Design of Continuously Tunable Low Noise Amplifier for Multiband Radio

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***Abstract*— this paper presents the design of continuously tunable low noise amplifier with frequency tuning range from 2.2 to 2.8 GHz. The amplifier achieves input matching and tunability through a transformer based input matching network. The proposed circuit uses an inductively degenerated common source cascode amplifier to design the amplification stage. The circuit includes a phase shifter circuit to shift the phase of the input signal to achieve tunability through transformer. The LNA achieves a maximum gain of more than 17dB in the entire tuning range. The LNA attains a perfect impedance match across the tuning range and has a stable operation. In addition, it achieves a low noise figure ranging from 1.4dB to 5.2dB.**

Keywords—software defined radio, tunable, impedance transformer, phase shifter, low noise amplifier

I. INTRODUCTION

Traditional radios are now being replaced with multiband software defined radios (SDR) [1], which can accommodate multiple standards either concurrently or discretely. The detriments of a traditional radio is that it carries a bulky device and costs expensive as well. Modern microprocessors are capable enough to perform computational-heavy information processing, which enables SDR as a promising technology with a goal of getting rid of unnecessary hardware. In particular, we can use computer algorithms to process the multiband radio signals in software.

In the receiver block of an SDR, a low noise amplifier (LNA) is the first active element that must provide wideband impedance matching, high gain, low noise figure (NF) and low power consumption [2]. For an efficient LNA, stable and linear operation is desired because the performance of LNA will significantly affect that of the whole receiver chain. The design issues are more challenging for tunable multiband LNAs, which can be tuned to different frequencies within a spectrum discretely, or continuously by varying an element in the input/output matching stage of the LNA. Consequently, tunable LNAs are divided into two categories, namely input tuning LNAs and output tuning LNAs.

It is important to choose an appropriate topology when designing a multiband LNA. Common gate topology has been implemented in [3, 4] to get the wideband response and stable operation. However, the topology is not perfectly suitable for designing an input tuning LNA due to the dependence of gain and NF on transconductance g_m. An inductively degenerated common source amplifier improves the gain performance and input return loss of the circuit as it brings an increase in the real part of the input impedance. This further helps to improve the noise matching. However, the design of tunable LNAs also leads to an increase in the chip area due to use of additional passives for the reconfigurable input matching networks with switched inductors [5] and switched capacitors [6]. This results in a substantial increase in the die area and implementation costs. In addition, tunable active inductors have been explored in [7, 8] to overcome the low quality factor of inductors and their large area consumption on chip. However, the drawbacks associated with the use of active inductor are higher power consumption and nonlinearity [9]. Finally, transformer based matching networks have been implemented in [10, 11] to get a wider tuning range and reduced power consumption.

This paper presents a design of a frequency tunable LNA that can be tuned continuously over a bandwidth of 600 MHz from 2.2 to 2.8 GHz. Input matching stage is designed using a transformer based matching network and the LNA uses cascode topology for wideband response and better isolation. The rest of the paper is organized as follows. Section II describes the design methodology of the proposed tunable LNA, and Section III discusses the simulation results for the designed tunable LNA. Finally, Section IV concludes this paper with our findings.

II. PROPOSED CIRCUIT TOPOLOGY

The input impedance matching network has to be either multiband or wideband for a multiband LNA. Input matching is realised by designing a transformer-based matching network for the proposed tunable LNA. The designed tunable LNA is shown in Fig. 1(a). The proposed amplifier design consists of four stages. The first stage is the input matching stage that consists of capacitor C_1 and a physical transformer. The second stage consists of a phase shifter network that comprises of two common gate transistors Q_7 and Q_8 connected in parallel to a common source transistor Q_9 to get a relative 0 or 180 degrees phase shift between the currents through primary and the secondary windings of the transformer. The third stage consists

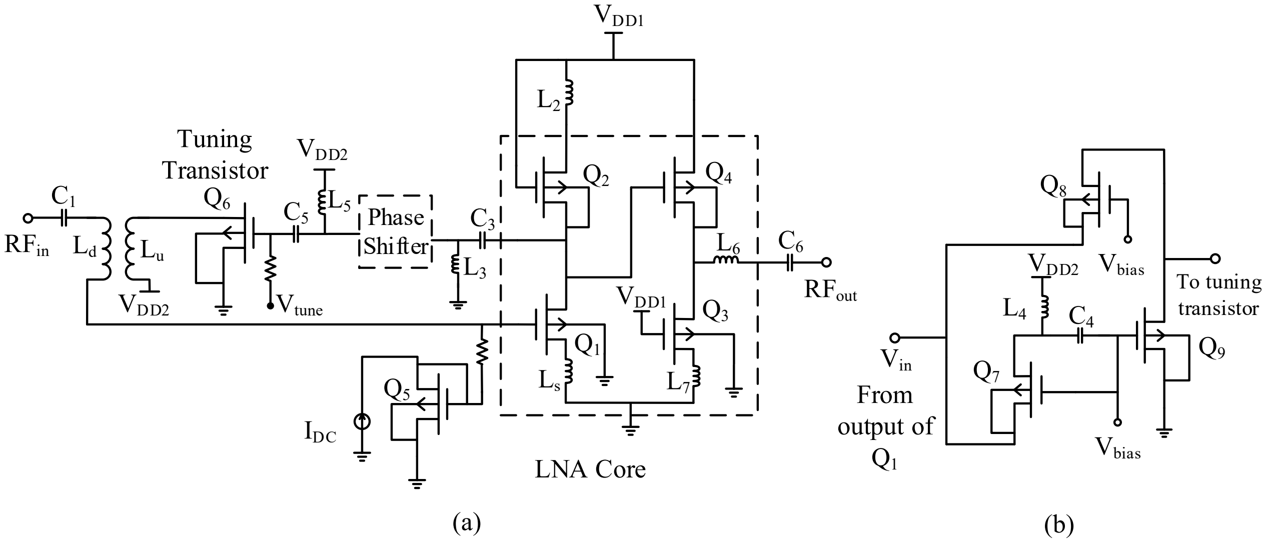

Fig. 1. (a) Proposed Tunable LNA (b) Phase shifter circuit

of tuning transistor Q_6 whose bias voltage V_{tune} can be varied to get the desired tunability. Finally, the fourth stage is the amplification stage that achieves a tunable wideband gain when V_{tune} is varied.

A. Input Matching Network

In the designed circuit, one end of primary winding L_u is connected to the output of Q_6 and the phase shifter is connected to the output of Q_1 via a coupling capacitor. The output signal from phase shifter is fed as input to Q_6 that feeds the current to the primary winding of the physical transformer.

An equivalent circuit for the physical transformer, implemented for achieving reconfigurable input matching network is shown in Fig. 2. The currents i_1 and i_2 through primary and secondary windings of the transformer have a relative phase shift of either 0° or 180°. The input impedance for designed LNA will depend on the inductance of secondary winding L_d due to secondary leakage inductance L_{t2} and source degeneration inductor L_s. Input impedance in *'s'* domain in a simplified form can be expressed as:

$$Z_{in}(s)=\left(sL_s+sL_d\pm s\alpha M-\frac{s}{C_{gs_1}}\right)+\frac{g_{m_1}L_s}{C_{gs_1}} \qquad (1)$$

where α is the ratio of complex currents i_2 and i_1 flowing through the secondary and primary windings, respectively, C_{gs1} is the gate source capacitance and g_{m1} is the transconductance of transistor Q_1, respectively and M is the mutual inductance. Since $\alpha = i_2/i_1$, current in the primary winding L_u of the transformer varies due to current variation from the output of Q_6, which changes when V_{tune} varies. Hence, the matching network can be tuned to different frequencies from 2.2 to 2.8 GHz by incrementing V_{tune} from 0.4V to 1.4V. The frequency of operation f_{op} of the proposed LNA can be determined as:

$$f_{op}=\frac{1}{2\pi(L_d\pm\alpha M)C_t} \qquad (2)$$

where C_t is the interwinding transformer capacitance. Design parameters of transformer circuit are summarised in Table I.

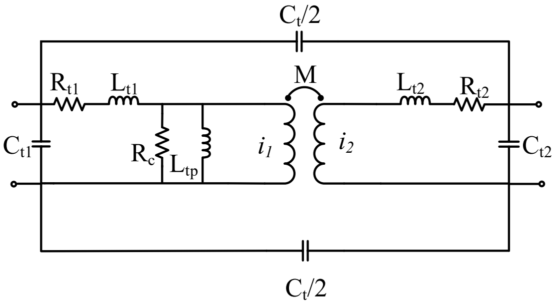

Fig. 2. Equivalent circuit of transformer model implemented in the designed tunable LNA

As the coefficient of coupling, k is directly proportional to mutual inductance, its value has been kept low to widen the tuning range and to achieve a better input match. The frequency of operation is also dependent on k. Mutual inductance and coupling coefficient are related to each other as:

$$M=k\sqrt{L_uL_d} \qquad (3)$$

B. Active Phase Shifter

An active phase shifter [12] has been implemented to shift the phase of the RF input signal of the proposed LNA. The proposed phase shifter circuit embeds two common gate transistors in parallel to a common source transistor. Schematic of the phase shifter circuit used in the design of tunable LNA is shown in Fig. 1(b). The output of the phase shifter is fed to transistor Q_6. Inductor L_4 and Capacitor C_4 form a resonant circuit. The shift in phase of the signal with constant signal amplitude is accomplished by variation in inductance or capacitance of the resonant circuit. The values of inductor L_4 and capacitor C_4 for 2.2 to 2.8 GHz band are 17.5nH and 10 pF, respectively.

TABLE I. TRANSFORMER DESIGN PARAMETERS

Parameter	***Value***
Turns Ratio 'N'	0.69
Magnetising Inductance 'L_{tp}'	2.23 *nH*
Cross loss resistance 'R_c'	1000 *Ω*
Coefficient of Coupling 'k'	0.11
Primary loss resistance 'R_{t1}'	0.91 *Ω*
Secondary loss resistance 'R_{t2}'	4.47 *Ω*
Primary capacitance 'C_{t1}'	924 *fF*
Secondary capacitance 'C_{t2}'	150 *fF*
Interwinding capacitance 'C_t'	340 *fF*

III. RESULTS AND DISCUSSIONS

Fixed bias is adopted and the bias voltage to the LNA core is 1.8V. The phase shifter transistor network has been biased with 2V. The analysis has been carried out using Keysight ADS simulation tool. The LNA outperforms existing designs in [8, 13, 14] at the expense of increased power consumption.

A. Gain and Return Loss

Fig. 3 shows simulated gain for the designed tunable LNA. The LNA gain can be tuned to different frequencies from 2.2 to 2.8 GHz by continuously varying V_{tune} from 0.4 to 1.5V. The cascode topology in the second stage allows the LNA to achieve a wider and higher gain. The designed LNA achieves a maximum gain of 17.5dB in the tuning range, while the minimum gain is 7dB.

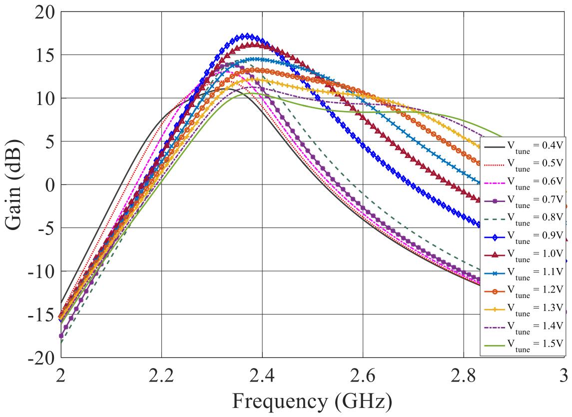

Fig. 3. Simulated gain for designed tunable LNA

The LNA gain depends upon transconductance g_{m_1} and g_{m_2}, gate source capacitance C_{gs_1}, C_{gs_2}, source degeneration inductor L_s and inductor L_2. Fig. 4 shows the variation of gain at a particular centre frequency with V_{tune}.

Fig. 5 shows the plot of simulated S_{11} for the designed tunable LNA. S_{11} is below -10dB at each centre frequency for the entire tuning range and achieves as low as -40.4 dB at 2.46 GHz. The LNA input matching network has been designed to match to 50Ω at a particular centre frequency in the tuning range. Centre frequency can be termed as a frequency where S_{11} is minimum.

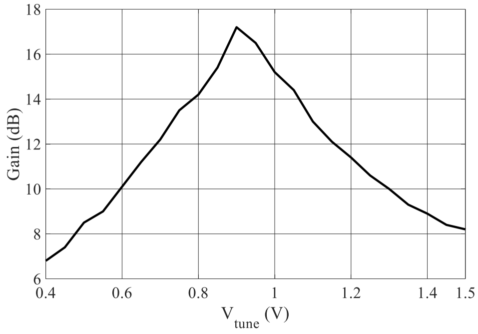

Fig. 4. Variation of gain with V_{tune} for designed tunable LNA

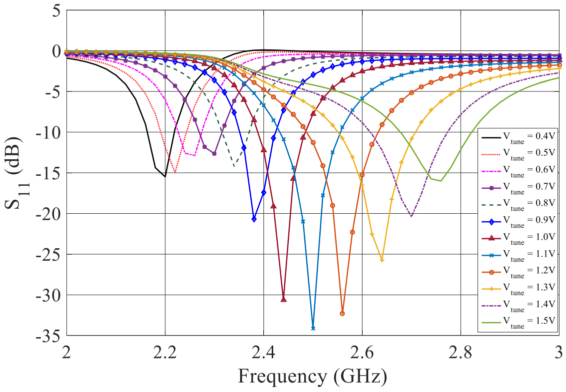

Fig. 5. Simulated S_{11} for the designed tunable LNA

B. Noise Figure and Stability

The LNA is able to achieve fairly low NF in the entire tuning range, despite of multiple noise sources in the design. Fig. 6 shows simulated frequency response of NF for the designed LNA and Fig. 7 shows the variation of NF with V_{tune}. NF for the designed LNA varies from 1.4 to 5.2dB in 600MHz tuning range.

As compared to other design in the literature, one of the reasons for our LNA design to achieve low NF at different centre frequencies is implementing less number of inductors and capacitors in the input and output matching network.

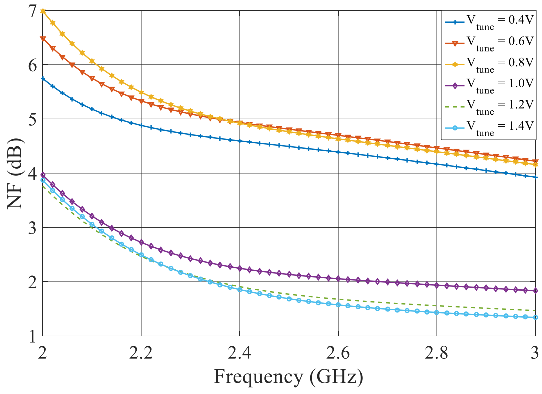

Fig. 6. Simulated noise figure for designed tunable LNA

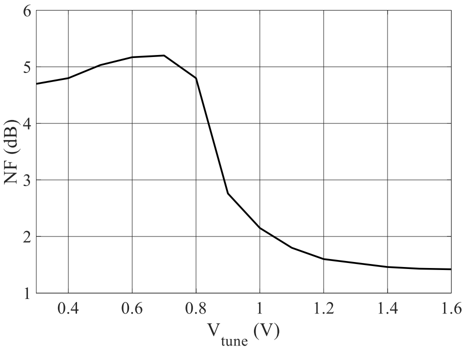

Fig. 7. Noise figure variation with V_{tune} for the designed tunable LNA

The LNA stability depends upon the source and the load matching networks, which depends on the frequency of operation. Therefore, the designed LNA is stable at a particular center frequency and unstable at other frequencies. Stability of LNA can be determined by calculating stability factor K and stability constant Δ or by plotting stability circles. For the designed LNA, $K > 1$ and $|\Delta| < 1$ at all center frequencies within in the tuning range. Consequently, the LNA is stable in the entire tuning range. Fig. 8 shows variation of stability with tuning voltage at different centre frequencies.

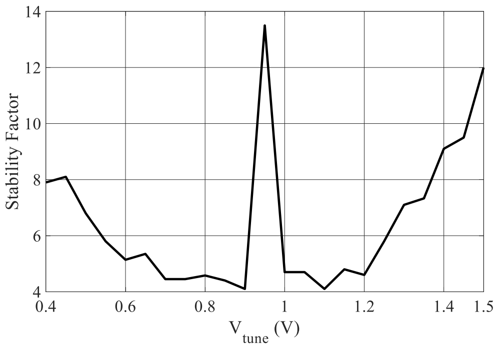

Fig. 8 Stability factor variation with V_{tune} for the designed tunable LNA

TABLE II. PERFORMANCE COMPARISON WITH PREVIOUS WORKS

	This work	**[8]**	**[13]**	**[14]**
Freq (GHz)	2.2 – 2.8	0.9,1.5,1.9,2.4	1.9 – 2.4	4.5 – 5.5
Tuning	continuous	discrete	continuous	continuous
S_{21} (dB)	7 – 17.5	17 – 21	10 – 14	3 – 23
S_{11}(dB)	-40 – -10	-27 – -11	-15 – -25	-6 – -8
S_{12} (dB)	-40 – -24	-	-	-
NF (dB)	1.4 – 5.2	1.7 – 3.6	3.2 – 3.7	2 – 6
IP_3 (dBm)	-35 to -48	-	-6.7	+10 – -6.5
V_{DD} (V)	1.8	1.8	1.2	1.2
P_{DC} (mW)	32.4	19.6	17	16

IV. CONCLUSION

A continuously tunable multiband low noise amplifier has been presented in this paper. The input matching stage is designed using a transformer based matching network whose primary impedance can be varied to get a tunable frequency response. The current in the primary winding is altered using a phase shifting circuit and a tuning transistor. The design effectively integrates the matching network into an inductively degenerated common source amplifier. The LNA achieves a tunable wideband gain from 7 to 17.5dB, low noise figure ranges from 1.4 to 5.2dB and the LNA is unconditionally stable in the complete tuning range. The designed multiband LNA can be implemented to improve the performance of SDR receiver circuits for military multiband communications.

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