such as $800-4200\ MHz$, $800-5200\ MHz$, $800-6200\ MHz$ and $800-7500\ MHz$. In the course of matching network designs of the amplifier, Simplified Real Frequency Technique is employed. Furthermore to accomplish tunability with wide range of variability, a tunable inductance topology in series configuration is developed. Finally the element values of front-end and back-end matching networks are optimized to maximize the gain of the amplifier.

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