

Design of a 60 GHz Receiver RF Front-end Integrated with Substrate Integrated Waveguide

Shufeng Sun¹ and Yi Huang²

¹ China Academy of Space Technology (Xi'an), Xi'an, 710100, China, e-mail: shufeng.sun@outlook.com

² Department of EEE, the University of Liverpool, Liverpool, L69 3GJ, UK, e-mail: Yi.Huang@liverpool.ac.uk

Abstract

In this paper, a 60 GHz radio frequency (RF) front-end for receivers is designed, which can work as a down-converter mode or a demodulator mode by slightly changing the assembly process. The RF covers 55 to 65 GHz while the IF is from 3 to 5 GHz as a converter and 0 to 5 GHz as a demodulator. The single-side band noise figure (NF) is predicted to be less than 4.53 dB and the conversion gain is higher than 27 dB (down-converter mode) or 24 dB (demodulator mode). In addition, all circuits are integrated on a 22 mm × 33.5 mm PCB. A Substrate Integrated Waveguide (SIW) is used to connect monolithic microwave integrated circuits (MMICs), and also designed as a passive circuit. This novel structure is suitable for hermetic sealing and has excellent electromagnetic compatibility (EMC) performance. The high performance and compact structure are most suitable for military and space applications.

1. Introduction

In recent years, the unlicensed 60 GHz band for high-data-rate multimedia access and measurement applications is of huge commercial interests [1-4]. Furthermore, this band also plays an important role in the inter-satellite communications owing to its propagation characteristics: high levels of oxygen absorption and rain attenuation which enable the inter-satellite service to avoid the harmful interference from the earth and also avoid being detected from the earth. The RF front-end is a key component of all 60 GHz systems. In addition to the basic requirements of commercial systems (e.g. a wide bandwidth, simplicity and low cost), better electronic performances (such as the lower noise figure, higher gain), higher reliability, longer life are also essential requirements of the RF front-end for military and space applications. The integration and packaging technology is one of the hot research fields in 60 GHz RF front-end, many methods and technologies have been explored. For example the low temperature co-fired ceramic (LTCC) technology [1], 3D-packag [2], system on package (SoP) technology [3]. Most of these designs are mainly for commercial communications and unsuitable for space applications. In this paper, a 60 GHz RF front-end design is proposed which meets the requirements of satellite applications, and the double operation modes are introduced to make this design adaptable to different systems. The advantages of this design are not only having met the technical specifications (a wide bandwidth, low noise figure and high gain), but also suitable for the packaging procedures and the reliability for space applications.

2. The RF front-end concept and budget

Figure 1(a) shows the diagram of the proposed 60 GHz RF front-end for receivers, which receives the signal in the band of 55 to 65 GHz then down converts it to below 5 GHz. When a 90-degree coupler is used to combine the I and Q signals from the output ports, the RF front-end works in the down-converter mode, and the IF frequency is in the band of 3 to 5 GHz. When the 90-degree coupler becomes two microstrip lines by a tiny assembly change, the RF front-end operates in the demodulator mode, and the I and Q signals are in the band of 0 to 5 GHz. In Figure 1(a), two low noise amplifiers (LNA1 & LNA2) CHA2159 manufactured by UMS provide up to 40 dB gain with less than 4 dB noise figure. Multifunction chip CHX1298 (UMS Co.) is used as a single-side-band sub-harmonic mixer. A 4-times frequency multiplier chip CHX2095 (UMS Co.), an amplifier chip HMC606 (Hittite Co.) and a high pass filter (HPF) compose the LO-link circuit to process the LO signal. All circuits are integrated on a 22 mm × 33.5 mm Rogers RO4003 board with relative permittivity 3.55 and thickness 0.203 mm. An innovation point of this design is the special configuration, as shown in Figure 1(b). A novel microstrip-to-waveguide transition using the SIW is employed to isolate the LNA1 from the waveguide cavity; this characteristic is suitable for sealing. Another feature is that each chip is mounted in a different cavity, which is better to reduce mutual interference, especially to the LNA MMICs. The SIW as the microwave signal transmission line is also beneficial to reduce the radiation to air.

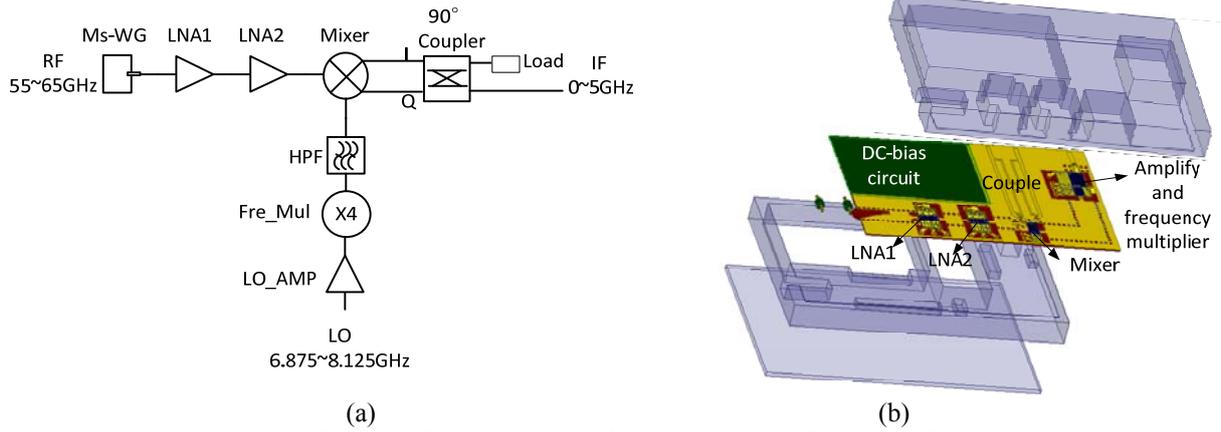


Figure 1. (a) Block diagram of the 60 GHz RF front-end, (b) Configuration of the RF Front-end

Table 1 shows the link budget of the RF front-end. As the down-converter mode, the mixer and the 90-degree coupler act as an image rejection mixer, the total gain is about 26 dB and the total noise figure is 4.53 dB. As the demodulator mode, the single-side-band noise figure is about 4.53 dB and the total gain is 23.5 dB.

Table 1. Link budget of the 60 GHz front-end

Section	WG-Ms	LNA1	LNA2	Mixer	90° Coupler	Total
Gain (dB)	-0.5	20	20	-16	2.5 ¹ ; 0 ²	26 ¹ ; 23.5 ²
Noise Figure (dB)	0.5	4	4	13 ¹ ; 16 ²	0.5 ¹ ; 0 ²	4.53 ¹ ; 4.53 ²

¹ Down-converter mode, ² Demodulator mode.

3. Circuits design and simulation results

In this section, three main circuits are designed in details, which are microstrip-to-waveguide transition, LNA circuit and mixer circuit. Simulation results of using HFSS and ADS software are provided.

3.1 Microstrip-to-waveguide transition

Figure 2(a) shows a novel configuration of the waveguide-to-microstrip transition. A SIW is used to connect the microstrip and waveguide and to isolate the following LNA circuit from the waveguide cavity. Using the transition, the quasi-TEM mode of the microstrip is transformed into the TE₁₀-like mode of SIW and WR-15 waveguide. A radiation probe with an exponential taper profile is used to transform the SIW to waveguide, which is defined by the function $y = \pm M \cdot \exp(-N \cdot x)$. At the tip of the probe, a semicircular substrate extends to match the SIW with the waveguide. After optimized by using HFSS software, the tapered line length L_{prob} is found to be 3.85 mm, the parameter M is 0.3069, N is 1.042, and the semicircular substrate radius R_{sub} is 1.05 mm. The simulation results are depicted in Figure 2(b). It can be seen that, in the band of 55 to 65 GHz, the reflection coefficient is close to -20 dB and the insertion loss is less than -0.3 dB which is of excellent performance.

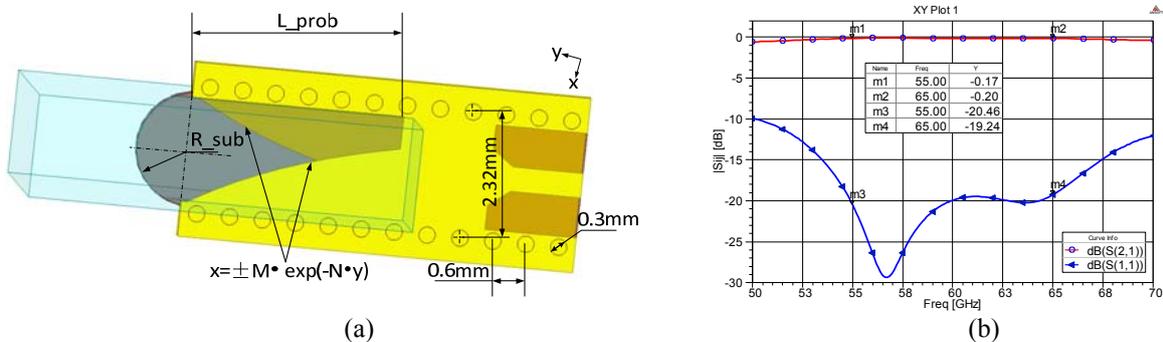


Figure 2. (a) Configuration of the waveguide-to-microstrip transition, (b) S-parameters

3.2 LNA

In the design of LNA circuit, the SIW plays an important role not only to form passive circuits but also to isolate the cavities for mounting chips. First, the microstrip-to-waveguide transition converts the waveguide port to microstrip port, and then two kinds of transformer, microstrip-SIW-microstrip (Ms-SIW-Ms) and microstrip-SIW-coplanar waveguide (Ms-SIW-CPW), are used for connecting the chips. Figure 3 gives the layouts and simulation results of the two transformers. In addition, the cavity is also considered in simulation to avoid resonance. The results shows that the insertion loss is less than -0.2 dB and the reflection coefficient is better than -20 dB in the band of 55 to 65 GHz.

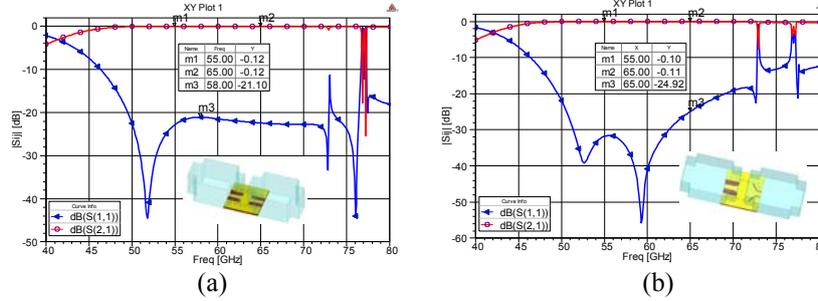


Figure 3. (a) Structure and the S-Parameters of Ms-SIW-Ms, (b) Structure and the S-Parameters of Ms-SIW-CPW

The LNA circuit is simulated using ADS software, the schematic diagram and the simulated results are displayed in Figure 4. Two CHA2159 chips are the main components; each is a four-stage low noise and medium power amplifier with 4.0 dB noise figure and 20 dB gain in the band of 55 to 65 GHz. In the schematic simulation, the S-parameters of microstrip-to-waveguide transition, Ms-SIW-Ms and Ms-SIW-CPW transformer are all from HFSS simulation results. The MMIC chips connect with microstrip by bonding wire, whose inductance effect is not negligible in 60 GHz band. Therefore, the matching between the chip and the microstrip is essential. Figure 4(b) shows the gain-frequency response curve of the LNA circuit. For the matched case, the gain slope (the different between maximum gain m1 and the minimum gain m2) is 2.83 dB, for the other cases (the different between maximum gain m3 and the minimum gain m4) is up to 8.93 dB, especially in high frequency band, the gain decreases rapidly.

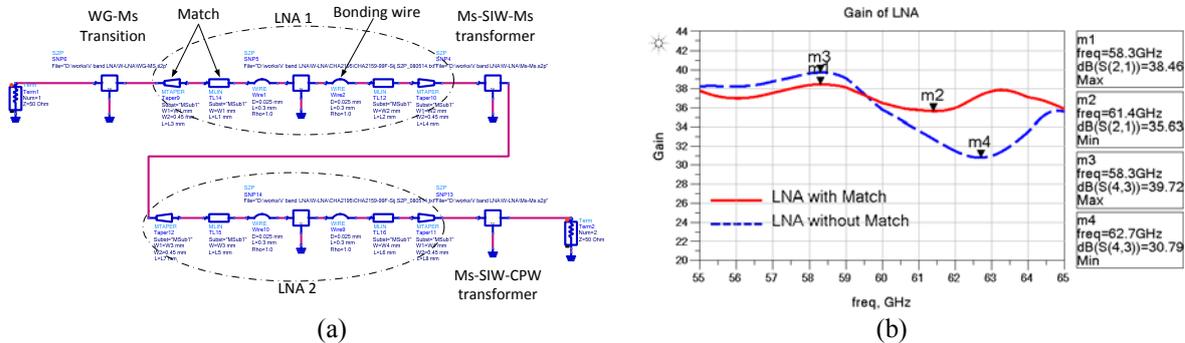


Figure 4. (a) Schematic diagram of the LNA circuits, (b) Gain-frequency response curves of the LNA circuits

3.3 Mixer circuit

The mixer circuit includes mixer chip and LO-link circuit. A single-side-band mixer chip CHM1298 is used to demodulate the RF signal to the I and Q signals, which is a multifunction chip integrating a LO buffer amplifier and a sub-harmonically balanced diode mixer for 2LO suppression and image rejection. When the I and O ports are connected with a 90 degree coupler, the circuit works at image rejection mixer mode, otherwise, it is a demodulator. Figure 5(a) displays the layout of the coupler, in which, microstrip to coplanar waveguide transition is designed to match the mixer ports on different layers. The 50-ohm transverse (horizontally drawn) microstrips connect the longitudinal (vertically drawn) microstrips by gold belts. Without the belts, the two transverse lines are independent microstrips to connect port 1 to port 3 and port 2 to port 4. The front-end can be easily switched to down-converter mode or demodulator mode by changing the belts. The coupler was simulated using HFSS software and depicted in Figures 5(b) and (c). The reflection coefficient S11 and the isolation S41 are less than -8 dB; the insertion loss S21 and S31 are less than -4.5 dB; the amplitude differences of S21 and S31 are within ± 0.7 dB, and the phase differences are within 90 ± 20 degrees over the frequency of interest (3 -5 GHz).

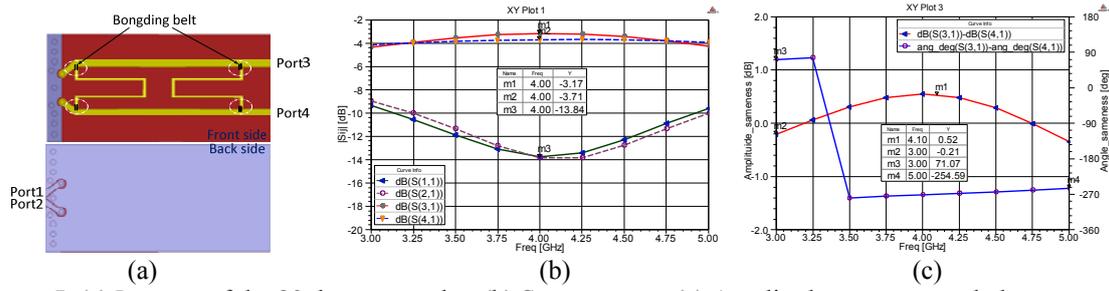


Figure 5. (a) Layouts of the 90 degree coupler, (b) S-parameters, (c) Amplitude sameness and phase sameness

In the LO-link circuit, a low phase-noise amplifier HMC606 is used to provide gain and driving power for frequency multiplier CHX2095. Figure 6(a) displays the output curves of the multiplier. Besides the useful 4th harmonic output, there are also 1st, 2nd and 3rd harmonics. According to the operation frequency and the working mode of the front-end, the LO frequency is set in the band of 6.875 to 8.125 GHz. Figure 6(b) gives the output power of the multiplier as a function of the frequency. It is noted that the amplitudes of the useless harmonics are very high, especially the 3rd harmonic. These useless harmonics will produce spurious signals at the IF port after mixing with RF signal. An Ms-SIW-Ms transformer is used as a high-pass filter (HPF) to restrain the useless harmonics, whose configuration and the simulation results are displayed in Figure 6(c). The rejection to the 3rd harmonic is up to -33 dB and the insertion loss is less than -0.5 dB.

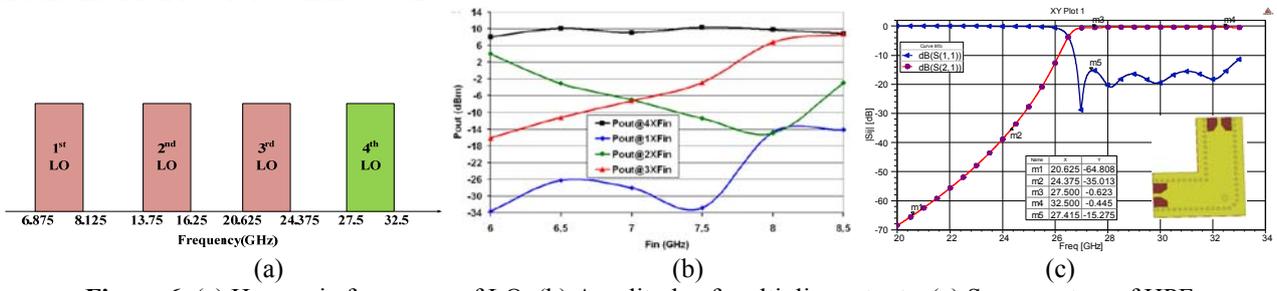


Figure 6. (a) Harmonic frequency of LO, (b) Amplitude of multiplier outputs, (c) S-parameters of HPF

4. Conclusion

In this paper, a high performance RF front-end of a 60 GHz receiver is designed and simulated, which not only has a good noise figure (4.53 dB), but also can provide two working modes. A SIW is used to connect chips and also to realize passive circuits. The SIW and the metal attachment separate the waveguide cavity and the active circuits, therefore, this structure is excellent for the sealing of MMIC chips. This innovative design achieves excellent EMC performance and is particularly suitable for military and space applications. The main circuits are simulated in details using HFSS and ADS, and the results agree well with the design goals.

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