A Triple-Band Transceiver Module for 2.3/2.5/3.5 GHz Mobile WiMAX Applications

Yeonsu Jang*, Sungchan Kang*, Young-Eil Kim, Jongryul Lee***, Jae-Hoon Yi****, and Kukjin Chun***

***Abstract*—A triple-band transceiver module for 2.3/2.5/3.5 GHz mobile WiMAX, IEEE 802.16e, applications is introduced. The suggested transceiver module consists of RFIC, reconfigurable/multi-resonance MIMO antenna, embedded PCB, mobile WiMAX base band, memory and channel selection front-end module. The RFIC is fabricated in 0.13μm RF CMOS process and has 3.5 dB noise figure(NF) of receiver and 1 dBm maximum power of transmitter with 68-pin QFN package, 8 × 8 mm^2 area. The area reduction of transceiver module is achieved by using embedded PCB which decreases area by 9% of the area of transceiver module with normal PCB. The developed triple-band mobile WiMAX transceiver module is tested by performing radio conformance test(RCT) and measuring carrier to interference plus noise ratio (CINR) and received signal strength indication (RSSI) in each 2.3/2.5/3.5 GHz frequency.**

***Index Terms*—Transceiver module, triple-Band, mobile WiMAX, IEEE 802.16e, RFIC, embedded PCB**

I. INTRODUCTION

As communication environment changes from wired to wireless, handling high data, such as music, video and multimedia, and multimode multiband wireless communication with mobile device in a large space are required. Mobile WiMAX, IEEE 802.16e, is an emerging system for handheld mobile application. The high data rates over a broad range are achieved by orthogonal frequency division multiple access(OFDMA) which has high peak-to-average ratio and needs high signal to noise ratio. Mobile WiMAX adopts multi-input multi-output (MIMO) for broadband wireless communication. Mobile WiMAX is spreading from laptop computer to smartphones and those mobile devices need compact design and low voltage operation [1-3].

The design and implementation of triple-band transceiver module are described in this paper. The RFIC, reconfigurable/multi-resonance MIMO antenna and embedded PCB are developed and gathered to form triple-band transceiver module with channel selection front-end module and modem.

II. ARCHITECTURE

Fig. 1 shows the architecture of the proposed triple-band transceiver module which consists of RFIC separated from 2 GHz to 5 GHz, reconfigurable/multi-resonance MIMO antenna, embedded PCB, mobile WiMAX base band, memory and channel selection front-end module[4]. The input and output ports of the suggested RFIC are separated by each band, 2 GHz band, 3 GHz band and 5 GHz band. This structure is called multi-chain structure. The triple-band mobile WiMAX RFIC and baseband modem are controlled by driver which is developed for setting up serial peripheral interface(SPI) table, RX/TX gain table, RX/TX mode

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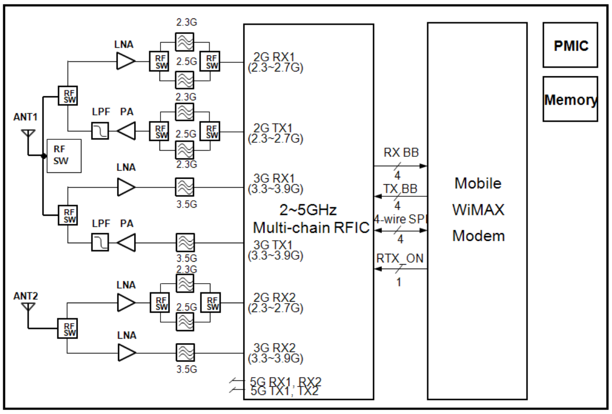

Fig. 1. Triple band transceiver module bock diagram.

change, configuration, RFIC filter and initial DC calibration.

III. Design

1. RFIC

The designed RFIC consists of two transmitters, two receivers, voltage-controlled oscillator(VCO), phase-locked loop(PLL), and local oscillation(LO) generation and distribution block as in Fig. 2.

The suggested RFIC is designed for covering 2/3/5 GHz bands. However, the 5 GHz band is out of frequency bands of mobile WiMAX and therefore the 5 GHz band is not covered in this paper. The one transmitter and two receivers of RFIC, except the second transmitter (TX2), are used for triple-band transceiver module as in Fig. 1.

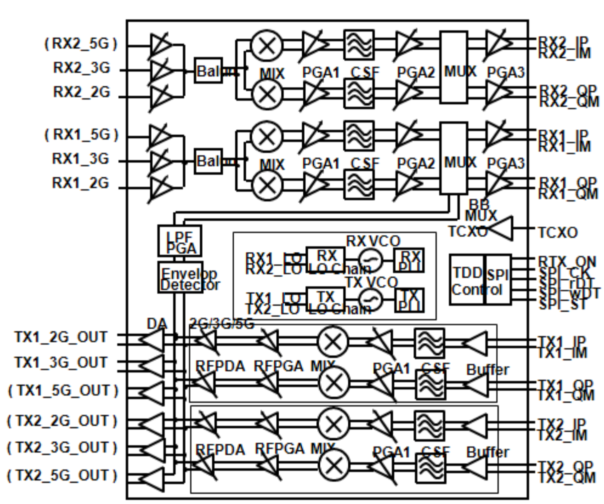

Fig. 2. Block diagram of RFIC.

The receiver consists of low noise amplifier(LNA), on-chip active balun, mixer, programmable gain amplifier(PGA), output buffer, and channel select filter(CSF). The transmitter consists of active Gilbert mixer, RF PGA, drive amplifier(DA), input buffer, CSF, and PGA.

The single-ended inputs are adopted for reducing external component, balun, in receiver. However, outputs of transmitter are differential and balun is used.

In 2/3/5 GHz bands, three VCOs are used for each band and each VCO is oscillating in twice higher frequency than each carrier frequency. The LO signal is generated at twice higher frequency than carrier frequency by VCO/PLL. Then the VCO signal is divided by two and supplied to receiver and transmitter. The fractional-N PLL structure is used for generation of precise frequency with 3rd order multi-stage noise shaping(MASH) structure [5].

Generally, a single VCO and a single PLL can cover RFIC for mobile WiMAX application because mobile WiMAX supports time division duplexing(TDD) that the frequency of receiver and transmitter is equal. However, the suggested RFIC in this paper is not only for 2 x 2 MIMO operations but also for operations of different frequency between the RX1/TX1 channel and the RX2/TX2 channel, double VCOs and double PLLs are placed in the RFIC.

When high data is transmitted by transmitter, the transmission speed can be expected by EVM. The first major effect on EVM is integrated phase noise of VCO/PLL. The second major effect on EVM is DC and AC mismatch of quadrature signal inputs, which are TX_IP, TX_IM, TX_QP and TX_QM, of transmitter mixer at signal path of transmitter. The DC and AC mismatch also determine LO leakage and image rejection ratio(IRR) performance at transmitter output and the envelop detector is used for calibration in modem. The output of envelop detector is transmitted by receiver MUX to input of ADC in modem and LO leakage and IRR performance can be measured and calibrated.

The one of the important challenges in RFIC for multimode multiband applications is design of wideband LNA and mixer [3-5]. The wideband LNA is designed by cascode amplifier structure with shunt feedback as in Fig. 3. The signal loss by following passive mixer is compensated and output of LNA is changed from single

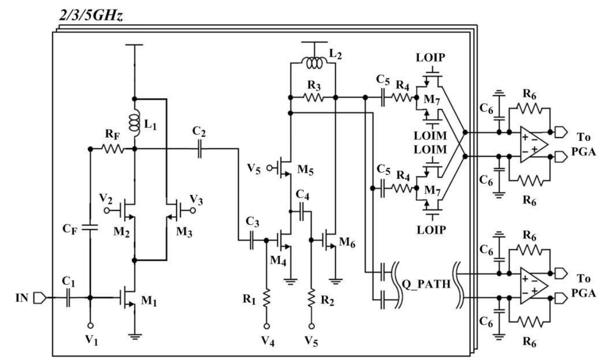

Fig. 3. Simplified schematic of designed RF front end with LNA.

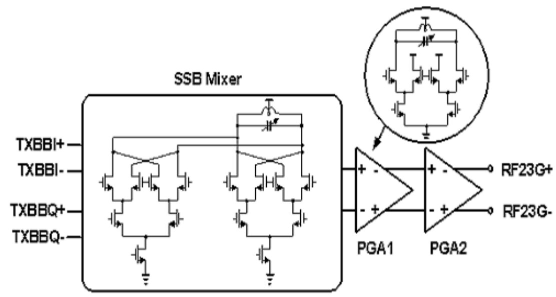

Fig. 4. Wideband mixer and RF PGA in transmitter.

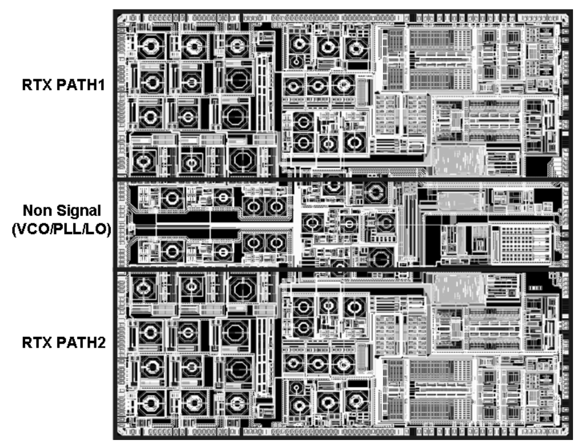

Fig. 5. Layout of RFIC for triple-band transceiver module.

to differential by the on-chip active balun. A 1/f noise of receiver is reduced and IIP3 of receiver is maximized by down-conversion mixer, which consists of passive quadrature mixers with transimpedance amplifier(TIA). A noise current from TIA because of finite output resistance of LO switches, M7, is prevented by degeneration resistor, R4, and then NF of passive mixer is decreased [5].

The cascode amplifier structure is suitable for wideband amplifier by reducing Miller effect at the input. Furthermore, shunt feedback by series connected resistor, R_F, and capacitor, C_F, achieves wideband input matching. The impedance of input and output is 50 ohm. An inductor, L_1, is used as load of LNA for high gain. However, at mid gain mode, gain can be decreased and NF can be increased by turning on MOS transistor, M_3, which controls current. The each input of LNA is separated by target band frequencies, 2/3/5 GHz, for multimode, multiband operation and has four gain modes which are high gain, mid gain, bypass and loss. The input transistor M_1 is not used in bypass gain mode and in loss gain mode that linearity is improved because LNA has no gain and no power consumption. Bypass gain mode and loss gain mode are separated from high gain mode for high IIP3 and P1 dB.

The schematic of mixer and RF PGA circuit in transmitter is shown in Fig. 4 [4]. The quadrature analog signal from modem is converted by baseband input buffer and channel filter, to four baseband signals which are operating signals in mixer. The voltage signal from input is changed to analog current by transconductance circuit in active Gilbert mixer. The suggested structure, which receives four input from baseband for mixer and four quadrature LO signal for LO switch, is called single-side band(SSB) mixing structure.

The differential outputs of mixer are connected to two stages RF PGA, then amplifying or attenuating the differential signal by over 60 dB gain ranges in 6 dB steps to achieve the dynamic range requirement.

Fig. 5 presents layout of the designed RFIC for mobile WiMAX triple-band application.

2. Embedded PCB

The advantage of embedded PCB is reducing area by inserting passive or active devices in PCB. Moreover, ground plane and transmission line can be implemented by redistribution wiring system. The area of triple band mobile WiMAX system is reduced by using 8-layer embedded PCB which has packaged discrete passive devices. The passive elements, 54 capacitors and 39 resistors, are embedded in PCB for triple-band mobile WiMAX transceiver module [6]. The embedded passives are not used for matching circuit but used for power and bypass circuit because tuning should be done in matching circuit after modularization.

IV. RESULTS

1. RFIC

The RFIC is fabricated in 0.13 μm RF CMOS process and is measured in 2 GHz band and 3GHz band on the evaluation board at the nominal supply voltage of 1.2 V and 1.8 V in room temperature as in Fig. 6. The frequencies for measurement are 2.5 GHz and 3.5 GHz. And the wanted signal power is measured in proper input power depending on gain mode. Those are -100 dBm in maximum gain mode and -30 dBm in minimum gain mode. The sensitivity can be measured with transceiver module, which is dongle type consists of RFIC, MIMO antenna, embedded PCB, mobile WiMAX base band, memory and channel selection front-end module and will be mentioned later in results section.

The Table 1 summarizes receiver performance of RFIC. When transmission channel has 10 MHz channel bandwidth, the adjacent channel is apart from transmission channel of 10 MHz and the alternate channel is apart from transmission channel of 20 MHz. The measured receiver NF is 2.9 dB and 3.8 dB for 2/3 GHz bands, respectively. The receiver NF of developed RFIC is better than that of [5] by 0.5 dB.

The Table 2 summarizes transmitter performance of RFIC. The power ratio of transmission channel to adjacent channel is the adjacent channel power ratio. And the power ratio of transmission channel to alternate channel is the alternate channel power ratio.

The measured transmitter EVM is -34 dB and -34 dB for 2/3 GHz bands at 2 dBm and -35 dB and -35 dB for 2/3 GHz bands at -10 dBm, respectively. The transmitter EVM of the developed RFIC is better than that of [5] by

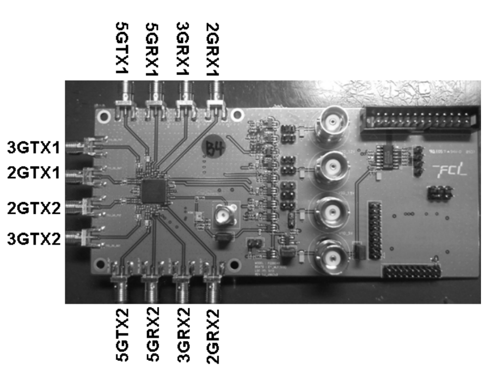

Fig. 6. Evaluation board of RFIC.

Table 1. RFIC RX performance summary

Process	Unit	0.13 μm CMOS	
Frequency	GHz	2.25 ~ 3.0	3.3 ~ 4.2
NF @ Max gain mode	dB	2.9	3.8
Gain Range	dB	20 ~ 91	20 ~ 88
IIP3 @ LNA Low gain mode	dBm	14	14
Filter cutoff frequency	MHz	1.75 ~ 18.3	1.75 ~ 18.3
Gain control step	dB	1	1
Adjacent ch rejection	dBc	> 30	> 30
Alternate ch rejection	dBc	> 50	> 50
EVM @-50 dBm, 64 QAM	dB	-36	-32

Table 2. RFIC TX performance summary

Process	Unit	0.13 μm CMOS	
Frequency	GHz	2.25 ~ 3.0	3.3 ~ 4.2
Dynamic Range	dBm	-52 ~ 2	-52 ~ 2
Adjacent ch power ratio	dBc	> 20	> 20
Alternate ch power ratio	dBc	> 40	> 40
Spectral flatness	dB	+/- 1 dB	+/- 1 dB
Output level step	dB	0.5	0.5
EVM @ 2 dBm, @ -10 dBm	dB	-34 -35	-34 -35

1 dB at 2 GHz band. The developed RFIC is designed by multi-chain covering each frequency band, whereas [5] has design of RF front-end using only a single-ended RF pin covering the multi frequency bands.

The performance of RFICs is compared in Table 3 [1, 7-9]. The power consumption of 2 x 2 MIMO mode of developed RFIC is not twice but about 1.5 times higher than that of SISO mode because single PLL/VCO are used in 2 x 2 MIMO operation.

The performance of this work is comparable to those of state-of-the-arts. The receiver achieves a NF of less than 3.5 dB and a dynamic range of 90 dB in 1 dB steps over an operational frequency range of 2.3~2.7 GHz and 3.3~3.8 GHz. The transmitter achieves a maximum power of 1 dBm and the dynamic range of 78 dB in 1 dB steps over an operational frequency range of 2.3~2.7 GHz and 3.3~3.8 GHz.

The operating frequency of the developed RFIC by FCI is wider than that of NXP RFIC. Moreover, power consumption and supply voltage of this work are lower than those of NXP RFIC. The transmitter dynamic range, receiver NF and transmitter power of this work are better than those of Infineon RFIC. The power consumption of this work is higher than that of Infineon RFIC. However, supply voltage of developed RFIC is lower than that of

Table 3. Comparison of RFIC

	Unit	NXP[1]	Infineon [7]	Fujitsu[8]	Marvell[9]	This Work (FCI)
Frequency	GHz	2.345 (2.3~2.7)	2.5/3.5 (2.3 ~ 2.7, 3.3 ~ 3.9)	2.3/2.5/3.5 (2.3~2.4, 2.5~2.7, 3.4~3.6)	2.5/3.5 (2.3 ~ 2.7, 3.3 ~ 3.8)	2.3/2.5/3.5 (2.3 ~ 2.7, 3.3 ~ 3.8)
Process	-	0.25 μm SiGe BiCMOS	0.13 μm CMOS	90 nm CMOS	90 nm CMOS	0.13 μm CMOS
MIMO	-	2 RX, 2 TX	2 RX, 1 TX	2 RX, 1 TX	2 RX, 2 TX	2 RX, 1 TX
Area, type	mm^2	6 x 6, HVQFN	N.A.	5 x 4.5, die	12.4, die	5.9 x 6.58, die 8 x 8, 68-pin QFN
RX NF	dB	2.3	3.4, 4	1.5 simulation	3.5	3.5
TX Max. Power	dBm	2.5	-3, -2	-	-	1
Number of RF IN and OUT	-	-	RX:4, TX:2	RX:4, TX:2	RX:2, TX:2	RX:4, TX:2
RX Power Consumption	mW	182 (SISO)	62.5~102 (SISO)	290~320 (MIMO)	165~190 (SISO)	108~162 (SISO)
TX Power Consumption	mW	288.4 (SISO)	70~112.5 (SISO)	290~330 (MIMO)	195~215 (SISO)	132~198 (SISO)
RX DR TX DR	dB	97, 1 step 75, 1 step	N.A. 45, 1 step	N.A. 56	115 78	90, 1 step 78, 1 step
Supply	V	2.8	2.5, 1.5	2.9, 1.2	1.8, 1.2	1.8, 1.2

Infineon RFIC. The transmitter dynamic range of this work is better than that of RFIC which is developed by Fujitsu and supply voltage of developed RFIC is lower than that of Fujitsu RFIC. The area of this work is larger than that of Marvell RFIC while other performances are comparable and power consumption is lower than that of Marvell RFIC.

2. Triple-Band Mobile WiMAX Transceiver Module

The mobile WiMAX triple-band transceiver module is developed as mobile USB type on the 8-layer embedded PCB as in Fig. 7 [6].

The reconfigurable multi-resonance MIMO antenna is mounted on board and radio conformance test(RCT) of the developed triple-band mobile WiMAX transceiver module is done with mobile WiMAX test set(E6651A, Agilent Technologies). In addition, WiMAX wireless test manager software(N6422C, Agilent Technologies) running on a computer as in Fig. 8.

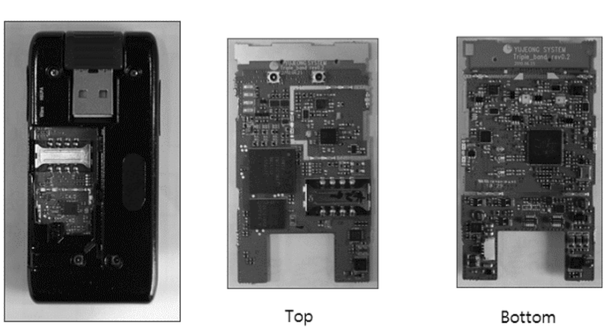

Fig. 7. Developed triple-band mobile WiMAX transceiver module.

Moreover, the developed transceiver module is tested with frequency converter board at 2.3 GHz band, SK WiBro and the connection of the Internet is successful in 2/3 GHz bands [10]. The receiver sensitivity of triple-band transceiver module is summarized in Fig. 9.

The carrier to interference noise ratio(CINR) and received signal strength indication(RSSI) shows that

Fig. 8. Diagram of triple-band mobile WiMAX transceiver module Test.

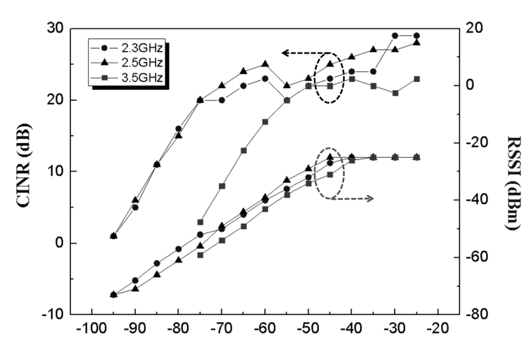

Fig. 9. Receiver sensitivity of triple-band transceiver module.

developed transceiver module is suitable for triple-band mobile WiMAX application.

V. CONCLUSIONS

The triple-band mobile WiMAX transceiver module with RFIC, reconfigurable/multi-resonance MIMO antenna, embedded PCB, mobile WiMAX base band, memory and channel selection front-end module has been presented. The RCT and receiver sensitivity test show that the transceiver module is suitable for 2.3/2.5/3.5 GHz mobile WiMAX application.

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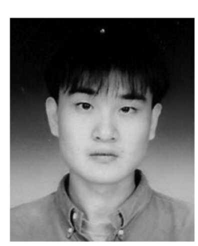

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