Design and Fabrication of a Broadband RF Module for 2.4GHz Band Applications

2.4GHz 대역에서의 응용을 위한 광대역 RF 모듈 설계 및 제작

강봉수[*], 양두영[**]
제주대학교 통신공학과[*], 제주대학교 통신컴퓨터공학부[**]

Bong-Soo Kang(yagagi@unitel.co.kr)[*], Doo-Yeong Yang(yeongyd@cheju.ac.kr)[**]

요약

본 논문에서는 2.4GHz 대역에서의 응용을 위한 광대역 RF 모듈을 설계하고 제작하였다. 무선 주파 신호를 중간 주파수로 변환하기 위한 RF 모듈은 3단 증폭기로 이루어진 저잡음 증폭기(LNA), 단종단 게이트 믹서, 정합 회로, 헤어핀 라인 대역 통과 필터, 체비셰프 저역 통과 필터로 구성하였다. 저잡음 증폭기는 높은 이득과 안정도를 갖도록 설계하였으며, 단종단 게이트 믹서는 높은 변환이득과 넓은 동작 영역을 갖도록 설계하였다. 광대역 RF 모듈의 해석에서는 복합화된 하모닉 밸런스드 기법을 사용하여 RF 모듈의 동작 특성을 해석하였다. 설계된 RF 모듈은 55.2dB의 변환이득, 1.54dB의 낮은 잡음 특성, -120~-60dBm의 넓은 RF 전력 동작 영역, -60dBm의 낮은 고조파 성분 그리고 RF, IF, LO 포트 간에 우수한 분리 특성을 갖는다.

■ 중심어 : | 광대역 RF 모듈 | 저잡음 증폭기 | 단종단 게이트 믹서 | 2.4GHZ 대역 응용 |

Abstract

In this paper, a broadband RF module is designed and tested for 2.4GHz band applications. The RF module is composed of a low noise amplifier (LNA) with a three stage amplifier, a single ended gate mixer, matching circuits, a hairpin line band pass filter and a Chebyshev low pass filter to convert the radio frequency (RF) into the intermediate frequency (IF). The LNA has a high gain and stability, and the single ended gate mixer has a high conversion gain and wide dynamic range. In the analysis of the broadband RF module, the composite harmonic balance technique is used to analyze the operating characteristics of an RF module circuit. The RF module has a 55.2dB conversion gain with a 1.54dB low noise figure, -120~-60dBm wide RF power dynamic range, -60dBm low harmonic spectrum and a good isolation factor among the RF, IF, and local oscillator (LO) ports.

■ keyword : | Broadband RF Module | Low Noise Amplifier | Single-ended Gate Mixer | | 2.4GHz Band Applications |

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I. INTRODUCTION

A broadband RF module for the 2.4GHz band communication plays a role as a linker of the wireless communication loops such as a wireless broadband internet service(WiBro) and an industrial scientific and medical(ISM) band including a wireless local area network(WLAN), Bluetooth and radio frequency identification(RFID) system.

The performance and the sensitivity of a receiver in the 2.4GHz applications are largely dependent on an RF module at the front end of the wireless communication system. The RF module converts the input radio frequency(RF) into the intermediate frequency(IF) to extract the original signal from the modulated RF signal. In general, an RF module consists of a preamplifier, a mixer circuits, a local oscillator(LO) and an IF amplifier[1]. The RF module developed by Kazuo consists of a low noise HEMT preamplifier, a novel structure mixer, a GaAs FET oscillator and an IF amplifier. He also uses a dielectric resonator to stabilize his converter's performance[2]. Reference[3] shows the design of a low power GaAs HFET RF module with a monolithic LNA and a mixer for the wireless portable application.

A good RF module should have a low noise figure, high conversion gain, wide dynamic range and good isolation among the RF, IF, and LO ports. The RF module in this paper is composed of a low noise amplifier(LNA) and a single ended gate mixer circuit, which includes the hairpin - line band pass filter(BPF) and Chebyshev low pass filter(LPF).

With the current trend to miniaturized wireless devices, LNAs are often fabricated as monolithic integrated circuits, usually referred to as MMIC (monolithic microwave integrated circuit). High volume applications such as cell phones call for even higher integration in the RF front end. Thus the LNA is integrated together with the mixer, local oscillator, and sometimes even parts of the transmitter or the antenna[4]. But depending on the IC technology, monolithic integration places several additional constraints on the LNA design. The available range of component values may be limited, in particular the maximum inductance and capacitance values are often smaller than required. For applications with low volume where monolithic integration is not cost effective, LNAs can be built as hybrid circuits, sometimes called MIC (microwave integrated circuit)[5].

The optimum characteristics of a LNA should include a minimum noise level and maximum power gain. The LNA design can be achieved by using a combination of the following methods: matching network, balanced amplifiers and feedback circuits [6-10].

In this paper, the broadband and high power gain LNA with three stage amplifier using the source series feedback circuit is designed for the RF module in 2.4GHz band applications. In the design of the three stage amplifier in the LNA, the 1st and 2nd stage of amplifier use the MESFET transistors having a low noise figure, and the 3rd stage amplifier uses a high power output MMIC device. Even though the MMIC transistor has a slightly high noise figure, it is used as the 3rd stage amplifier since the total noise figure of the LNA is basically determined by the noise figure of the 1st and 2nd stage of the LNA. In order to improve the noise figure and voltage standing wave ratio(VSWR) of the LNA, we carefully select the points of reflection coefficient to achieve an optimum noise figure, a low VSWR, and a high power gain of the amplifier, simultaneously.

The MESFET mixer utilizes the non linearity in trans conductance, capacitance in gate source and conductance in drain source of the MESFET to generate an IF output spectrum, consisting of the sum and difference signal of RF and LO signals. In the non linearity analysis of the GaAs MESFET mixer, Serenade simulator[11] with the harmonic balance technique[12] is used to analyze the operating characteristics of the mixer circuits. To obtain a high conversion gain, wide dynamic range and good isolation factor among the RF, IF and LO ports, this mixer is composed of a hairpin line BPF, a GaAs MESFET, a Chebyshev LPF, and two input, output matching circuits. A general mixer has an IF amplifier at the IF output port, but this mixer does not need an IF amplifier since it has a high conversion gain itself.

This paper presents a composite technique for designing the broadband RF module. In addition, the designing procedures of the broadband LNA and the single ended gate mixer with an excellent performance are briefly described. With these techniques, the RF module is designed and tested for the 2.4GHz frequency range from 2.2GHz to 2.6GHz. The remainder of this paper is organized as follows. In section Ⅱ, the design theory of the broadband RF module is explained. In section Ⅲ, the experimental results are presented and compare with theoretical results. And the conclusion is given in section Ⅳ.

Ⅱ. DESIGN OF THE BROADBAND RF MODULE

The RF module has an LNA, a hairpin line BPF, a mixer circuit, a Chebyshev LPF and RF, LO and IF ports. Generally, the first consideration of the process in the designing of an RF module with a given specification is the choice of an appropriate MESFET. The selection should be based on the suppression of the third order inter modulation distortion(IMD)[13]. The high conversion gain and the stability of the output signal are based on the function of the LO signal. However, it's very difficult to achieve the high conversion gain and the maximum isolation among the RF, LO and IF ports, simultaneously.

In an RF module, the RF signal has a carrier frequency of fc, and the LO signal has a pure sinusoidal frequency of fo. The RF and LO signals are supplied to the LNA and the gate of the mixer. The amplified RF signal by the LNA and LO signal are mixed together to produce the IF signal at the drain of the mixer. The mixer produces a sum of the frequency component (fc+fo), and the difference frequency component (fc-fo), with the product of the LO and RF sinusoidal signals. The difference frequencies can be selected by the IF LPF at the end of the RF module, and becomes an IF signal. This method using an LPF has much better sensitivity and noise characteristics than the direct detection scheme[14].

However, the RF module has the conversion loss and produces a great number of spurious harmonic frequency components because of a non linearity in the characteristic of a mixer. Spurious harmonics can be filtered out by a BPF, and the design procedure of the BPF is described in [15]. The conversion loss of the mixer is strongly affected by the power level of the LO signal. The minimum conversion loss usually occurs at the low LO power level between 0dBm and 10dBm. The low LO signal power has been used to reduce the conversion loss and the low noise figure.

1. Broadband low noise amplifier design

A MESFET selection for the designing of a multi stage LNA should be based on the requirement of the characteristics in each stage of the LNA; a low noise figure, high power gain and stability of output power. It is very important to have a very low noise figure for an amplifier in the 1st stage in a multistage LNA using GaAs MESFET device, since the noise figure of the 1st stage amplifier plays an important role in the total noise figure of the overall LNA. Therefore, a premium low noise transistor is used in the 1st and 2nd stage amplifier. The 1st and 2nd stage of the amplifier are GaAs MESFETs (EPA060B-70) which have a low noise figure (0.5dB) and a high gain up to 2GHz. In the 3rd stage, even though the MMIC transistor has a slightly higher noise figure, a high power output in a wide frequency band MMIC(AH1) is used.

A transistor typically has a larger noise figure as the frequency increases. In order to have a low noise figure and a low VSWR, an important step during amplifier design is drawing a stability circle for the transistor, and selecting the proper point for the desired reflection coefficient. The source series feedback circuit using a lossless micro strip line is applied to select the point with a low reflection coefficient in the stability circle. The source series feedback circuits are used to improve the flatness of gain and the stability condition in a broadband design.

[Fig. 1] shows the LNA circuit design with the 3 stage amplifier. It consists of input and output matching circuits, the 1st, 2nd and 3rd stage transistors, two source series feedback circuits, and two inter stage matching circuits between the transistors. The input/output matching circuits are used to match the LNA to the input and output ports, and the source series feedback circuits are used to make the transistor stable. In addition, the inter stage matching circuits have been used to achieve a flat gain over the broad frequency band. Since the stability circles of a GaAs MESFET (EPA060B-70) are potentially unstable before the source series feedback, it was hard to select the design point among the power gain circle, the noise figure circle, and the operating power gain circle. After the feedback, the centers of the noise figure circles and power gain circles are concentrated in the specific area and located in the unconditionally stable region. Therefore, it allowed us to locate the amplifier design point at the concentrated area of circles, and to find the reflection coefficient of the transistor to be matched to that of the input and output ports using the matching circuit. The source series feedback circuit is constructed between the

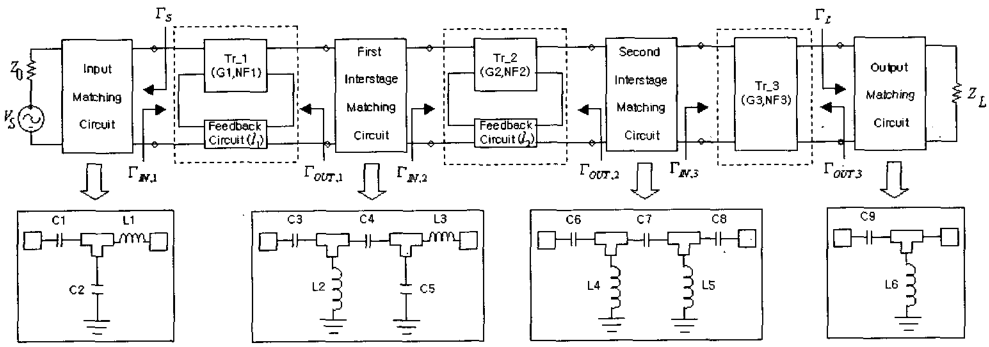

Fig. 1. Circuit diagram of LNA with three-stage amplifier

source port of the transistor(EPA060B-70) and the conducting ground, as shown in [Fig. 1]. The optimum length of the source series feedback of the micro strip line is 0.0125 wavelength(λ) at the center frequency of 2.4GHz.

The available and operating power gains of a transistor are defined and their relationships among these parameters are explained[4]. The available power gain is a function of the source reflection coefficient (Γ_S) at the input port and of the scattering parameters of a transistor. The operating power gain is a function of the load reflection coefficient(Γ_L) at the output port and of the scattering parameters of a transistor.

The input reflection coefficient(Γ_{IN}) will be decided by Γ_L, and the output reflection coefficient (Γ_{OUT}) will be decided by Γ_S. The value of Γ_S and Γ_L should not be too close in their respective stability circles, because oscillation might occur due to the component variation. Since the value of Γ_S affects the output power and the voltage standing wave ratio(VSWR), the value of Γ_S should be selected close to the center of the Smith Chart to have a small input VSWR. In addition, to reduce the noise level of the 1st stage amplifier, reflection coefficients are selected from the 0.5dB noise circle and the 16.5dB gain circle as $\Gamma_S = 0.16\angle 61.5^\circ$ and $\Gamma_{OUT,1} = 0.57\angle -23.89^\circ$. Therefore, the design specification of the available power gain and the noise figure level of the EPA060B-70 with the source series feedback are 16.5dB and 0.5dB, respectively.

The broadband amplifier design contains the double T-type matching circuit to achieve a constant gain over the operating frequency range of the amplifier. In this paper, there are double T-type matching circuits in the inter stage matching between the 1st and 2nd stage and between the 2nd and 3rd stage of the amplifier. At the 2nd stage amplifier, $\Gamma_{IN,2} = 0.37\angle -62.16^\circ$ and $\Gamma_{OUT,2} = 0.57\angle -17.91^\circ$ are used.

Table 1. Design parameters of the three stage LNA

Element	Design value	Element	Design value	Element	Design value
C_1	39pF	C_7	39pF	L_4	3.9nH
C_2	0.5pF	C_8	1.5pF	L_5	2.2nH
C_3	39pF	C_9	2.5pF	L_6	3.3nH
C_4	39pF	L_1	3.3nH	l_1	2mm
C_5	0.5pF	L_2	3.9nH	l_2	2mm
C_6	39pF	L_3	3.3nH		

Because the noise figure of the LNA is mainly decided by the noise figures of the 1st and 2nd stage of the amplifier, the input and output reflection coefficients of the 3rd stage are selected on the high power gain circles and on the slightly higher noise circle of the 3rd stage amplifier of the LNA. Therefore, the input and output reflection coefficients of the output stage (3rd stage) are selected as $\Gamma_{IN,3} = 0.52\angle -175.68^\circ$ and $\Gamma_{OUT,3} = 0.05\angle -94.02^\circ$ with the 13dB power gain and 2.5dB noise figure level. According to the relationship of the load reflection coefficient, $\Gamma_L = \Gamma^*_{OUT,3}$, the load matching circuit of the 3rd stage is designed to have a maximum transducer power gain. The parameters of the LNA circuit in [Fig. 1] are shown in [Table 1].

2. The single-ended gate mixer module design

In a mixer, it's very difficult to achieve a high conversion gain and maximum isolation among the RF, LO and IF ports simultaneously. To design the mixer, a MESFET has been carefully selected, and matching circuits and the filters have been added. The circuit diagram of the single ended gate mixer module is shown in [Fig. 2].

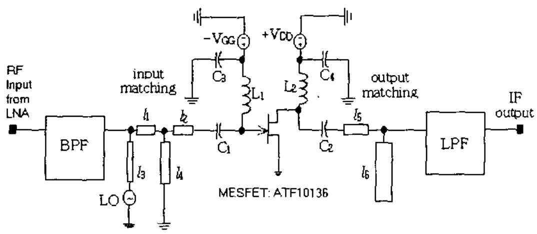

Fig. 2. Circuit diagram of the single-ended gate mixer module

The mixer has RF, LO and IF ports, matching circuits located between the RF and LO input ports and between the output port of the transistor and the input port of the IF filter. It also has a BPF, an LPF and a bias circuit at the gate and drain of the transistor. In addition, bypass capacitors and choke inductors are used.

The gate mixer uses the low voltage current characteristics in the pinch off region for making frequency conversions due to the non linearity of the Schottky barrier between the gate and the source of the transistor. The operating bias conditions of the MESFET(ATF10136) in the pinch off region are $V_{GG} = 1\,V$, $I_D - 1.28mA$, and $V_{DD} = 3\,V$. The RF signal frequency is 2.4GHz. The LO frequency is 2.26GHz, and the IF frequency is 140MHz.

Two impedance matching circuits have been used at the gate and drain of the transistor. Stub impedance matching circuits at the input and output ports help the MESFET develop a very good signal sensitivity and a low noise figure in the RF, LO and IF ports. In addition, the matching circuit has been designed to create good isolation among the RF, LO and IF ports. The input 50Ω stub matching circuit is optimized at 2dBm LO power to minimize the distortion and the conversion loss, and to transfer the RF signal to the input port of the transistor effectively. The input reflection coefficients of the MESFET(ATF10136) is, $\Gamma_{IN} = 0.48\angle -125.14^{\circ}$ and the output reflection coefficient is $\Gamma_{OUT} = 0.66\angle -1.93^{\circ}$. The input impedance matching stub circuit matches to 50Ω of the RF input port, and the output matching stub circuit matches to 50Ω of the LPF input port. The conversion gain of the mixer will be the maximum value when the source impedance is matched to the impedance of Γ_{IN}^{*}, and the load impedance is matched to Γ_{OUT}^{*}. The parameters of the stub matching circuits of the bypass capacitors and the chokes are shown in [Table 2]. The mixer circuit has been simulated and optimized with the modified large signal model using a harmonic balance simulator. The hairpin line BPF is used at the RF input port which blocks the LO leakage into the RF port[11]. The hairpin line BPF is a compact sized filter and improves the quality factor of the filter by adjusting the number of coupling lines. It is composed of three pole resonators with quarter wavelength 50Ω micro strip lines. A 7th order Chebyshev LPF at the IF output port plays a role as the IF filter of a RF module to remove the unnecessary high frequency and harmonic frequency components.

Table 2. Circuit parameter values of the mixer

Element	Design Value	Element	Design Value w(width), d(length)	
V_{GG}	-1V	l_1	w	1.894mm
			d	1.0mm
V_{DD}	3V	l_2	w	1.894mm
			d	2.78mm
L_1, L_2	150nH	l_3	w	1.6mm
			d	11.49mm
C_1	6pF	l_4	w	0.7mm
			d	3.96mm
C_2	10pF	l_5	w	1.894mm
			d	2.0mm
C_3, C_4	220pF	l_6	w	2.6mm
			d	5.0mm

III. EXPERIMENTAL RESULTS

A broadband RF module is simulated and fabricated based on the design specification. The characteristics of Teflon substrate are tangent loss=0.0024, thickness=31mil, and the relative dielectric constant = 2.3. [Fig. 3] shows a photograph of the fabricated RF module on the Teflon substrate; it has an LNA, a mixer, a BPF and an LPF. A vector network analyzer and a spectrum analyzer are used for testing the RF module.

[Fig. 4] shows the measured and the simulated scattering parameters of the LNA in the RF module.

From the measured result, the LNA has a gain (41 ± 0.5dB) over the broadband of between 2.2GHz and 2.6GHz. It is more than 3dB higher than the gain of other LNA with three stage amplifier, and good enough for the desired bandwidth at the 2.4GHz band applications.

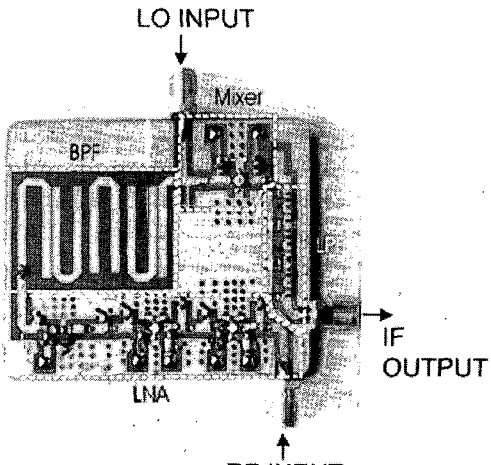

Fig. 3. Photograph of the fabricated RF module

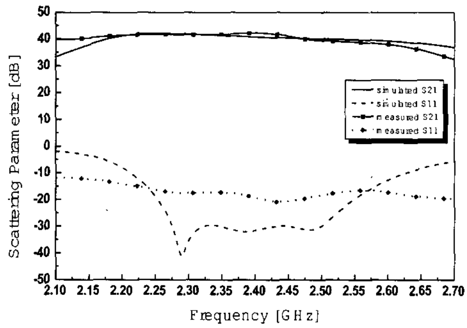

Fig. 4. Simulated and measured scattering parameters of LNA

The measured and the simulated gains are well agreed. The S11 parameters of the LNA should be lower than -14dB to achieve the lower than 1.5 VSWR. In Fig. 4, the frequency band having lower than -14dB of S_{11} is from 2.2GHz to 2.6GHz, which is wider than the specification of a general LNA.

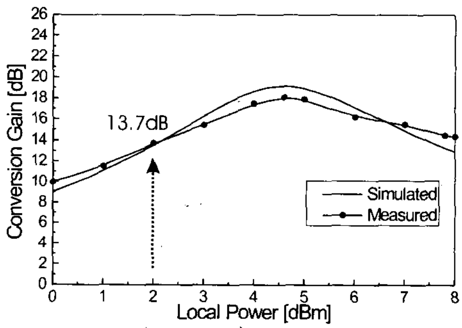

Fig. 5. Conversion gain of the fabricated mixer

[Fig. 5] shows the conversion gain of the fabricated mixer when the LO signal changes from 0dBm to 8dBm. The x axis indicates the LO power in [Fig. 5]. The peak measured and the simulated conversion gain at 4.5dBm of the LO power are

19.15dB and 18dB, respectively.

Since a larger LO power generates a higher noise power, the specified LO power is 2dBm to minimize the distortion and the conversion loss. Therefore, the simulated and measured conversion gains with 2dBm of the LO power are matched at 13.7dB.

[Fig. 6] shows the comparison of the simulated and the measured results of the RF input power versus the IF output power of the RF module. In [Fig. 6], the measured and simulated powers of the RF and IF are in good agreement and have a linear relationship up to the 1dB gain compression point of the IF power. [Fig. 6] shows a wide dynamic range of IF power from -63.5dBm to -5.5dBm when the power of the RF input is from -120dBm to -60dBm. The linear RF power range of -120dBm~-60dBm is wider than that of the general RF power range (-110~-70dBm) at the receiving antenna of the 2.4GHz band.

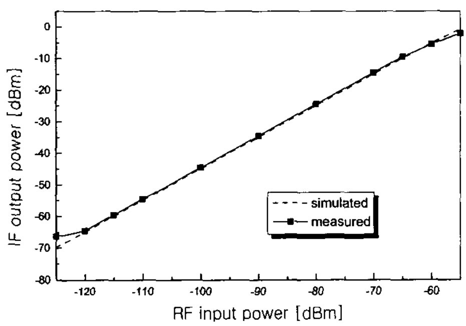

Fig. 6. Comparison of the RF input power vs. the IF output power

[Fig. 7] shows the measured IF output power spectrum of the fabricated RF module by a spectrum analyzer. The RF module produces an IF output power of -14.5dBm when the RF and LO powers are applied -70dBm and 2dBm, respectively. Thus, the conversion gain is 55.2dB. This conversion gain is in good agreement with the sum of the measured results of the gain of the LNA (41.5dB) and the mixer (13.7dB), as shown in [Fig. 4] and [Fig. 5].

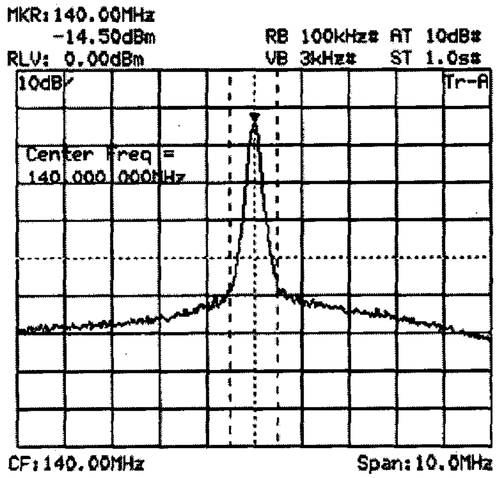

Fig. 7. Measured IF output power spectrum of the fabricated mixer

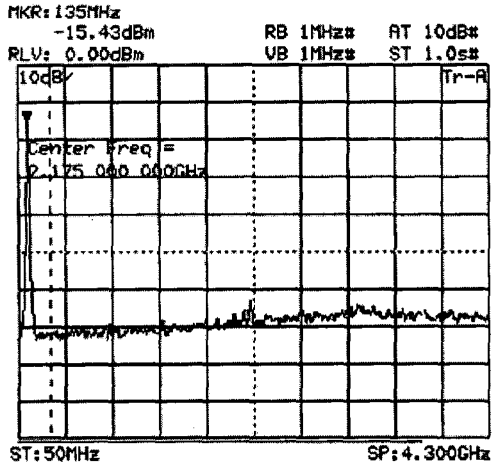

Fig. 8. Measured IF harmonic spectrum characteristics of the mixer

[Fig. 8] is the expanded version of [Fig. 7] and shows the harmonic spectrum of the fabricated mixer. In [Fig. 8], the harmonic spectrum is very low at -60dBm.

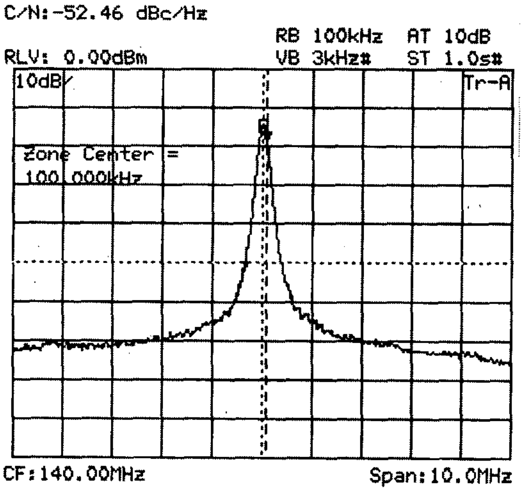

Fig. 9. Measured result of the carrier-to-noise ratio (C/N) of the fabricated RF module

[Fig. 9] shows the measured result of the carrier to noise ratio(C/N) of the fabricated RF module. The carrier to noise ratio at the output port of the RF module is measured when the applied RF input power is -70dBm. C/N is measured as -52.46dBm at the offset frequency of 100KHz away from the center frequency (2.4GHz) by a spectrum analyzer. The noise figure of this system is given by the following equation;

$$NF = P_{RF} - P_n - 10\log(RB/Hz) + C/N \text{ [dB]} \quad (1)$$

Where, P_{RF} is the input power of the signal at the center frequency, and P_n is a noise power per 1Hz at the normal temperature ($T = 290°K$). The value of the P_n is 174dBm/Hz generally. The RB is the resolution bandwidth (100KHz), which is the same as the offset frequency in the measurement. Thus, the noise figure is 1.54dB in the 2.4GHz band. The noise figure of the fabricated RF module is less than that of the design specification(2~3dB) for an ISM band and wireless broadband internet service.

IV. CONCLUSION

An RF module with high conversion gain and good isolation among the RF, IF and LO ports is analyzed and fabricated. A high conversion gain and good isolation of the RF module are achieved simultaneously by using the LNA, the single ended gate mixer, matching circuits, the hairpin line BPF and the Chebyshev IF filter. The transducer power gain of the fabricated LNA is 41± 0.5dB over the broadband of between 2.2GHz and 2.6GHz. The conversion gain of the mixer at 140MHz IF frequency has obtained 13.72dB with 2dBm LO power level. The conversion gain of the RF module is 55.5dB when the applied RF and LO powers are -70dBm and 2dBm, respectively. Notably, a very wide dynamic linear range for the IF output power (-63.5dBm and -5.5dBm) has been achieved when the RF input power is supplied from -120dBm to -60dBm. In addition, a total noise figure for the RF module lower than 1.6dB is achieved. The experimental results are agreed well with the simulated results and with the specification of the 2.4GHz band communications. Therefore, the RF module has been designed successfully with the techniques given in this paper.

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저 자 소 개

강 봉 수(Bong-Soo Kang) 정회원

- 1996년 : 명지대학교 전자공학과 (공학사)
- 2002년 : 제주대학교 대학원 통신공학과(공학석사)
- 2004년 : 제주대학교 대학원 통신공학과(박사수료)

<관심분야> : 안테나 및 전파전파, 전자파 수치해석, 안테나 설계

양 두 영(Doo-Yeong Yang) 정회원

- 1984년 2월 : 제주대학교 통신공학과(공학사)
- 1989년 2월 : 한양대학교 대학원 전자통신공학과(공학석사)
- 1992년 2월 : 한양대학교 대학원 전자통신공학과(공학박사)
- 1992년 3월~현재 : 제주대학교 통신컴퓨터공학부 교수

<관심분야> : RF회로 및 RFID, 이동통신, 위성통신