A 2.4 GHz Transceiver RF Front-end for ISM-Band Digital Wireless Communications

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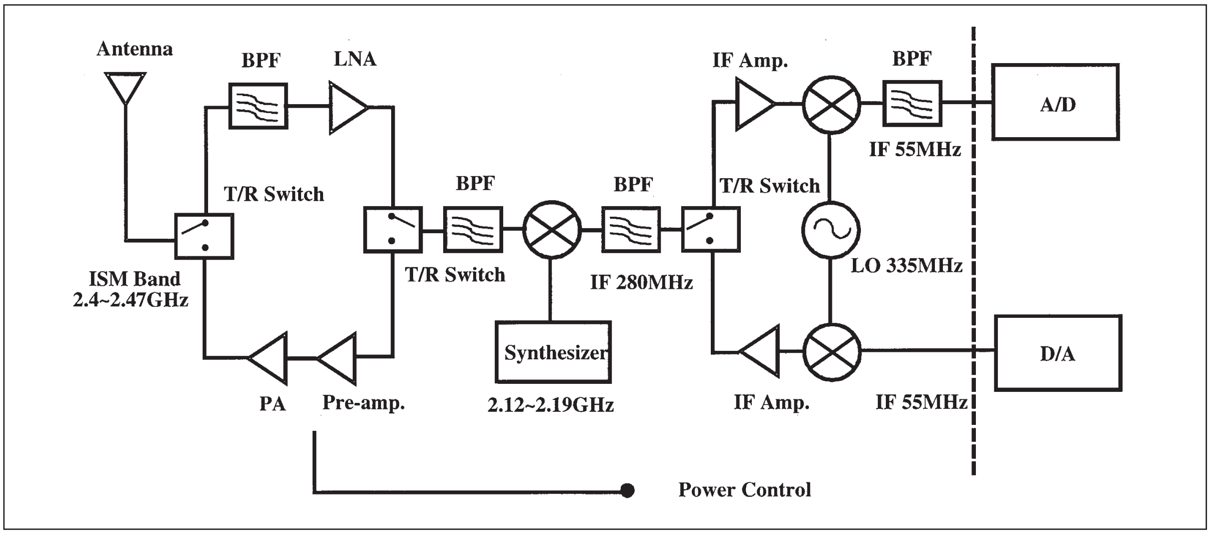
This paper is a comprehensive presentation of the design, implementation, and measured performance of a 2.4 GHz transceiver RF front-end for ISM-band digital wireless communication. A dual frequency conversion strategy is employed in this RF front-end (2.4 - 2.47 GHz). The 1st and 2nd IFs are 280 MHz and 55 MHz, respectively. The TDD duplexing method is adopted in this module, controlled by T/R switch. A Class-A two-stage power amplifier, a preamplifier, single-ended resistive mixer and low noise amplifier are designed and combined with suitable IF RFICs, filters and switches to form a transceiver RF front-end (not including frequency synthesizer). The transceiver RF front-end has 22 dBm transmitting power, with 15 dB conversion gain and 9 dB noise figure for receiving.

In digital modulation measurements using 384 kbps π/4 DQPSK, the error vector magnitude (EVM) is 4 percent (P_{in} = –3dBm) for the transmit mode and 1 percent (P_{in}= –50dBm) for the receive mode. The measured adjacent channel power (ACP) for the transmit mode at 2.4 GHz is –30 dBc with a channel bandwidth of 380 kHz. The receiver sensitivity is about –102 dBm for 10^{-5} BER. For spread spectrum signal measurements (1.228 Mbps OQPSK with a channel bandwidth of 1.5 MHz), the ACP is –36 dBc at 2.4 GHz.

Transceiver description

The ever-increasing demand for radio spectrum in the fast growing area of wireless communication systems is driving RF design into higher microwave frequency bands at 2.4 GHz and beyond. This paper presents the design, implementation and extensive measurements of a 2.4 GHz transceiver RF front-end for ISM-Band digital wireless communications. The 1st LO is from 2.12 GHz to 2.19 GHz and the first IF is at 280 MHz. The 2nd LO is at 335 MHz



■ **Figure 1. Block diagram of a 2.4 GHz transceiver front-end for digital wireless communications.**

and the second IF is at 55 MHz. The TDD duplexing method is adopted in this module, controlled by T/R switches. A class-A two-stage power amplifier (24 dBm output power), a pre-amplifier, single-ended resistive mixer (6 dB conversion loss), and low noise amplifier (21 dB gain and 2.5 dB noise figure) were designed for the transceiver. These RF circuits, along with IF RFICs, filters, and switches, form a transceiver RF front-end, except for the frequency synthesizer. In the transmit mode, the output power reaches 22 dBm (1 dB compression point) after the loss of the T/R switch. In the receive mode, 15 dB conversion gain, 9 dB noise figure, and –6 dBm 1 dB compression point were measured.

To investigate the performance of the transceiver RF front-end in digital wireless communications, a 384 kbps π/4 DQPSK digital modulation signal from a digital modulation signal generator (Anritsu MG 3660A) was applied to the RF front-end and analyzed using an HP 89410A vector signal analyzer. The error vector magnitude (EVM) was measured for both the transmit and receive modes. The measurement of adjacent channel power (ACP) for π/4 DQPSK digital modulation and spread spectrum signals has also been performed and will be discussed.

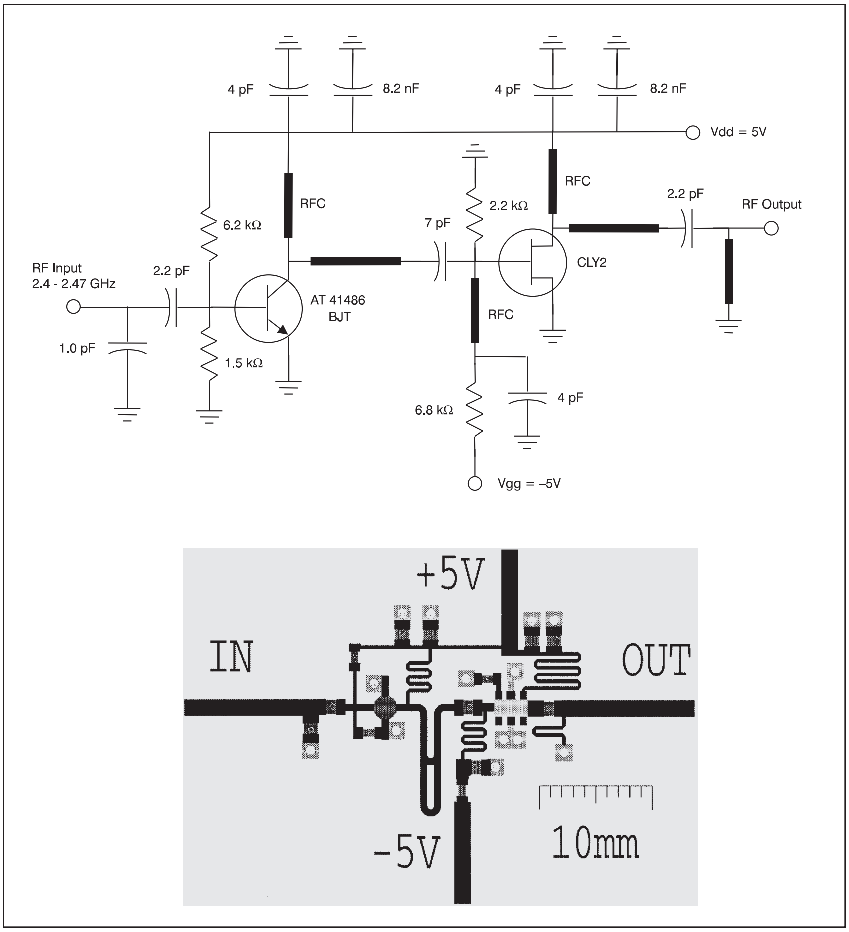


Figure 2. 2.4 GHz two-stage power amplifier — circuit diagram (top) and board layout (bottom).

Circuit design, realization and measurement

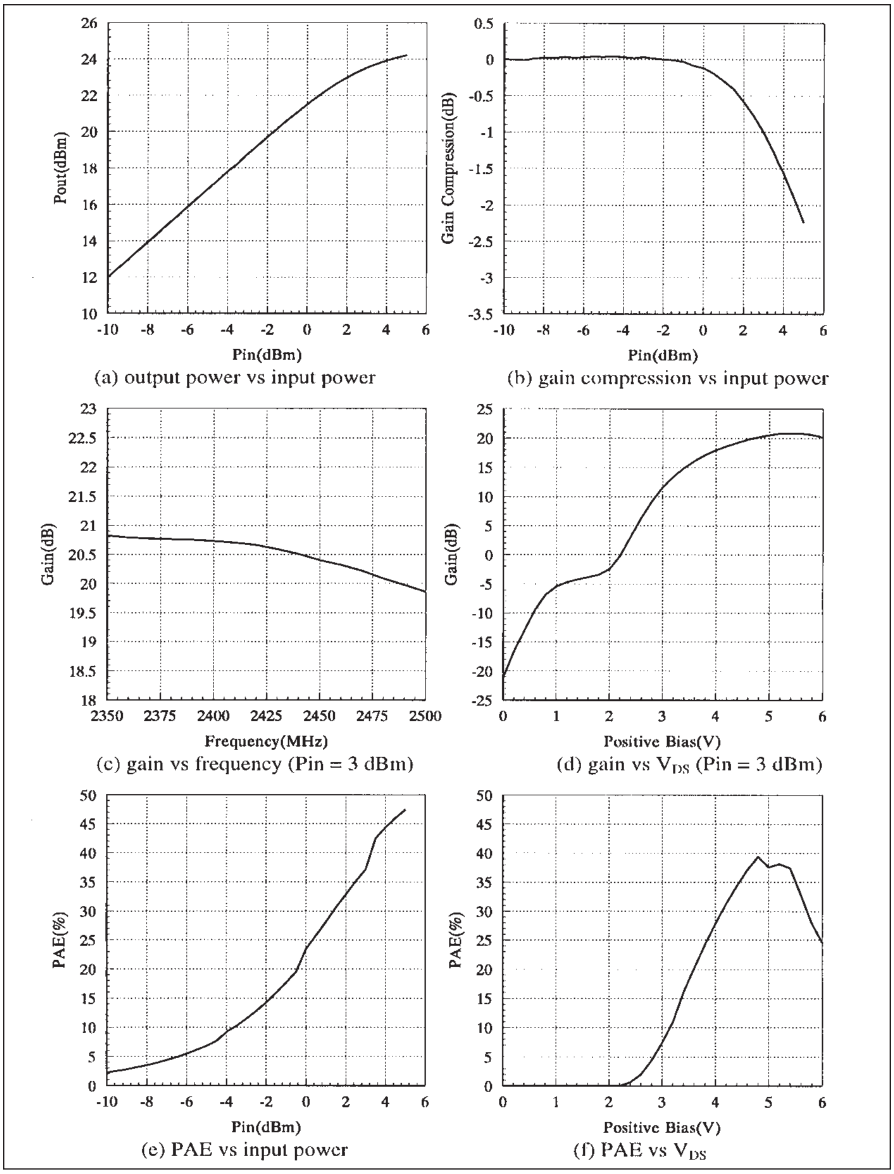
Figure 1 shows the block diagram of this ISM-band 2.4 GHz transceiver RF front-end. The transmitting and receiving parts are isolated by T/R switches. A 2.45 GHz bandpass filter is placed before the low noise amplifier (LNA). The power amplifier (PA) is driven by a preamplifier. The 1st IF is at 280 MHz. A single-ended resistive FET mixer is designed for both up-conversion (280 MHz IF to 2.4 GHz RF) and down-conversion (2.4 GHz RF to 280 MHz IF). The 2nd IF is at 55 MHz and the 2nd LO is chosen to be at 335 MHz.

Transmitter

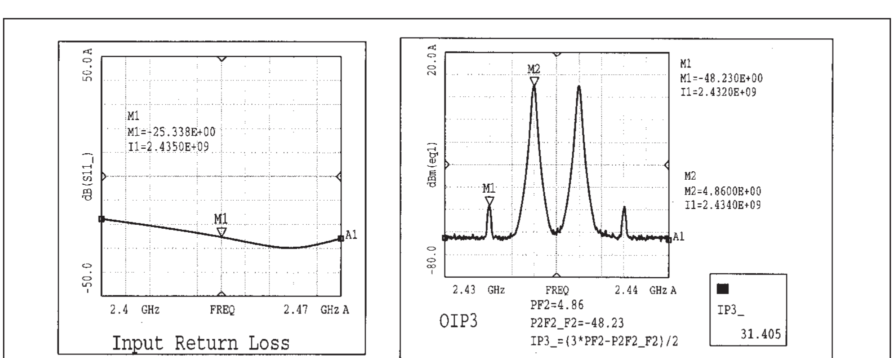
PA and driver circuits — As shown in Figure 2, the two-stage 5-volt PA uses an HP AT-41486 BJT as the driver and a Siemens CLY-2 MESFET as the output stage. Since the goal is to design a high-linearity Class-A amplifier, the bias point of the CLY-2 is chosen at V_{GS} = –1.3 V and V_{DS} = 5 V (40 percent I_{DSS}). Figures 3(a) and 3(b) show the measured output power and gain compression of the PA as a function of the input power at 2.435 GHz. It can be observed that the 1 dB gain compression point (P_{1dB}) is about 24 dBm. Figure 3(c) shows the PA gain as a function of the frequency at 3 dBm input power. It can be seen that the gain is about 21 dB and the gain flatness is about ±0.5 dB. The power-added efficiency (PAE) of a power amplifier as a function of the input power is shown in Figure 3(d). An efficiency of about 40 percent can be achieved at the high output power level. Figures 3(e) and 3(f) depict the measured gain and PAE as a function of the DC voltage V_{DS}. The measured input return loss, which is shown in Figure 4, is less than 20 dB from 2.4 to 2.47 GHz. The 3rd-order intercept point (IP_3) is an index for the measurement of the intermodulation distortion (IMD). It is defined as:

$$P_{IP_3} = \frac{3P_{f1} - P_{(2f_2 - f_1)}}{2} \qquad (2)$$

where P_{f1} and P_{f2} are the power strengths (which are set to equal) of the two fundamental frequency components at the frequencies f_1 and f_2, and $P_{(2f2-f1)}$ is the 3rd-order IMD at the frequency ($2f_2 - f_1$). To measure the output IP_3, two RF signals at 2.432 GHz and 2.434 GHz (from two RF signal generators) are summed in a combiner and then sent to the PA. The HP-MDS (Microwave Design System) RF/ Microwave CAD software (installed in a workstation) is used to capture the measured spectrum on a HP-8594E spectrum analyzer through the GPIB bus and compute the OIP_3. The measured output



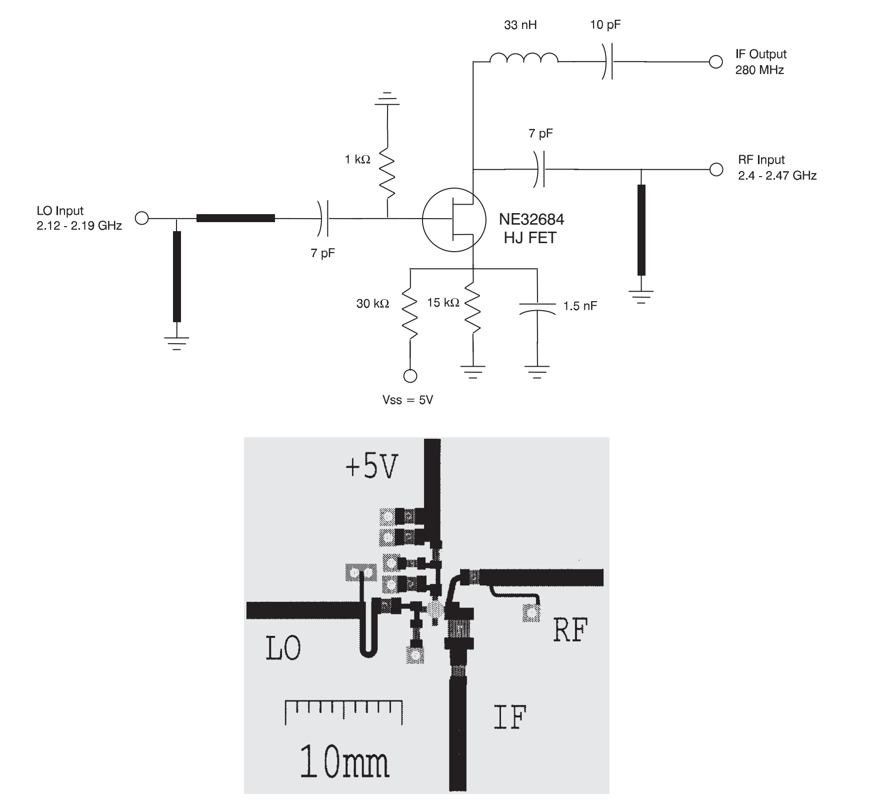
■ **Figure 3. Measured performance of the 2.4 GHz power amplifier: (a) output power level, (b) gain compression vs. input power, (c) gain vs. frequency at 3 dBm input power, (d) gain vs. VDS at 3 dBm input power, (e) power-added efficiency (PAE) vs. input power, and (f) PAE vs. VDS at 2.435 GHz.**



■ **Figure 4. Measured input return loss and two-tone test of the 2.4 GHz two-stage power amplifier.**

spectrum and the computed OIP_3 (31.4 dBm) of the PA are also shown in Figure 4. Also, in order to compensate for signal losses at the mixer, filters and antenna switch, a two-stage pre-amplifier (using AT-41486 BJTs) is used before the PA. The pre-amplifier has a gain of 22 dB and OIP_3 of 21.3 dBm. The performance characteristics are summarized in Table 1.

1st IF Mixers — The 1st IF is at 280 MHz, and a T/R switch separates the LNA and PA circuits to let the 1st mixer be used for both up-conversion and down-conversion. The 1st mixer is designed as a single-ended resistive FET mixer using a NE 32684 HJFET, with the mixer circuit shown in Figure 5. The FET mixer uses a self-biasing circuit with 30k ohm and 15k ohm resistors (and a 1.5 nF bypass capacitor) connected to the source terminal to achieve –1.6 V V_{GS}. A 3 pF capacitor connected to the drain terminal is to maintain a high impedance for the 280 MHz IF signal. The 33 nH inductor connected to the drain terminal blocks the RF and LO signals. The matching networks at the LO and RF ports are designed using microstrip lines (see Figure 5).



■ **Figure 5 2.4 GHz single-ended resistive FET mixer — circuit diagram (top) and board layout (bottom).**

Figure 6 shows the measurements of the mixer's performance. Figures 6(a) and 6(b) show that the input return loss of both the RF and LO terminals is more than 10 dB. Figure 6(c) shows that the VSWR of the IF terminal is less than 1.3 at 280 MHz. The conversion loss *vs.* frequency, gate voltage and LO power are shown in Figures 6(d), 6(e) and 6(f). The conversion loss is about 6 dB from 2.4 to 2.47 GHz, generally unchanged for gate voltages from 3 to 6 V. The smallest conversion loss is achieved when the LO power is 3 dBm. Figures

2.4GHz Two-Stage Power Amplifier (PA)

Frequency Range	2.4-2.47 GHz	VSWR (Input)	<1.2
VDD	5V	1 dB Compression Point	24 dBm
VGG	–5V	3rd Order Intercept Point (OIP_3)	31.4 dBm
Gain	21 dB	EVM (384 kbps digital modulation	3%
Gain Flatness	±0.5 dB	Power Added Efficiency	40%

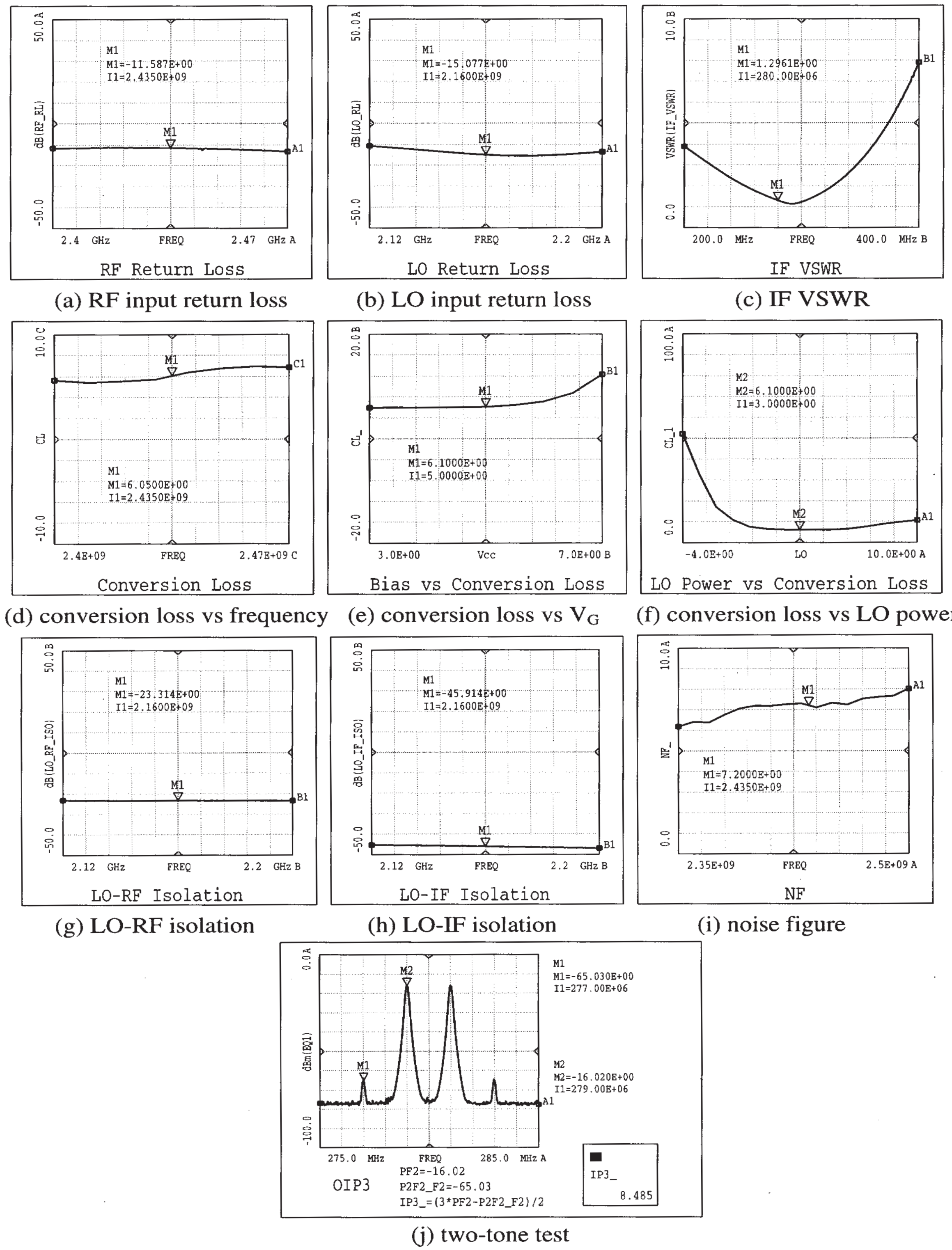
2.4 GHz Single-ended Resistive Mixer

RF Frequency Range	2.4-2.47 GHz	IF VSWR	1.3
LO Frequency Range	2.12-2.19 GHz	LO-RF Isolation	23 dB
IF Frequency	280 MHz	LO-IF Isolation	45 dB
Conversion Loss	6 dB	3rd Order Intercept Point (OIP_3)	8.5 dBm
RF Return Loss	10 dB	Noise Figure	7 dB
LO Return Loss	10 dB		

2.4 GHz Two-Stage Low Noise Amplifier (LNA)

Frequency Range	2.4-2.47 GHz	Output Return Loss	>15 dB
VCC	5V	Noise Figure	2.5 dB
Gain	21.7 dB	3rd Order Intercept Point (OIP_3)	23.6 dBm
Input Return Loss	>15 dB		

■ **Table 1. Summary of measured performance characteristics of the 2.4 GHz PA, mixer, and LNA.**



■ **Figure 6. Measured characteristics of the 2.4 GHz single-ended resistive FET mixer.**

6(g) and 6(h) show that the LO-RF and LO-IF isolation are about 23 dB and 45 dB, respectively. The noise figure is about 7.5 dB as shown in Figure 6(i). Figure 6(j) shows the measured spectrum of the two-tone test. RF signals are at 2.434 and 2.436 GHz, the LO is at 2.415 GHz and IFs are 279 and 281 MHz. OIP_3 is about 8.5 dBm. The performance characteristics are included in Table 1.

Receiver

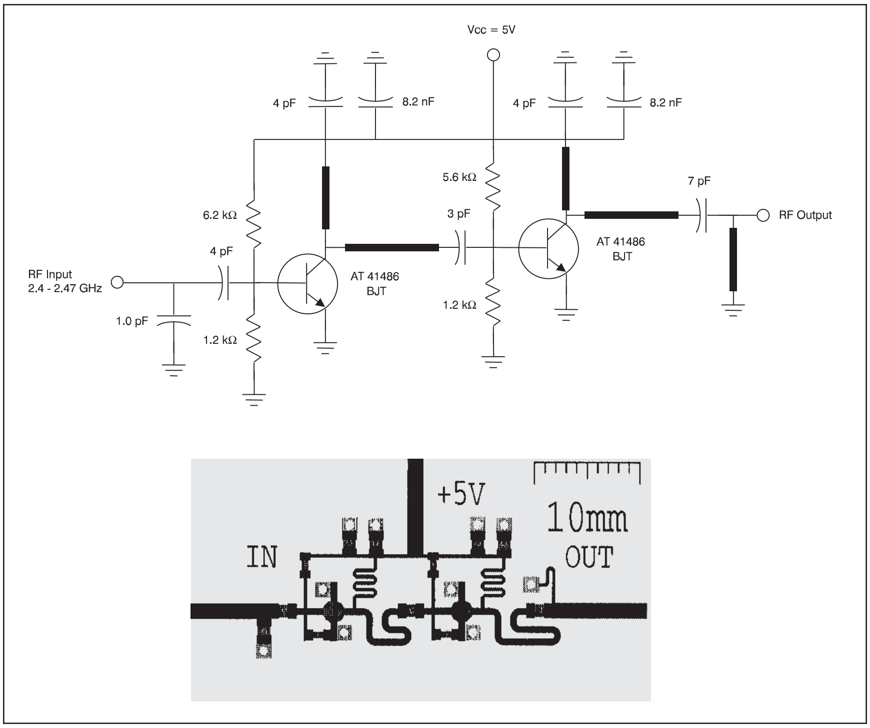
Low Noise Amplifier (LNA) — The two-stage LNA uses the HP AT-41486 BJT. The design goal is to emphasize low noise figure at the 1st stage and have high gain at the 2nd stage, and the conjugate matching is designed between the two stages. The bias point is V_{CE} = 5 V and I_C = 5 mA for the 1st stage, and V_{CE} = 5 V and I_C = 15 mA for the 2nd stage. Figure 7 shows the LNA circuit and layout. Figure 8 shows the measured characteristics of the 2.4 GHz LNA. The input and output return loss are all lower than 15 dB over the 2.4 to 2.47 GHz range. The gain is about 21.7 dB and the noise figure is about 2.5 dB. The two-tone test shows that the OIP_3 is about 51.53 dBm. The performance characteristics are also shown in Table 1.

2nd IF Mixer and Amplifier — The 2nd IF mixer (Mini-Circuits RMS-2) down-converts the 280 MHz 1st IF signal to the 55 MHz 2nd IF, with an IF amplifier using a Mini-Circuits MAR-6 before the mixer. Figure 9 shows measured characteristics of the 2nd IF mixer. The conversion loss with an LO power of 5 dBm is about 8.4 dB, and the OIP_3 of the mixer is about 5.47 dBm. The LO-RF and LO-IF isolation are more than 25 dB and 37 dB, respectively. Figure 10 shows the measured characteristics of the 2nd IF amplifier. The gain of the IF amplifier is about 7.7 dB and the OIP_3 is about 18.56 dBm.

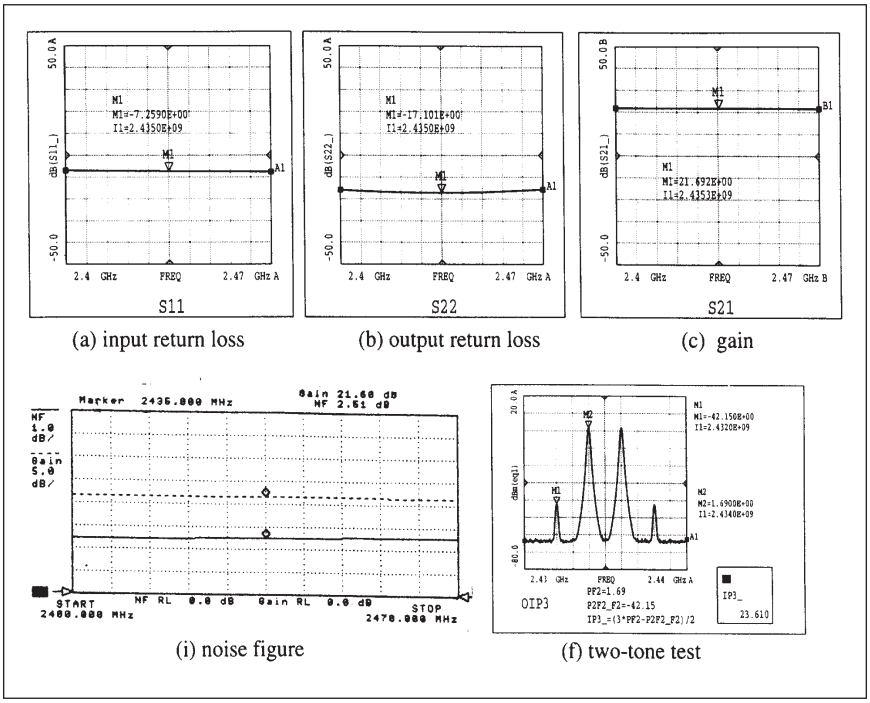
T/R Switches — Three T/R switches are used in the RF front-end module to switch between transmitting and receiving modes (see Figure 1). The Mini-Circuits MSTW-4-20 switch is used, and the measured characteristics after proper matching are shown in Figure 11. The insertion loss is about 1.5 dB and the isolation is about 17.6 dB at 2.4 GHz.

Filters — Two 2.45 GHz RF bandpass filters are used between the antenna switch and LNA and before the mixer (FDK 2450B, with a passband of 100 MHz). The measured characteristics are shown in Figure 12. The return loss is about 20 dB and the insertion loss is less than 1 dB within the passband.

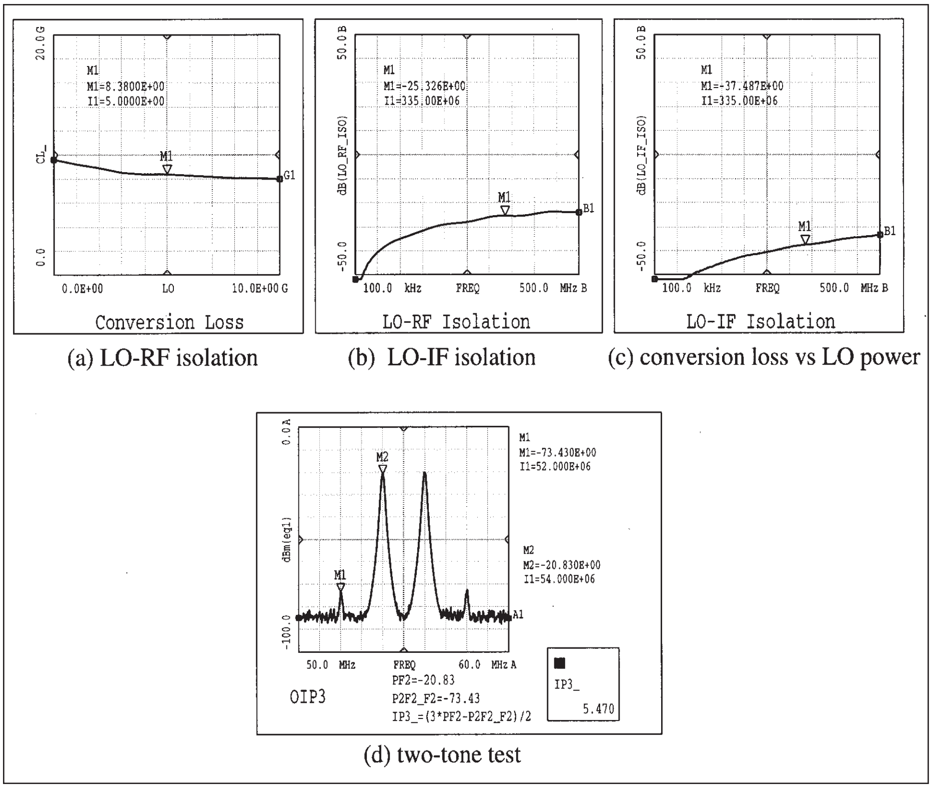
A 280-MHz IF bandpass filter is used after the first mixer, a Toyocom SAW filter. An impedance matching network of 150 nH and 39 nH chip inductors is used before and after the SAW filter. The measured characteristics are shown in Figure 13. The insertion loss is about 3.9 dB and the group delay is about 227 ns at 280 MHz. A 55 MHz IF bandpass filter is put after the 2nd mixer. A Mini-Circuits PIF-50 bandpass filter is used. Figure 14 shows the measured characteristics.



■ **Figure 7. 2.4 GHz two-stage low noise amplifier (LNA) — circuit diagram (top) and board layout (bottom).**



■ **Figure 8. Measured characteristics of the 2.4 GHz two-stage low noise amplifier (LNA).**



(a) LO-RF isolation (b) LO-IF isolation (c) conversion loss vs LO power

(d) two-tone test

■ **Figure 9. Measured characteristics of the 280 MHz 2nd IF mixer (Mini-Circuits RMS-2).**

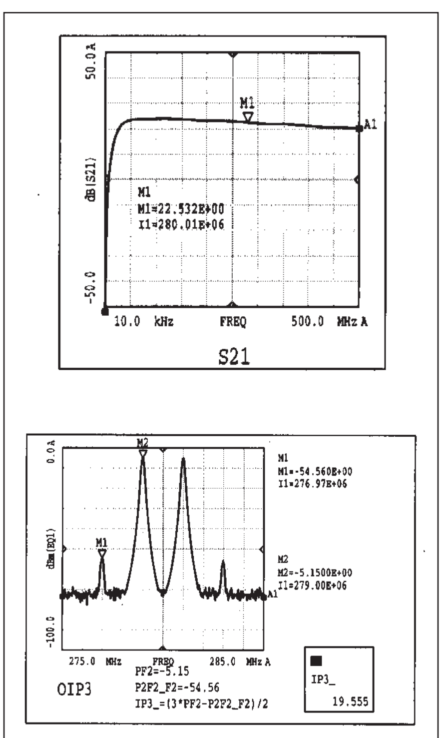
The insertion loss is less than 1 dB and the return loss is lower than 20 dB at 55 MHz.

RF front-end integration and performance measurement

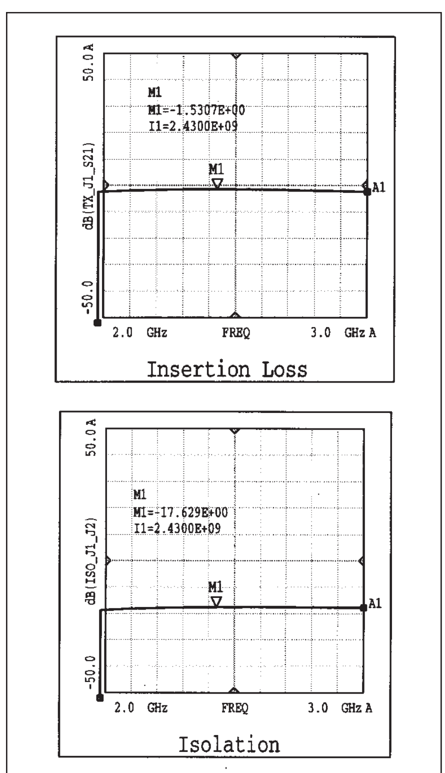
The complete circuit of the 2.4 GHz transceiver RF front-end (not including the frequency synthesizer) is assembled on an FR-4 (ε_r = 4.7) printed circuit board. The circuit layout and the photograph of an assembled module are shown in Figure 15. The photographs and plot in Figure 16 illustrate the test equipment used and the digital modulation measurement setup. Measured performance data are presented as follows.

Transmit Mode

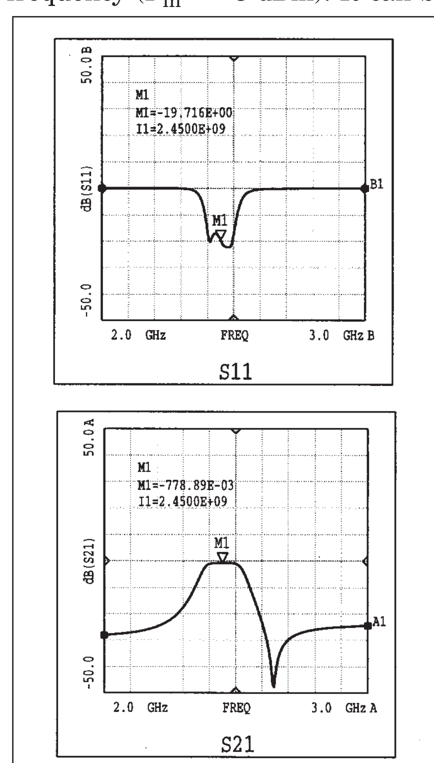
In transmit mode, the 55 MHz IF signal is up-converted two times to 2.4 GHz. Figures 17(a) and 17(b) show the measured output power and gain compression as a function of the input power at 2.435 GHz. Figure 17(c) shows the measured output power as a function of the frequency (P_{in} = –3 dBm). It can be



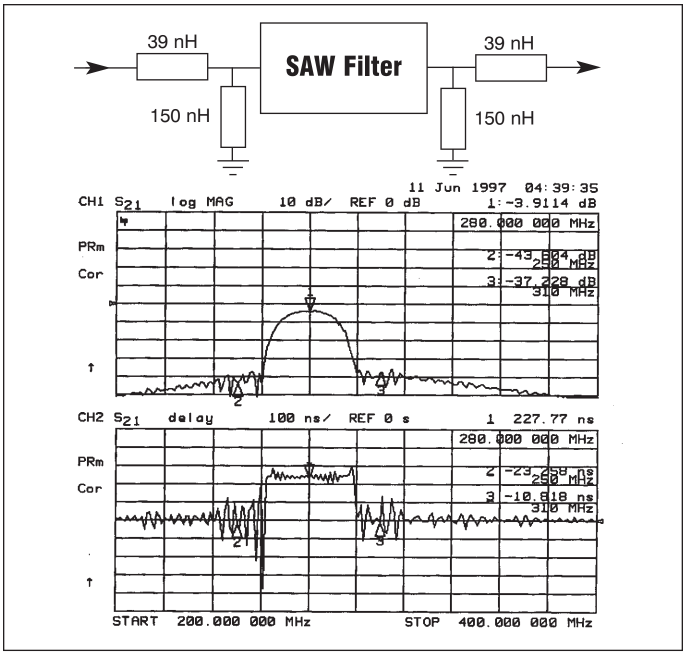
■ **Figure 10. Measured characteristics of the 280 MHz 2nd IF amplifier (MAR-6).**



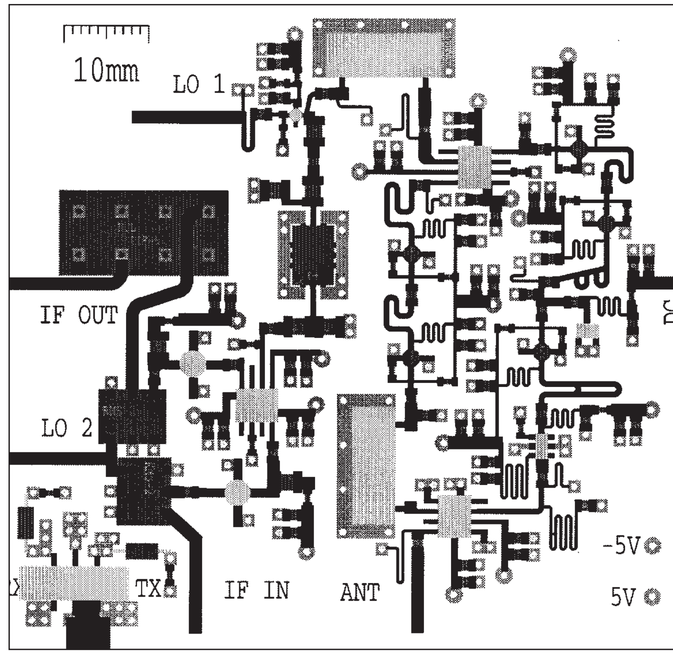
■ **Figure 11. Measured characteristics of the T/R switch (MSTW-4-20).**



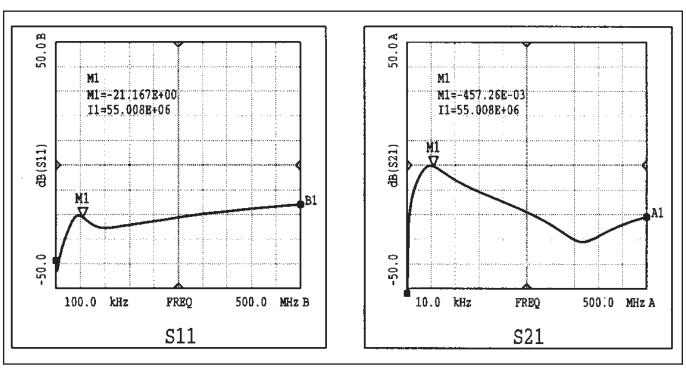
■ **Figure 12. Measured characteristics of the 2.4 GHz bandpass filter (FDK 2450B).**



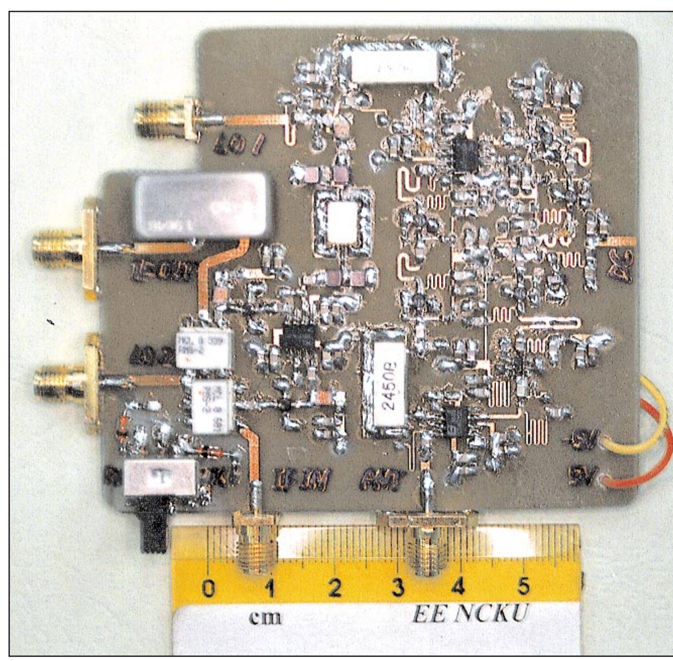
■ **Figure 13. Measured characteristics of the 280 MHz bandpass filter (Toyocom SAW filter): Top is S21, bottom is group delay.**



■ **Figure 15(a). Circuit layout of the 2.4 GHz transceiver RF front-end.**



■ **Figure 14. Measured characteristics of the 55 MHz 2nd IF bandpass filter (PIF-50).**



■ **Figure 15(b). Photograph of the assembled transceiver (RF front-end, not including frequency synthesizer), as constructed on FR-4 board.**

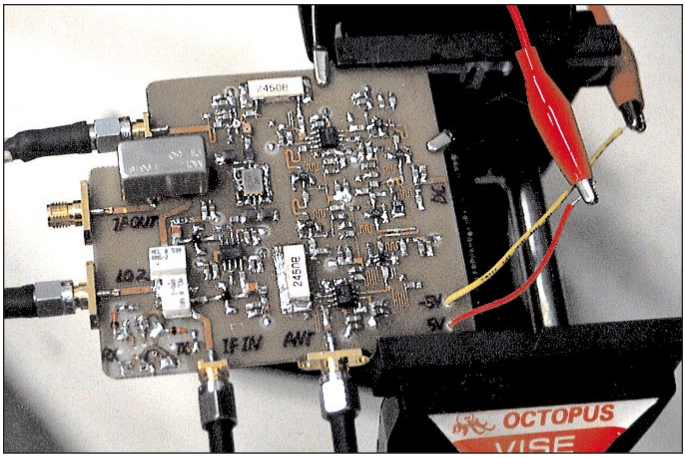
seen that the gain is about 26 dB and the output power is about 22 dBm.

Receive Mode

Figure 18 shows measured results of the transceiver in the receive mode. It can be observed that the gain is about 15.5 dB and noise figure is about 8.8 dB at 2.435 GHz. The input VSWR is 1.6 at 2.435 GHz. The 1 dB gain compression point is –6 dBm when the input power is –21 dBm.

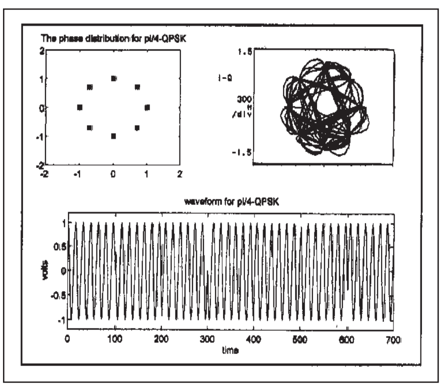
Digital modulation measurement

Figure 16(b) shows the digital modulation measurement setup with an Anritsu MG 3660A digital modulation signal generator and an HP 89410A vector signal analyzer. A 384 kbps $\pi/4$ DQPSK digital modulation signal (–50 dBm) is applied to the transceiver RF front-end. Figure 19 shows that the EVM is about 3.89 percent in the transmit mode and about 1.37 percent in the receive mode at 2.47 GHz. To determine the receive sensitivity of the RF front-end, the 384 kbps $\pi/4$ DQPSK signal from the vector signal generator with –95 dBm signal power (the smallest input power allowed for the vector signal analyzer HP 89410A) was applied to the RF front-end (in receive mode). The measured EVM is 20 percent

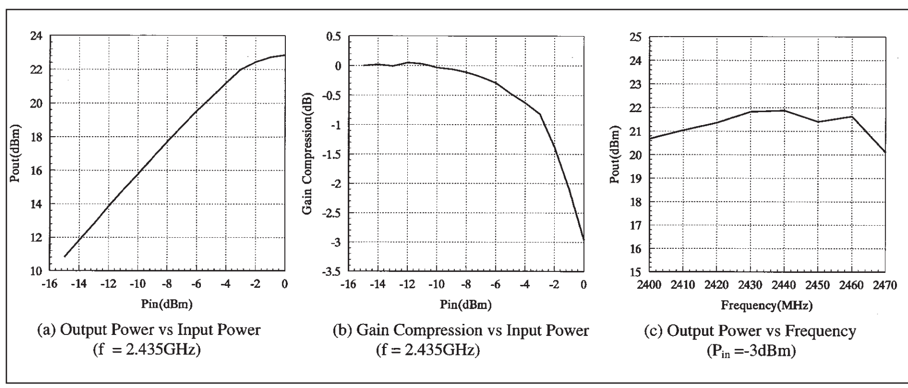


■ **Figure 16(a). Photo showing connection of test cables to the RF transceiver board.**

■ **Figure 16(b). The test setup: Anritsu MG 3660A digital modulation generator and HP 89410A vector signal analyzer.**



■ **Figure 16(c). Digital modulation test display.**



■ **Figure 17. Measurement plots of transmit mode performance of the 2.4 GHz transceiver.**

at 2.47 GHz. By using the following formula:

$$S/N = -20\log(EVM) \tag{2}$$

the corresponding ratio for EVM of 20 percent is 14 dB. Since

$$S/N = \frac{(E_S R_S)}{N_0 B} \tag{3}$$

where E_S is the energy of a symbol, R_S is the symbol rate, N_0 is the noise power density, and B is the bandwidth. For a π/4 DQPSK signal and 14 dB ratio, it can be determined that:

$$E_S/N_0 = S/N(B/R_S) = 17\text{ dB} \tag{4}$$

Assuming the bit error rate (BER) is 10^{-5}, the required E_S/N_0 is 10 dB. Hence, from the definition of the sensitivity:

$$\begin{aligned}\text{Sensitivity} &= -144 + NF + R_S + E_S/N_0 \\ &= -144 + 8.8 + 10\log(384/2) + 10 \\ &= -102\text{ dB}\end{aligned} \tag{5}$$

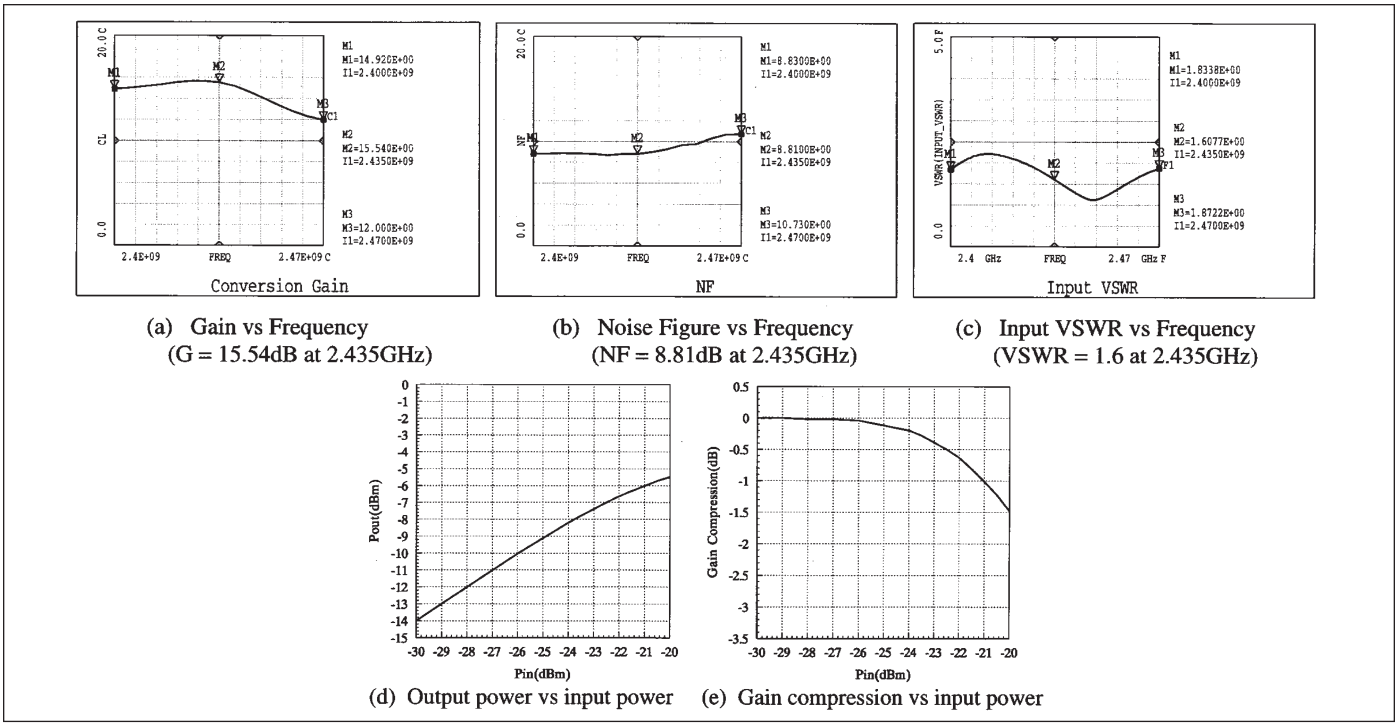
This is consistent with the obtained E_S/N_0 of 17 dB from measurement at –95 dBm input power (since –102 + (17–10) = –95). Hence, it was determined that the receive sensitivity of the RF front-end is about –102 dBm. The dynamic range (DR) can then be determined as:

$$\text{DR} = P_{i(1\text{ dB})} - \text{Sensitivity} = -21 - 102 = 81\text{ dB} \tag{6}$$

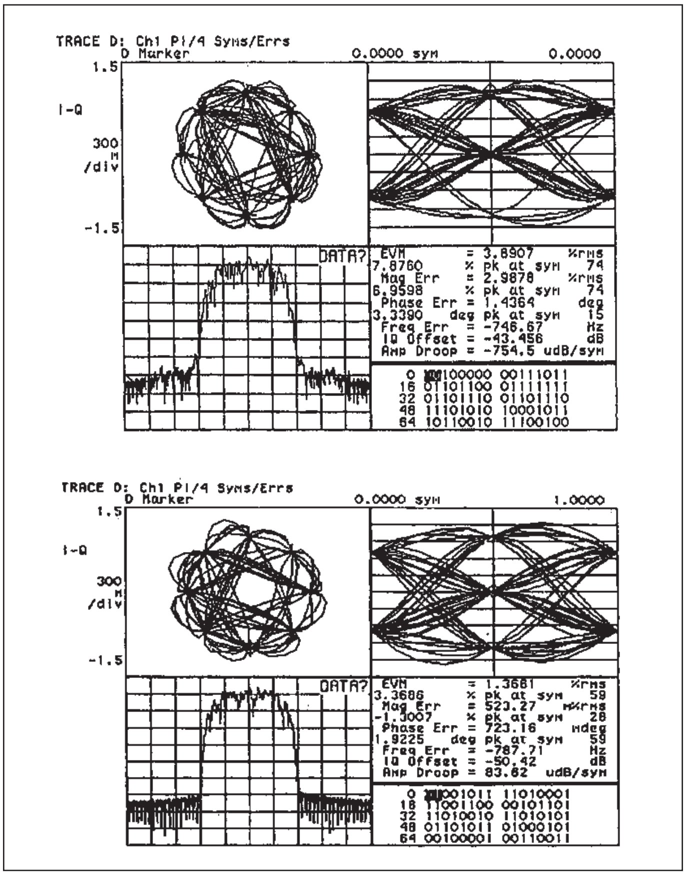
ACP (adjacent channel power) measurement

The ACP (for the transmitting mode) can also be measured by the vector signal generator. By applying a 384 Kbps π/4 DQPSK signal (–3 dBm) with a channel bandwidth of 380 kHz to the RF front-end, Figure 20 shows the measured ACP is –30 dBc at 2.4 GHz. To measure the ACP for spread spectrum signal, a 1.228 Mbps OQPSK signal (–3 dBm) with a channel bandwidth of 1.5 MHz is applied. Figure 20 shows the measured ACP is –36 dBc at 2.4 GHz.

Table 2 summarizes the measured gain and noise figure of each stage and the computed total gain/noise figure (ideal value) of the RF front-end. Table 3 shows the performance characteristics of the RF front-end at 384 kbps π/4 DQPSK digital modulation.



■ **Figure 18. Measurement plots for the receive mode performance of the 2.4 GHz transceiver.**



■ **Figure 19. 384 kbps π/4 DQPSK digital modulation measurement of the transceiver (top is transmit mode, bottom is receive mode.**

Conclusion

The design, implementation and extensive measurements of a 2.4 GHz transceiver RF front-end (not including frequency synthesizer) for ISM-Band digital wireless communications have been described. The module uses dual conversion. The 1st LO is from 2.12 GHz to 2.19 GHz and the first IF is at 280 MHz. The 2nd LO is at 335 MHz and the second IF is at 55 MHz. The TDD duplexing method is used, controlled by T/R switches. A Class-A two-stage power amplifier (24 dBm output power), a pre-amplifier, single-ended resistive mixer (6 dB conversion loss), and low noise amplifier (21 dB gain and 2.5 dB noise figure) are designed and combined with suitable IF RFICs, filters, and switches to form a transceiver RF front-end. In the transmit mode, the output power is 22 dBm (1 dB gain compression) after the T/R switch. In the receive mode, 15 dB conversion gain, 9 dB noise figure, and –6 dBm 1 dB compression point are measured. In digital modulation measurements (384 kbps π/4 DQPSK), the EVM (error vector magnitude) is 4 percent (P_{in} = –3 dBm) for the transmit mode and 1 percent (P_{in}= –50 dBm) for the receive mode. The receive sensitivity is about –102 dBm for 10^{-5} BER. The measured ACP (adjacent channel power) for the transmitting mode at 2.4 GHz is –30 dBc with a channel bandwidth of 380 kHz. For spread spectrum signals (1.228 Mbps OQPSK) measurements, the ACP is –36 dBc with a channel bandwidth of 1.5 MHz at 2.4 GHz. ■

Acknowledgments

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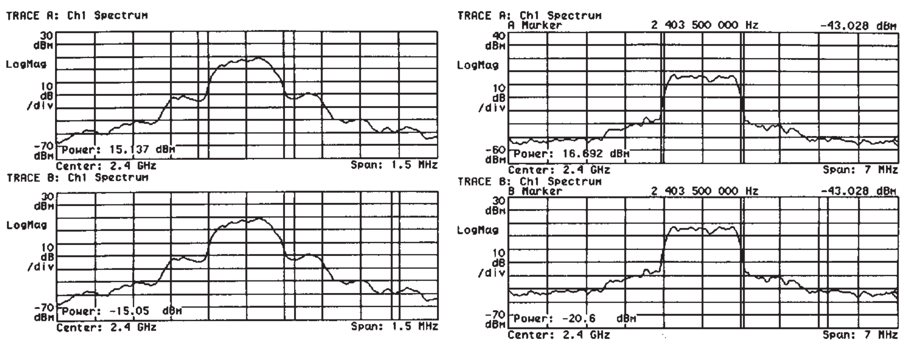

■ **Figure 20. ACP measurement of the transceiver in transmit mode: (a) 384 kbps π/4 DQPSK signal (–3 dBm) with 380 kHz channel bandwidth; (b) 1.228 Mbps OQPSK spread spectrum signal (–3 dBm) with 1.5 MHz channel bandwidth.**

Stage	Gain (dB)
IF Mixer	–8
IF Amp	7.7
T/R Switch	–1
SAW Filter	–4
Mixer	–6
RF Filter	–1
T/R Switch	–1.5
Preamp	22
PA	21
T/R Switch	–1.5
TOTAL	27.7

(a) Transmit Mode

Stage	Noise Figure (dB)	Gain (dB)
T/R Switch+RF Filter	2.5	–2.5
LNA	2.5	21.7
T/R Switch+RF Filter	2.5	–2.5
Mixer	7.5	–6
SAW Filter+T/R Switch	5	–5
IF Amp	3	22
2nd Mixer	9	–8
2nd IF Filter	1	–1
TOTAL GAIN		18.7 dB
TOTAL NF	5.72519 dB	(3.73696 lin.)
TOTAL NOISE TEMP	793.71993K	

(b) Receive mode

■ **Table 2. Measured gain and noise figure of each stage and computed total gain/noise figure (ideal value) of the 2.4 GHz transceiver RF front-end.**

Transmit Mode

Max. Output Power	Linear Gain	EVM (Pin = -3 dBm)	ACP (Pin = -3 dBm)
22 dBm	26 dB	1.5% (f = 2.4 GHz)	–30 dBc (f = 2.4 GHz)
22 dBm		3.9% (f = 2.47 GHz)	–24 dBc (f = 2.47 GHz)

Receive Mode

Noise Figure (NF)	Gain	P1dB
9 dB	15 dB	Input = –21 dBm Output = –6 dBm
Sensitivity	Dynamic Range	EVM
–102.2 dBm (Bit error rate: BER=10^{-5})	81.2 dB	1% (P_{in} = –50 dBm) 20% (P_{in}= –95 dBm)

■ **Table 3. Performance characteristics of the 2.4 GHz transceiver RF front-end (384 kbps π/4 DSPSK digital modulation).**

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