A Radio Frequency CMOS Band Pass Amplifier Using High-Q Active Inductor Loads with Binary Code for Multi-Band Selecting

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Abstract: - In this paper, a CMOS radio frequency (RF) multi-band band-pass amplifier using a high-Q active inductor load with a binary code band selector suitable for multi-standards wireless applications is proposed. By employing the improved high-Q active inductor including two bits binary controlled code, the RF multi-band amplifier operating at four different frequency bands is realized. The proposed amplifier circuit is designed in TSMC 0.18-um CMOS technology. Based on the simulation results, the amplifier can operate at 900MHz, 1.8GHz, 2.4GHz, and 3.6GHz with forward gain (S_{21}) of 21.9 dB, 21.9dB, 21.8dB, and 12.5 dB, respectively. Furthermore, the power dissipation of this amplifier can retain constant at all operating frequency bands and consume around 5.27 mW from 1.8-V power supply.

Key-Words: - CMOS, High-Q Active Inductor, Bands Selector, Multi-Band Amplifier, and Multi-Standards.

1 Introduction

In recently years, the evolution of wireless communications has motivated a strong interest toward the development of multi-standards and multi-services with operating frequencies of 900MHz/1.8GHz/1.9GHz bands for GSM, 1.5GHz band for GPS, 2.3GHz band for WCS, 2.5GHz to 2.7GHz bands for MMDS, 2.4GHz band for ISM, and 3.5GHz to 3.7GHz bands for ETSIT. Therefore, it is desirable to combine more standard bands in one mobile unite [1]-[2]. One of the design challenges is to realize a full integrated multi-band amplifier with frequency selecting capability. Typical design strategies have used different amplifiers for different frequency bands [3]-[4]. However, this way inevitably increases cost and power consumption. Recently, various circuit techniques have been proposed by employing switched passive spiral inductors and switched capacitors for the load [5]-[6] and the matching networking of the amplifiers [7]-[9]. Nevertheless, most of these techniques demand additional passive components for the load and the input/output matching networks, leading to a significant increase in chip size and the implementation cost. In this paper, a non-inductor RF multi-band amplifier using TSMC 0.18-um CMOS technology applying high-Q active inductor for multi-standards or multi-services is presented. The amplifier exhibits constant power consumption at all operating frequency bands and can be operated at four frequency bands selecting capability with the center frequency of 900MHz, 1.8GH, 2.4GHz, and 3.6GHz by using a two bits binary controlled code.

The organization of this paper is described as follows. Constant power consumption with a band selectable high-Q active inductor is described in section **2**. In section **3,** the band selector using two bits binary code is proposed. The proposed band-pass amplifier using the high-Q active inductor with steady power and multi-band frequencies selecting is introduced in section **4**. Simulation results of the proposed multi-band amplifier are indicated in section **5**. Finally, the conclusion is summarized in section **6**.

2 High-Q Active Inductor with Bands Selector

Based on the gyrator theory [10], the simple grounded active inductor circuit and its equivalent circuit are shown in Fig. 1 (a) and (b). Each MOS transistor is modeled by the equivalent device components including g_m, g_{ds}, C_{gs}, and C_{gd}. Assumed that $g_m >> g_{ds}$ and $C_{gs} >> C_{gd}$ are established, and then the equivalent input impedance (Z_{in}) of this inductor can be derived as Eq. (1). According to the Eq. (1), the component values of the inductor are expressed from Eq. (2) to Eq. (5). The Q value and the resonant frequency ω_0 are shown in Eq. (6) and (7), respectively.

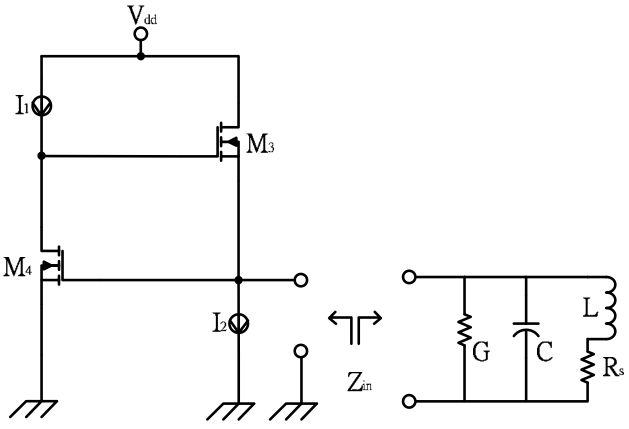


Fig. 1 Simple active inductor and equivalent circuit

$$Z_{in} \approx \frac{(g_{ds3}+g_{m4})+S(C_{gs3}+C_{gd4}+C_{gd3})}{(SC_{gd3}+g_{ds3}+g_{m4})(S(C_{gs3}+C_{gd4})+g_{m3})} \quad (1)$$

$$G \approx g_{ds3}+g_{m4} \approx g_{m4} \quad (2)$$

$$R_s \approx \frac{g_{ds4}}{g_{m4}g_{m3}} \quad (3)$$

$$L \approx \frac{C_{gs3}}{g_{m4}g_{m3}} \quad (4)$$

$$C \approx C_{gs4} \quad (5)$$

$$Q \approx \sqrt{\frac{g_{m4}g_{m3}C_{gs3}}{g_{ds4}{}^2C_{gs4}}} \quad (6)$$

$$\omega_0 \approx \sqrt{\frac{g_{m4}g_{m3}}{C_{gs4}C_{gs3}}} \quad (7)$$

where g_{mi}, g_{dsi}, and C_{gsi} are the transconductance, the output conductance, and the gate-source capacitance of correspondence transistors, respectively. By Eq. (2), the increasing parallel conductance loss of (G) will reduce the Q value of the inductor. Therefore, in order to improve the performance such as the Q value, a high-Q active inductor using a feedback resistor is proposed.

The improved high-Q active inductor circuit is illustrated in Fig. 2. This circuit is composed of common-source transistor M_4, common-drain transistor M_3, feedback resistor R_f and two biasing current sources I_1 and I_2. Feedback resistor and transistor M_4 construct a gain network. This network produces a gain factor to reduce the parallel conductance (G). Hence, the equivalent internal loss of the inductor will be decreased, and then the Q value will be increased. Moreover, the inductance (L) is also increased due to the feedback resistor. At high frequency, this circuit is equivalent to a resonator as well, which is the same as Fig. 1(b). The component values of this inductor including three parameters, C_{gsi}, g_{dsi}, and g_{mi} are derived as from Eq. (8) to Eq. (11). The Q value and the resonant frequency ω_0 are shown in Eq. (12) and (13), respectively.

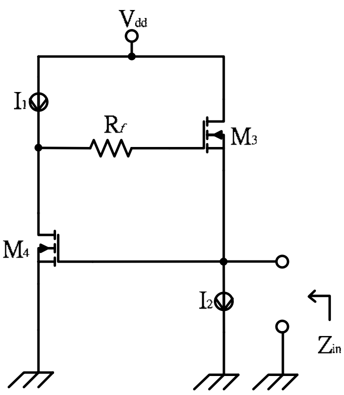


Fig. 2 High-Q active inductor

$$G \approx g_{ds3}+\frac{g_{m4}}{1+R_f g_{ds4}} \quad (8)$$

$$R_s \approx \frac{g_{ds4}}{g_{m4}g_{m3}} \quad (9)$$

$$L \approx \frac{C_{gs3}\left(1+R_f g_{ds4}\right)}{g_{m4}g_{m3}} \quad (10)$$

$$C \approx C_{gs4} \quad (11)$$

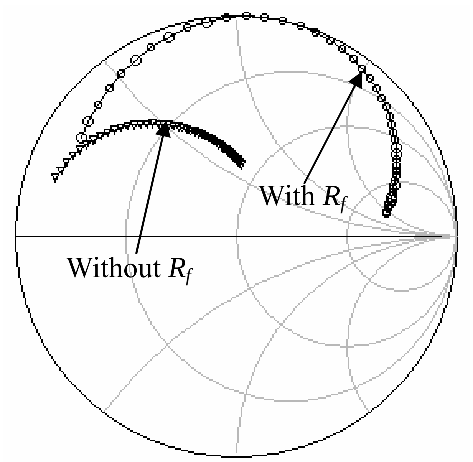
$$Q \approx \sqrt{\frac{g_{m4}g_{m3}C_{gs3}}{g_{ds4}{}^2C_{gs4}}\times\left(1+R_f g_{ds4}\right)} \quad (12)$$

$$\omega_0 \approx \sqrt{\frac{g_{m4}g_{m3}}{C_{gs4}C_{gs3}(1+R_f g_{ds4})}} \quad (13)$$

By Eq. (8) and (10), the effect of the factor, $(1+R_f g_{ds4})$, is designed to be a value greater than unity. This factor will result in the equivalent conductance loss (G) to be minimized and the equivalent inductance (L) to be increase as well. From Eq. (12) and (13), the Q-value is promoted with the feedback resistance by the $\sqrt{1+R_f g_{ds4}}$

factor and the resonant frequency ω_0 is inverse proportion of the $\sqrt{1+R_f g_{ds4}}$ factor.

In Fig. 3, the result of scattering parameter (S_{11}) performance of the inductor is illustrated. This figure can be treated as the moving trend of the curve inclining to the outside and the right side of the circle as adding the feedback resistance. Hence, it indicates that the loss is decreased, but the Q-value is increased between 600MHz and 5GHz frequency range. Therefore, the performances of the active inductor containing the Q value and the inductance will be tremendously improved by applying a simple feedback resistance R_f.



Frequency (600MHz to 5GHz)

Fig. 3 Microwave performance of the high-Q active inductor (S_{11})

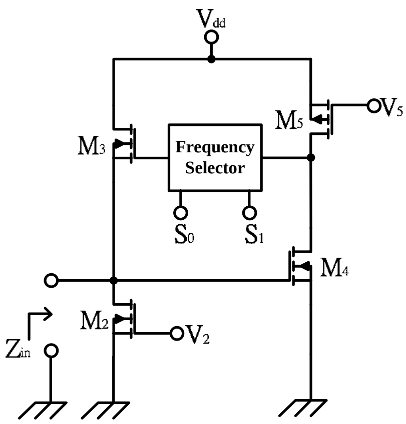


Fig. 4 High-Q active inductor circuit with band selector

In order to change the characteristics of the active inductor including the Q value, the inductance (L), and the resonant frequency (ω_0), the active inductor can use a simple network to control the feedback resistance. In Fig. 4, the simple network is instead of the feedback resistance to change the inductance, the Q value, and the resonating frequency of the inductor. In this simple network, the different feedback resistances can be selected by using digital code to form a band selector. The band selector can choose all kinds of resistance using different binary code, and then the inductance, the Q-value, and the resonating frequency ω_0 of the inductor will be changed.

3 Bands Selector Circuit

In the improved high-Q active inductor design, the characteristics of the inductor can be changed by selecting a different feedback resistance. The different values of the feedback resistance can be obtained by using two bits binary code to obtain a band selection configure. In Fig. 5 shows the band selecting configuration to replace the feedback resistor selection. The band selector circuit is combined with four different resistors and a 4 to 1 multiplex to process resistance selection, which uses two bits binary controlled code (S_0S_1).

As input binary code (S_0S_1) of the multiplex apply with individual 00, 01, 10, and 11, and then the feedback resistance of R_{900}, R_{1800}, R_{2400}, and R_{3600} will be selected, respectively. As a result, the characteristics of the inductor will be selected, hence it can be achieved the function of bands selecting.

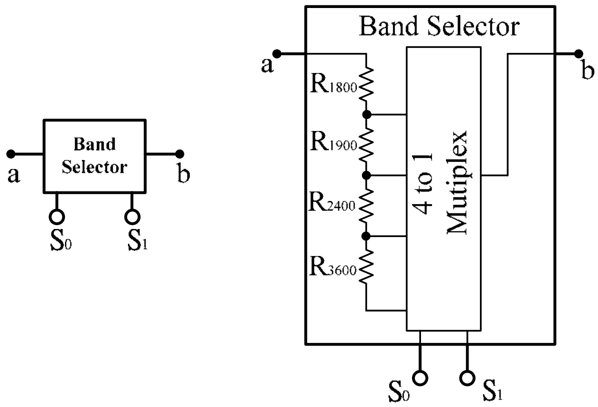


Fig. 5 Bands selector circuit

Moreover, the proposed active inductor, due to the DC bias current does not pass through the band selector; the voltage drop of the band selector is zero. Hence, the DC voltage drop of the band selector will not be affected the bias of the inductor while the feedback resistor is changed. Consequently, the characteristics of the active inductor can be changed, but the power consumption will retain constant. Therefore, based on the selected feedback resistance and the constant power dissipation can be applied to design a multi-band and constant power consumption RF multi-bands amplifier circuit for multi-standard or multi-service.

4 Proposed RF Multi-Band Band-Pass Amplifiers

In the RF multi-band amplifier designs, an inductance load is required to obtain the enough gain at the frequency interest. Typically, the inductance load is applied with a passive spiral inductor. However, inherently low Q-factors and occupied large chip area, the gain and the cost-performance of the amplifier designs will be significantly decreased. Hence, an active inductor can employ in the load of the amplifier to improve above these disadvantages. Furthermore, a matching network is required to reduce the reflection coefficient at the operating frequency in RF amplifier designs. For the multi-band applications, it can be realized by a broadband matching technique.

In order to simplify the design mechanism, the common-gate configuration is employed for the input gain stage to obtain the required matching. Therefore, a bands selectable, steady power consumption, and inductor-less multi-band amplifier is proposed, which showed in Fig. 6. The amplifier is composed of a common-gate gain stage, a high-Q active inductor load, and an output buffer stage. In the common-gate configuration, transistors M_1 and M_2 are employed as the input stage for input impedance matching. Assumed $g_m >> g_{ds}$ and $C_{gs} >> C_{gd}$ are established, and then the input impedance (Z_{in}) of this amplifier can be approximated as Eq. (14).

$$Z_{in} \approx \frac{1}{(g_{ds1} + g_{m2} + j\omega C_{gs2} + j\omega C_{gd1})} \approx \frac{1}{g_{m2}} \qquad (14)$$

where g_{mi}, g_{dsi}, C_{gdi} and C_{gsi} are the transconductance, the output conductance, the gate-drain capacitance, and the gate-source capacitance of correspondence transistors, respectively. Hence, the input matching of the amplifier can be easily achieved by setting $1/g_{m2}$.

Using a passive spiral inductor load, low Q value and occupied large chip area will result in low gain and high cost in amplifier fabrication. To improve these problems, the amplifier employs a high-Q active inductor. In this design, a proposed high-Q active inductor is treated as the load of the common-gate amplifier to achieve high gain and small chip area. In the active inductor, it is composed of a band selector and transistors M_2 to M_5. In the band selector, using two controlled binary bits S_0S_1 can produce four different binary codes such as 00, 01, 10, and 11 then four operating frequency bands, including 900MHz, 1.8GHz, 2.4GHz, and 3.6GHz can be obtained for multi-standard. In the output stage, it uses a common-drain configuration, which is formed by transistors of M_6 and M_7 to acquire 50Ω output matching.

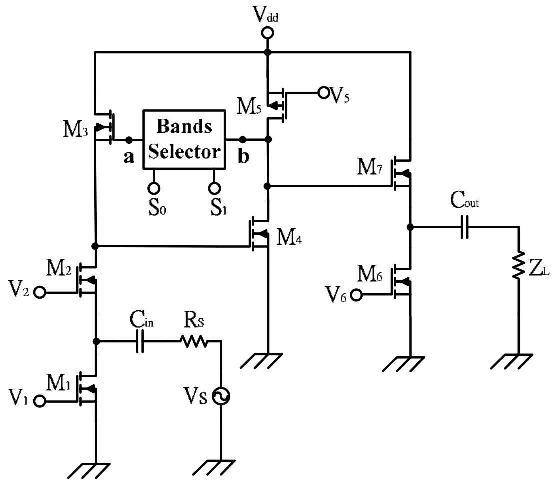


Fig. 6 Proposed RF multi-band band-pass amplifier circuit

5 Simulation Results

The proposed high-Q active inductor and the RF multi-band amplifier were designed in standard TSMC 0.18-um CMOS technology. The simulation tool of Agilent ADS (advanced design system) was applied in these designs. It is desirable that the frequency bands of the amplifier design can be selected by selecting the feedback resistance in band selector to obtain four different frequency bands. From the simulation results, the bands of the center frequency can be selected from 900MHz to 3.6GHz, which includes 900MHz, 1.8GHz, 2.4GHz, and 3.6GHz. At these frequency bands, the forward gain (S_{21}), input and output reflection coefficients are displayed in Fig. 7, 8, and 9, respectively. In the Fig. 7, the selected frequency bands of 900MHz, 1.8GHz, 2.4GHz, and 3.6GHz, with the forward gain can achieve 21.9dB, 21.9dB, 21.8, and 12.5dB, respectively. In Fig. 8 and 9, the input and output reflection coefficients are smaller than -10dB and -4dB, respectively. In Fig. 10, the noise figure (NF) at four frequency bands is less than 10dB.

Furthermore, the steady DC power dissipation of the multi-bands amplifier is about 5.27 mW from a 1.8-V supply voltage at all frequency bands for GSM, Bluetooth, and ETSIT applications.

6 Conclusion

In this study, based on the proposed high-Q active inductor with the band elector, a multi-band amplifier with steady power consumption is obtained. The amplifier can operate at four different frequency bands, which uses two bits binary controlled codes for GSM, Bluetooth, and ETSIT applications. In the amplifier, operating at the selected frequency bands, the enough forward gain, the reasonable input and output reflection coefficients, and the acceptable noise figure can be obtained. Furthermore, the constant power consumption of 5.27 mW under 1.8V DC power supply is achieved.

Acknowledgments

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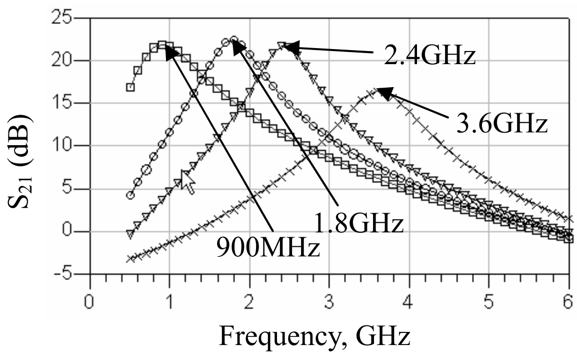

Fig. 7 Gain (S_{21}) of proposed multi-band amplifier

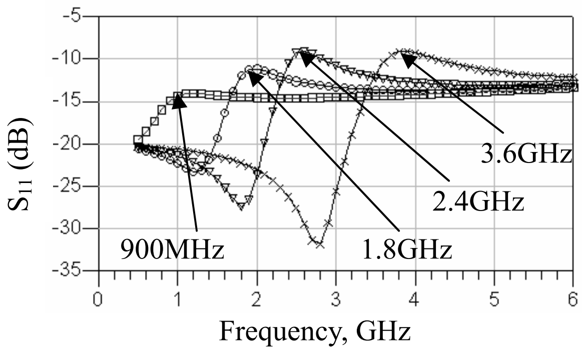

Fig. 8 Input matching (S_{11}) of proposed multi-band amplifier

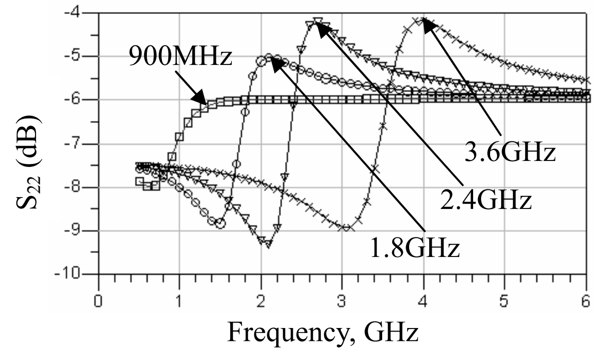

Fig. 9 Output matching (S_{22}) of proposed multi-band amplifier

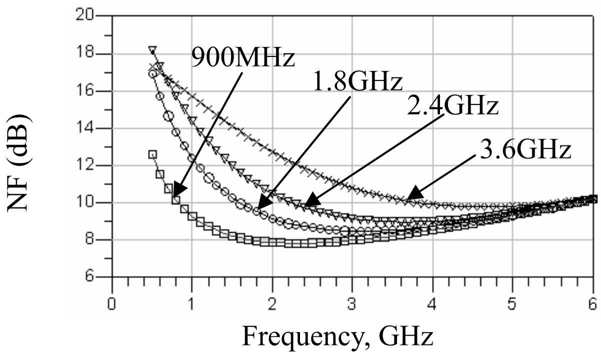

Fig. 10 Noise figure (NF) of proposed multi-band amplifier

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