A 0.8-1.5 GHz Multi-Standard WCDMA Receiver with an Inter-Stage Tunable Notch Filter

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***Abstract*—This paper proposes a multi-standard WCDMA receiver using a tunable notch filter, which consists of a multiband LNA, a multiband mixer, and an inter-stage tunable notch filter. The notch filter is used to suppress Tx leakage, and 0.8-1.5GHz (49%) of tuning range is achieved. Measured results show that the conversion gain is 31dB, IIP_2 is 45dBm, and IIP_3 is -1dBm at 0.8GHz. The power consumption is 121mW from a 1.8-V power supply. The receiver is implemented in a 0.18-μm CMOS process.**

I. Introduction

Wireless communication systems have been developed for various consumer applications, *e.g.*, GSM/UMTS/LTE, WiFi, Bluetooth, GPS, and so on. Recently, a multi-standard RFIC is required to save footprint size in mobile terminals. To cover the present wireless systems, several RFICs are required for each wireless standard, which causes increase in total chip area, power consumption, and cost. To improve this situation, the software defined radio (SDR) is proposed in [1]. The multi-standard RF front-end for all frequency bands is needed to realize the SDR.

To realize the multiband WCDMA receiver, Tx leakage is a critical problem. The present narrow-band WCDMA receivers employ an external SAW filter to suppress the leakage. However, the frequency band of SAW filter cannot be tuned, so several SAW filters would be needed for a multi-standard receiver. Thus, a SAW-less technique is indispensable to realize a multi-standard one. In [2], a feed-forward canceling technique is reported. The canceling technique using an on-chip filter is also proposed in [3]. Circuits in [2, 3] realize the high linearity. These circuits need several receivers for each band. In [4], the receiver is implemented by only linearity improvement without an inter-stage filter. However, the linearity is still a remaining issue. This paper proposes a multiband WCDMA receiver using a tunable notch filter. This receiver can work for several bands by the tunable notch filter.

II. Receiver Architecture

Fig. 1 shows the proposed receiver architecture. A wideband LNA and a wideband mixer are utilized, and an inter-stage tunable notch filter suppresses the Tx leakage. The notch filter can be tuned from 0.8 to 1.5GHz. The tuning is realized by a capacitor bank. The rejection ratio is also adjusted by a Q-enhance block.

TABLE I
Required Performance for LNA and Mixer

	Gain	Noise	IIP_3	IIP_2
LNA	18-23dB	3dB(NF)	0dBm	-
Mixer	12-15dB	$9nV/\sqrt{Hz}$	12dBm	75dBm

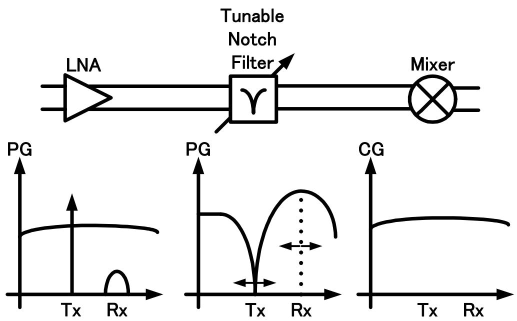


Fig. 1 Receiver architecture

A. Necessity of the Notch Filter

Since WCDMA is a FDD system, Tx signal leaks into the receiver side. The Tx leakage and CW blocker causes IM3 at Rx frequency band, and deteriorates SNR as shown in Fig. 2. IM3 is proportional to the square of the Tx leakage. The Tx leakage depends on the isolation of external duplexer, and it becomes more than -30dBm at LNA input. Table I shows requirements for multi-standard LNA and mixer [5], and the requirement for the mixer is much severe. A double balanced mixer realizes high IIP_2, however in actual, IIP_2 is limited up to 40-50dBm because of PVT variations. This paper deals with this problem by using a notch filter.

B. Distortion Calculation

Ignoring the distortion of the LNA, IIP_3 of the receiver without filters is given as follows:

$$\mathrm{IIP}_{3\,\mathrm{wofilter}} = \frac{P_{\mathrm{in}} + G_{\mathrm{Rx}} - P_{\mathrm{IM3,Mixer}}}{2} + P_{\mathrm{in}} \qquad (1)$$

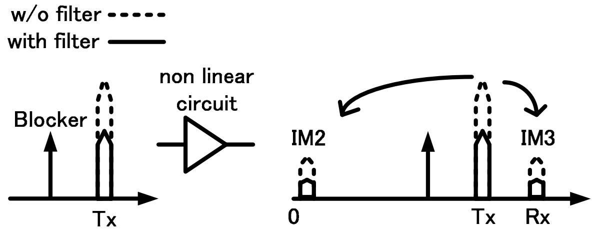


Fig. 2 Tx and IM3 suppression by notch filter

where G_{Rx} is the sum of the LNA and mixer gain at Rx frequency, and $P_{\mathrm{IM3,Mixer}}$ is the output power of the third-order distortion. When the notch filter suppresses the Tx leakage $G_{\mathrm{sup,Tx}}$ [dB], the distortion drops by $2G_{\mathrm{sup,Tx}}$ [dB]. IIP_3 of the receiver using the notch filter can be calculated as follows:

$$\mathrm{IIP}_{3\,\mathrm{wifilter}} = \frac{P_{\mathrm{in}} + \left(G_{\mathrm{Rx}} - G_{\mathrm{loss,Rx}}\right) - \left(P_{\mathrm{IM3,Mixer}} - 2G_{\mathrm{sup,Tx}}\right)}{2} + P_{\mathrm{in}} \tag{2}$$

where $G_{\mathrm{loss,Rx}}$ is the loss of the Rx frequency of the notch filter. Eq. (2) can be expressed by using $\mathrm{IIP}_{3\mathrm{wofilter}}$ as follows:

$$\mathrm{IIP}_{3\,\mathrm{wifilter}} = \mathrm{IIP}_{3\,\mathrm{wofilter}} + \left(G_{\mathrm{sup,Tx}} - \frac{G_{\mathrm{loss,Rx}}}{2}\right) \tag{3}$$

Eq. (3) shows that the notch filter can improve the receiver linearity.

III. Circuit Design

In this section, the circuits of the notch filter, low noise amplifier, and mixer are explained.

A. Notch Filter

Fig. 3 shows the circuit schematic of the tunable notch filter. The filter consists of an LC resonator and a Q enhancer. This filter uses both series and parallel resonances. The impedance of the resonator can be calculated as follows.

$$Z_{\mathrm{N}} = j\frac{\omega(C_1 + C_2) - 1/\omega L}{\omega C_1 (1/\omega L - \omega C_2)} \tag{4}$$

The zero and pole frequencies can be calculated as follows:

$$f_{\mathrm{zero}} = \frac{1}{2\pi\sqrt{L(C_1 + C_2)}} \tag{5}$$

$$f_{\mathrm{pole}} = \frac{1}{2\pi\sqrt{LC_2}} \tag{6}$$

At the pole frequency, all signals can path through the resonator. On the other hand, all signals will be suppressed at the zero frequency. The filter can suppress only the Tx leakage by adjusting f_{zero}, to the Tx frequency band, and f_{pole} to the Rx frequency band.

The voltage gain of the notch filter is calculated as follows:

$$A_{\mathrm{V}} = \frac{v_{\mathrm{out}}}{v_{\mathrm{in}}} = \frac{\left(Z_{\mathrm{N}} // R_{\mathrm{L}}\right)}{R_{\mathrm{S}} + \left(Z_{\mathrm{N}} // R_{\mathrm{L}}\right)} \tag{7}$$

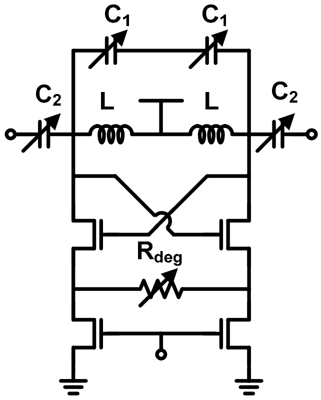
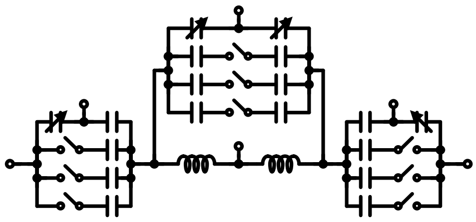
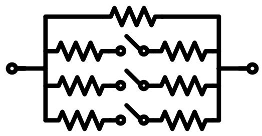


Fig. 3 Schematic of the proposed tunable notch filter



(a) C_1 and C_2



(b) R_{deg}

Fig. 4 Detail of the C_1, C_2, and R_{deg}

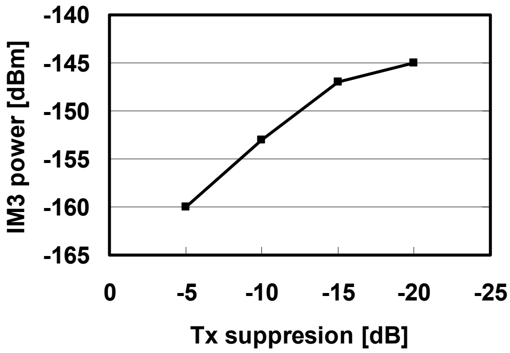


Fig. 5 Trade-off between the Tx suppression and linearity

where R_{S} is the output impedance of the low noise amplifier, Z_{N} is the impedance of the notch filter, and R_{L} is the input impedance of the mixer. With $Z_{\mathrm{N}} << R_{\mathrm{L}}$, the voltage gain at the Tx frequency band can be calculated as follows.

$$A_{\mathrm{V}} = \frac{Z_{\mathrm{N}}}{R_{\mathrm{S}} + Z_{\mathrm{N}}} \tag{8}$$

A_{V} becomes smaller as R_{S} is increasing. To suppress the Tx leakage, the output impedance of the low noise amplifier should be high.

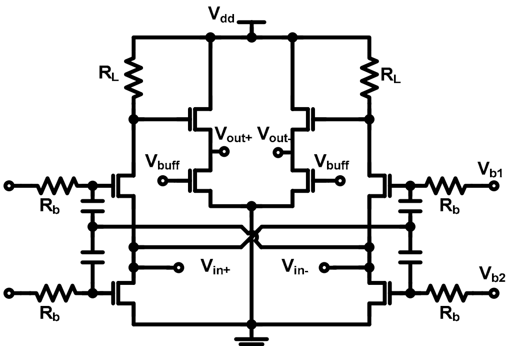


Fig. 6 Schematic of the low noise amplifier

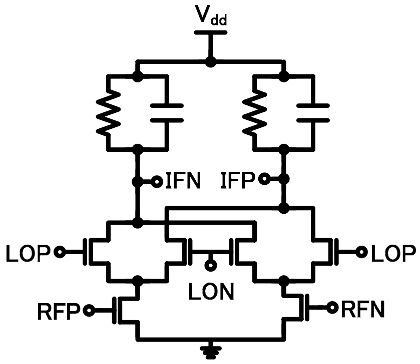


Fig. 7 Schematic of the mixer

Next, we calculate the noise of the notch filter. The output noise of the notch filter can be expressed as follows.

$$V_{\text{nout}}^2 = \left(\overline{I_{\text{nN}}^2} + \overline{I_{\text{nS}}^2}\right)\left\{\frac{R_{\text{S}}\left(Z_{\text{N}} // R_{\text{L}}\right)}{R_{\text{S}} + \left(Z_{\text{N}} // R_{\text{L}}\right)}\right\}^2 \tag{9}$$

where I_{nN} and I_{nS} represent noise current of notch filter and source resistance, respectively. Then, the noise factor of the notch filter is calculated as follows.

$$F = \frac{V_{\text{out}}^2}{A_{\text{V}}^2}\frac{1}{4kTR_{\text{S}}} = 1 + \frac{R_{\text{S}}}{4kT}\overline{I_{\text{nN}}^2} \tag{10}$$

Eqs. (8)(10) show there is trade-offs between the Tx suppression, noise figure and linearity. Fig. 5 is a simulation result of Tx suppression versus output IM3 power of the notch filter. Thus, the output impedance of the low noise amplifier is needed to be optimized depending on the required performance.

To obtain high IIP_2, a differential topology is employed. A resonator [3, 6] also has a varactor and capacitor bank as shown in Fig. 4(a), which realizes wide tuning range in capacitance. A Q-enhancement block is realized by a cross-coupled transistor pair, and it compensates the parasitic conductance as a negative resistance. To improve the linearity of the notch filter, source degeneration is employed, and it is realized by using R_{deg} as shown in Fig. 4(b). The resistance is adjusted by switches, and the quality factor can be tuned by tail current.

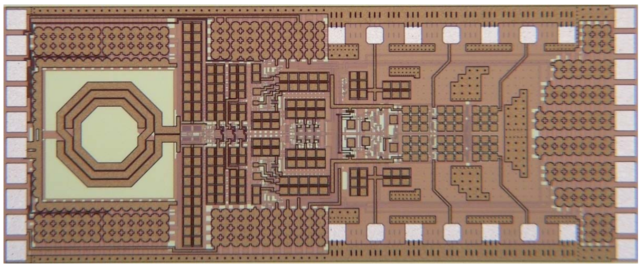


Fig. 8 Die photograph of the receiver

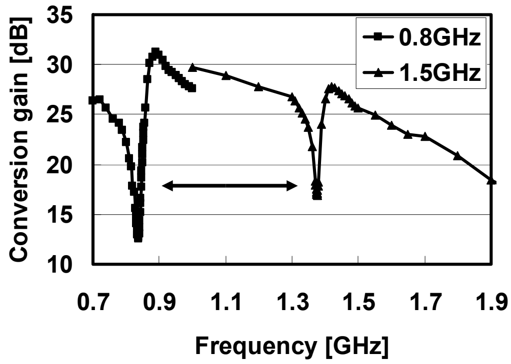


Fig. 9 Measured conversion gain

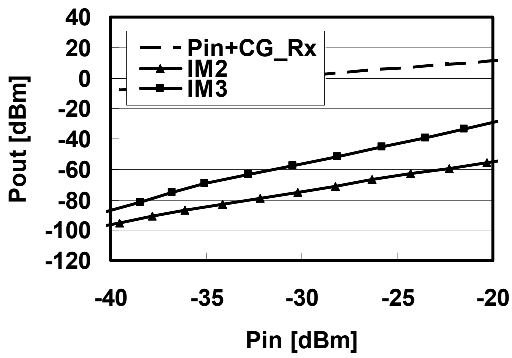


Fig. 10 Measured IM_2 and IM_3 at 0.8GHz

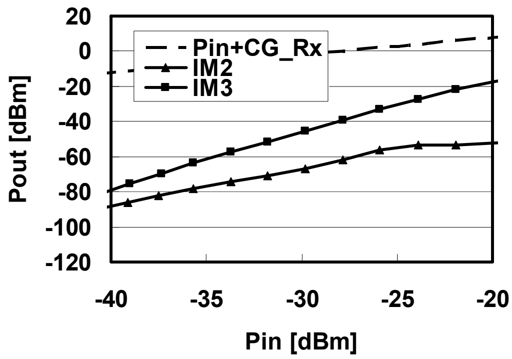


Fig. 11 Measured IM_2 and IM_3 at 1.5GHz

TABLE II

PERFORMANCE COMPARISON BETWEEN SAW-LESS WCDMA RECEIVERS

Reference	Freq[GHz]	NF[dB]	Gain[dB]	IIP_3[dBm]	IIP_2[dBm]	Pdc[mW]	Topology	band
[3]	2.1/1.9/0.8	2.8	102	-2	65	101.5-175	Notch filter	Multi band
[8]	2.1	3.1	30	-12	>39	12	LNA + mixer	narrow
[9]	2.1	5.5	30.5	5.3	58	33.6	IM3cancel	narrow
[10]	2.1	4.9	96.5	-7.4	>38.8	83.7	LNA + mixer	narrow
[11]	1.8	2.9	37	-7	63	75	Dual mode	Multiband
This Work	0.8	6*	31	-1	>45	121	Notch filter	**Tunable & Multiband**
	1.5	6.2*	28	-4	>37	114		

*simulation

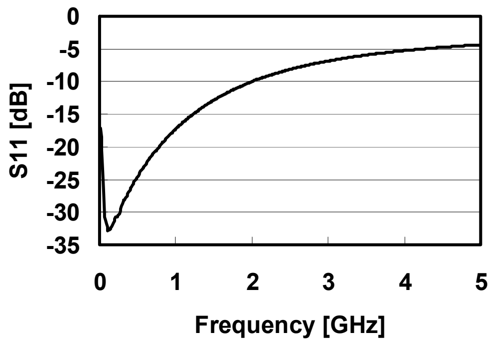


Fig. 12 S11 of the LNA

B. *Design of LNA and Mixer*

Fig. 6 shows the schematic of the low noise amplifier, which has a capacitive cross-couple [7] and source-follower buffers. The capacitive cross-couple contributes to cancel the noise generated at the common-gate transistors, and high power gain is required to minimize the influence of filter noise. The source follower buffer is connected to make the power gain high at the output node. The output impedance of the low noise amplifier is set to 80Ω to get high suppression of the Tx leakage. Fig. 7 shows the circuit schematic of the wideband mixer. The mixer employs a double balanced Gilbert cell topology for high IIP_2. The output has low pass characteristics resulting from a RC filter. The cut-off frequency is designed to be 10MHz.

IV. MEASUREMENT RESULTS

Fig.8 shows the die photograph of the fabricated tunable multi-standard receiver. The chip is implemented by using a 0.18-μm CMOS process and occupies a chip area of 2.5 mm^2. Fig.9 shows the measured conversion gain at 0.8 and 1.5 GHz. Figs. 10 and 11 show the output power, IM2 power and IM3 power versus input power at 0.8GHz and 1.5GHz, respectively. In the measured results, IIP_2 is 45dBm, and IIP_3 is -1dBm at 0.8 GHz. The measured result of S_{11} of the LNA is shown in Fig. 12. The simulated NF is 6-to-6.2 dB around the entire frequency range. The total power consumption is 121mW. Table II shows a performance comparison among SAW-less WCDMA receivers.

V. CONCLUSIONS

In this paper, the multiband WCDMA receiver with a tunable notch filter is proposed to achieve the CMOS one-chip multiband receiver. The tunable notch filter realizes a 49% tuning range. A 31dB conversion gain, 45dBm IIP_2, and -1dBm IIP_3 is realized by the multi-standard receiver integrating the proposed tunable notch filter.

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