Design of a 20-to-40 GHz Bandpass MMIC Amplifier

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Abstract — **A millimeterwave bandpass MMIC amplifier, which integrates both features of gain amplifier and bandpass filter, is presented. A synthesis method for such amplifier is developed from the image-parameter filter theory. By employing the proposed bandpass amplifier in a receiver, the bulky off-chip filter may not be required. An experimental chip fabricated by 0.1 μm PHEMT shows 14.2-dB gain from 20 to 40 GHz and 60-dB attenuation below 7 GHz and above 60 GHz. This confirms the proposed method and shows the feasibility of the function integration of gain amplifier with bandpass filter in the millimeterwave range.**

I. Introduction

Typical RF front-ends for wireless communication include low-noise amplifiers, bandpass filters, mixers, voltage-control oscillators, and power amplifiers. Recent research has been focused on high-level integration of multiple functions in the same circuit such as the integration of low-noise amplifier and bandpass filter. In the lower GHz range, various CMOS bandpass amplifier designs were reported [1]-[4]. Narrowband bandpass CMOS amplifiers were shown to have 8-dB gain and 6.4-dB noise figure at 1.5 GHz [1]. For higher gain improvement, the positive-feedback Q-enhancement technique was used and reached 17-dB gain, 6.0-dB noise figure in the 869-893 MHz range [2]. In [3] the bandpass amplifier was designed with cascade of flat gain stages and frequency-selective gain stages, where a LC tank is incorporated at the drain terminal to have bandpass effect. With combination of cascode gain stage, Q-compensation circuit, and notch filter, a 22-dB gain and 10-dB noise figure CMOS bandpass amplifier was demonstrated in [4]. In the millimeter-wave range, the bandpass amplifier was achieved by the inter-stage impedance matching networks among broadband shunt-feedback PHEMTgain stages or equalizer-type PHEMT gain stages [5]. An 18-dB gain was obtained from 20 to 30 GHz.

To be able to synthesize a multistage amplifier, a lowpass filter synthesis technique is applied to design broadband lowpass amplifiers [6]. In this paper, a bandpass synthesis method of a bandpass amplifier is developed by using the image parameter filter theory [7]-[9]. Closed-form equations for circuit elements are obtained, subject to a pre-described bandpass amplifier performance, such as specified passband gain over a certain passband frequency range and desired attenuation over other stopband frequency range. If in the frequency range of interest the layout or device parasitic is important, these calculated element values can be further optimized by a nonlinear circuit simulator to include parasitic effects. A 20-40 GHz bandpass amplifier is designed and measured to verify the proposed method and shows the feasible function integration of an amplifier and a bandpass filter in a single circuit. By incorporating the designed bandpass amplifier in a receiver, the bulky off-chip band-selection filter or the image filter is not required.

II. Circuit Design

The bandpass amplifier, as shown in Fig. 1, is treated as cascade of input stage, broadband high-gain stage, and output stage. The high-gain FET stage provides adequate gain over the required passband range. The impedance match circuit, in conjunction with the high-pass nature of the DC blocking and RF choking circuit, gives a bandpass characteristic. The input and output match networks with their adjacent DC blocking and RF choking circuits are analyzed with the image-parameter filter theory. The broadband flat gain stage is calculated with the small-signal PHEMT model. Once the transmission matrix of all stages are derived, analytic expression of the overall bandpass amplifier can be obtained.

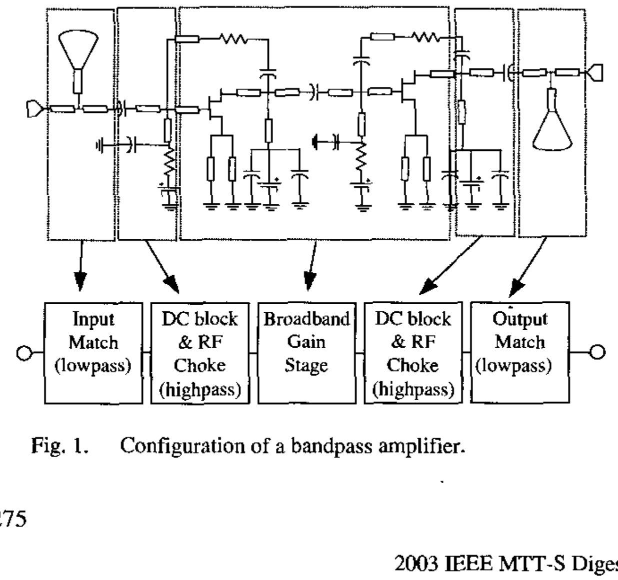

Fig. 1. Configuration of a bandpass amplifier.

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A. Design of Low-Pass Circuitry

The low-pass circuitry is designed with the m-derived T-type network, as shown in Fig. 2(a). Its transmission matrix is derived as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \frac{1}{1-\frac{\omega^2}{\omega_\infty^2}} \begin{bmatrix} 1-(1+m^2)\frac{\omega^2}{\omega_c^2} & j2\omega L_1\left(1-\frac{\omega^2}{\omega_c^2}\right) \\ j\omega C_2 & 1-(1+m^2)\frac{\omega^2}{\omega_c^2} \end{bmatrix}. \quad (1)$$

The element values can be calculated from the image parameter theory [6],

$$L_1 = \frac{m}{2}L, \quad L_2 = \frac{1-m^2}{4m}L, \quad C_2 = mC \quad (2)$$

$$L = \frac{2Z_0}{\omega_c}, \quad C = \frac{2}{\omega_c Z_0}, \quad m = \sqrt{1-\left(\frac{\omega_c}{\omega_\infty}\right)^2} \quad (3)$$

where Z_0 is the system characteristic impedance, ω_c is the higher passabnd cutoff angular frequency, and ω_∞ is the transmission zero frequency, generated from the series resonance of the L_2 and C_2. For the case of a 20-40 GHz bandpass amplifier with attenuation above 60 GHz, f_c and f_∞ can be selected as 44 GHz and 57 GHz, respectively, which give m=0.64, L_1=0.12 nH, L_2=0.085 nH, C_2= 0.09 pF.

B. Design of High-Pass Circuitry

The high-pass circuitry is designed with the m-derived L-type network, as shown in Fig. 2(b), where the element values are,

$$C_1 = \frac{2}{m}C, \quad C_2 = \frac{2m}{1-m^2}C, \quad L_2 = \frac{2}{m}L \quad (4)$$

$$L = \frac{R_0}{2\omega_c}, \quad C = \frac{1}{2\omega_c R_0}, \quad m = \sqrt{1-\left(\frac{\omega_\infty}{\omega_c}\right)^2} \quad (5)$$

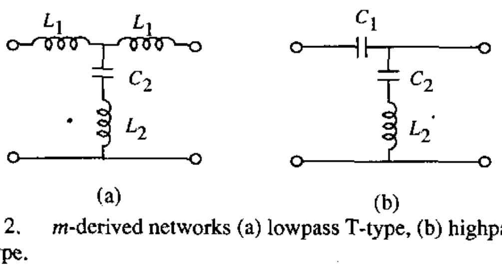

Fig. 2. m-derived networks (a) lowpass T-type, (b) highpass L-type.

For the 20-40 GHz bandpass amplifier with attenuation below 10 GHz, f_c and f_∞ are chosen as 18 GHz and 7 GHz, respectively, which gives m=0.92, C_1= 0.19 pF, C_2= 1.08 pF, L_2= 0.48 nH.

C. Design of Stable Gain Stage

The FET gain stage must provide adequate gain over the required bandwidth. In this case, two resistive shunt-feedback PHEMT amplifiers are cascaded. In Fig. 3, only single shunt-feedback PHEMT amplifier is shown. It is actually a multiple feedback network with an external shunt-shunt feedback through R_f, L_f, and C_f, and two internal feedbacks in the intrinsic pHEMT transistor, which are series-series feedback by R_s and L_s and shunt-shunt feedback through C_{gd}. The S parameters of this multiple-feedback amplifier can be derived and, for brevity, only S_{21} is shown as follows, which has the same form as derived by [10],

$$S_{21} = -2\frac{g'_m R'_{ds}\left(R'_{ds}+Z_L\right)}{2R'_{ds}+Z_L}\frac{1-s/\omega_z}{D(s)} \quad (6)$$

where

$$\begin{aligned} D(s) = 1 + s\{ & C'_{gs}\left(Z_s+R'_g+R'_{in}\right)+C'_{ds}\left(Z_L+R'_d\right)+ \\ & C'_{gd}\left[g'_m\left(Z_s+R'_g\right)\left(Z_L+R'_d\right)+\left(Z_s+R'_g\right)+\left(Z_L+R'_d\right)\right]\}+ \\ & s^2\{\left(C'_{gd}C'_{gs}+C'_{gd}C'_{ds}+C'_{gs}C'_{ds}\right)\left(Z_s+R'_g\right)\left(Z_L+R'_d\right)+ \\ & \quad \left(C'_{gd}C'_{gs}+C'_{gs}C'_{ds}\right)R'_i\left(Z_L+R'_d\right)+C'_{gd}C'_{gs}R'_i\left(Z_S+R'_g\right)\}+ \\ & s^3 C'_{gd}C'_{gs}C'_{ds}R'_{in}\left(Z_s+R'_g\right)\left(Z_L+R'_d\right) \end{aligned}$$

$$C'_{gs} = \frac{C_{gs}}{1+g_m R'_s}, \quad C'_{ds} = \frac{C_{ds}}{1+g_m R'_s}, \quad C'_{gd} = C_{gd} + \frac{1}{s\left(R_f+sL_f\right)},$$

$$R'_i = R_i + R_s, \quad R'_{ds} = R_{ds}\left(1+g_m R'_s\right), \quad R'_s = R_s + sL_s,$$

$$R'_g = R_g + sL_g, \quad R'_d = R_d + sL_d, \quad g'_m = \frac{g_{mo}e^{-s\tau}}{1+g_{mo}e^{-s\tau}R'_s},$$

$$\omega_z = \frac{g_m}{\left(1+sC'_{gs}R'_i\right)C'_{gd}}$$

Based on (6), a calculated gain of 6.5 ± 0.6 dB from 20 to 40 GHz is obtained for a four-finger 80-μm gate periphery PHEMT with R_f = 250 Ω, C_f = 0.8 pF, L_f = 0.4 nH.

D. Overall Bandpass Amplifier

By cascading the input, output, and gain stage, a bandpass amplifier can be built. For the case of interest, a bandpass amplifier is designed with (2)-(5). For MMIC implementation, the inductors are realized with high-impedance short microstrip lines and some capacitors with radial open stubs. The calculated circuit element values are substituted in the nonlinear circuit simulator for performance optimization, where the parasitic components such as microstrip T-junction, bends and via holes are obtained by EM simulator. The microphotograph of the chip is shown in Fig. 4, where the chip size is 3 mm × 1 mm.

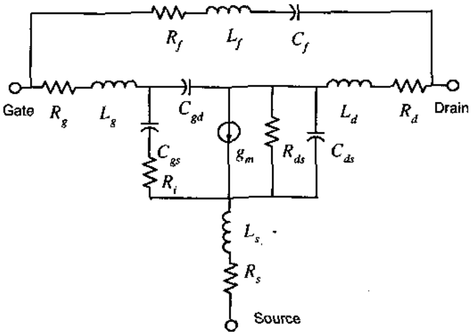

Fig. 3. Small signal model of a resistive shunt-feedback pHEMT transistor.

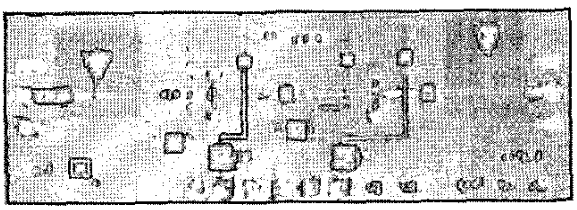

Fig. 4. Chip microphotograph of the designed 20-to-40-GHz bandpass MMIC amplifier.

III. Circuit Performance

Fig. 5 shows the bandpass amplifier performance by the proposed method, the circuit simulator, and on-wafer measurement. The measured gain is 14.2 ± 0.8 dB from 20 to 40 GHz and the attenuation higher than 60 dB below 7 and above 60 GHz. The calculated and simulated results agree well with the measurement except their slightly wider passband bandwidth. This is due to the microstrip conductor loss and dielectric loss is totally neglected in the proposed method and partially included in the circuit simulator. The input return loss and output return loss from simulation and measurement have the same frequency dependence despite a 5-8 dB degradation.

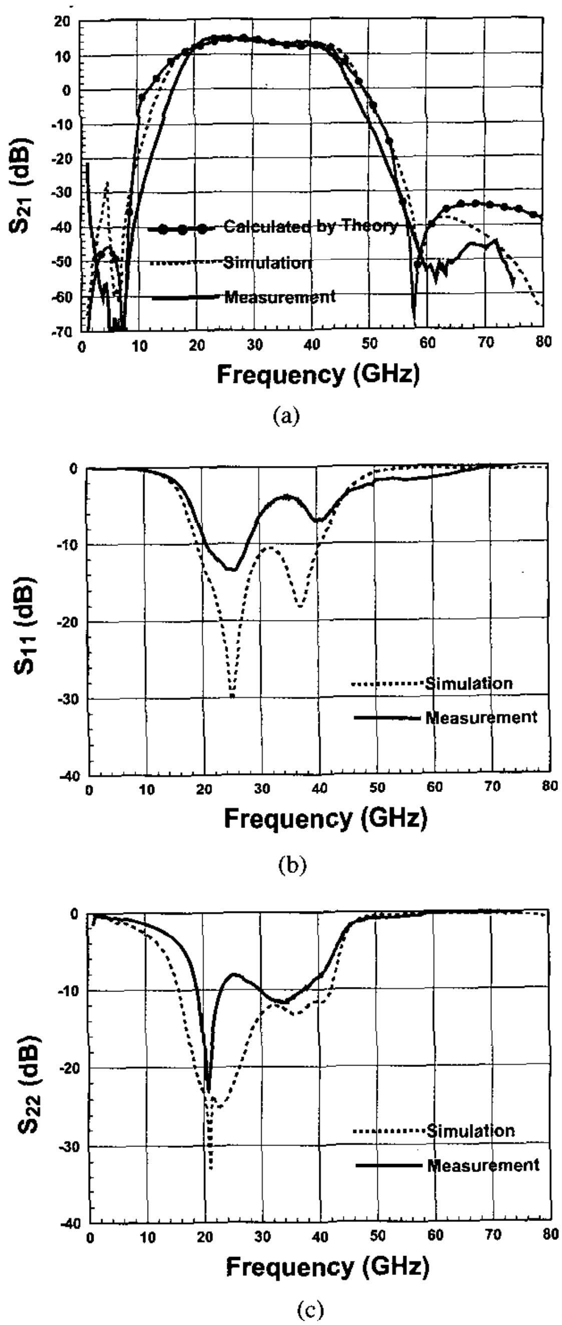

Fig. 5. Designed Bandpass amplifier performance, (a) forward gain, (b) input return loss, (c) output return loss.

IV. Conclusion

A synthesis method of a millimeterwave bandpass MMIC amplifier is described, where the bandpass characteristic is provided by match circuit and the combined DC block and RF choke circuit and the broadband gain is offered by the shunt-feedback PHEMT amplifier. The image parameter theory was applied to derive closed-form equations for synthesizing circuit elements, subject to the pre-specified performance. The proposed synthesis method allows accurate results close to the initial design specifications. If the layout parasitic is considerable, the synthesized element values are used as the initial values for optimization by a nonlinear circuit simulator. A 20-40 GHz bandpass MMIC amplifier is designed and shows a measured 14.2 ± 0.8 dB gain over the passabnd from 20 to 40 GHz and a 60-dB attenuation below 7 and above 60 GHz. The simulation results agree well with the measurement, which verifies the proposed method. The good performance of the bandpass amplifier also demonstrates the feasibility of function integration of millimeterwave gain amplifier and bandpass filter in a single circuit.

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