Short Papers

Monolithic Rat-Race Mixers for Millimeter Waves

Hiroyuki Matsuura, Kentaro Tezuka, Ikuro Aoki, Mineo Yamanaka, Shinji Kobayashi, Tadashige Fujita, and Akira Miura

***Abstract*—In this paper, we report on fully monolithic millimeter-wave Schottky-barrier diode (SBD) down-converters with an IF amplifier using heterojunction bipolar transistors (HBT's). A rat-race circuit is used for the mixer, and is analyzed using a harmonic-balance simulator. The measured conversion gain and the isolation are 7.1 and 29 dB in the V-band design, and 8.0 and 25 dB in the W-band design, respectively. The conversion gains are well matched with the circuit simulation.**

***Index Terms*—CPW, GaAs, HBT, millimeter wave, MMIC, V-band, W-band.**

I. Introduction

Recently, several applications in the millimeter-wave frequency range (e.g., an automobile collision-avoidance radar and a wireless local-area network system) are being developed by a number of organizations. The monolithic microwave integrated circuit (MMIC) technology is very important not only for these applications, but also for measuring instruments in this frequency range. A high-performance low-cost measuring instrument in the millimeter-wave frequency range will contribute to making these applications realistic. A frequency down-converter technology described in this paper can be used as a front-end module of a millimeter-wave spectrum analyzer.

We have already reported the monolithic W-band frequency down-converters using Schottky-barrier diodes (SBD's) and heterojunction bipolar transistors (HBT's) [1]. In this paper, we show the consideration of the W-band circuit design, and the performance of this device combination for V-band down-converters.

II. Circuit Configuration

Fig. 1 shows a schematic of the down-converter. The mixer section uses a rat-race and two SBD's. A rat-race circuit has four ports that match 50 Ω, thus we assigned one each to the LO signal, the RF signal, and two diodes. An IF signal with a frequency lower than that of the LO and RF signals can be derived from any point on the rat-race circuit. One method of connecting the IF line is via the RF port on the rat-race circuit with a low-pass filter [2]. The IF line can also be connected at the mixing diodes of the rat-race circuit [3]–[5]. In [6], the IF port is connected on the opposite side of the RF port on the rat-race circuit (point Q in Fig. 1). Another choice for the connection is point P in Fig. 1, because the isolation from the LO port to the RF port is good. Point P is two quarter-wavelengths and four quarter-wavelengths from both the LO and RF ports. Therefore, the RF and LO signals are canceled out at point P. Thus, there are two ways of designing W-band down-converters. In V-band design, we connected the IF port to point Q only, but designed two patterns using different diode sizes. Thus, we have designed four patterns of down-converters (these specifications are given in Table I, with measured values). The dimensions of the 70-Ω coplanar waveguide (CPW) used in the rat-race are a center conductor width of 16 μm and a ground-to-ground spacing of 84 μm.

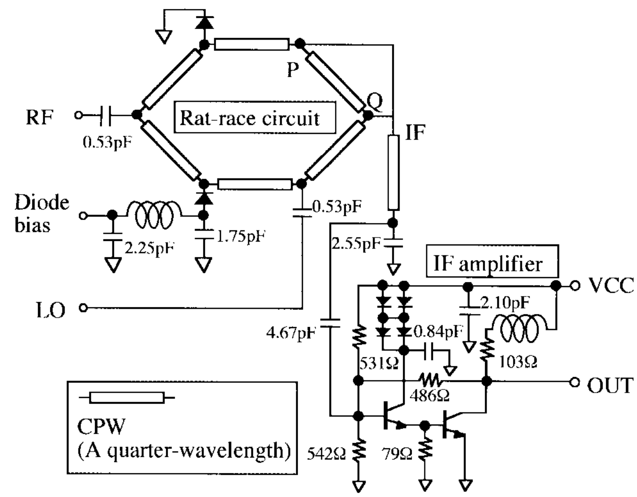

Fig. 1. Schematic of the monolithic down-converter.

TABLE I
Summary of the Down-Converters

Pattern name	V-Band 1	V-Band 2	W-Band 1	W-Band 2
IF connection	Q	Q	Q	P
CPW length	500 μm	500 μm	300 μm	300 μm
Diode size	2.1 μm x 5 μm	2.1 μm x 10 μm	2.1 μm x 5 μm	2.1 μm x 5 μm
Diode bias	1.10 V	1.10 V	1.48 V	1.43 V
Conversion gain	+6.7 dB	+7.1 dB	+7.7 dB	+8.0 dB
Leakage (LO-RF)	-22 dB	-29 dB	-24 dB	-25 dB
RF signal	62 GHz / -4.5 dBm		94 GHz / -8 dBm	
LO signal	60.9 GHz / +10.5 dBm		93 GHz / +6 dBm	

All the mixers include a 50-Ω quarter-wavelength CPW with a shunt capacitor at the IF port on the rat-race circuit for filtering out the RF and LO signals. This filtering circuit acts as a high-impedance element at millimeter-wave frequency, so there was no influence of the filter on the characteristics of the rat-race in the design. We connected an HBT IF amplifier next to the filter.

We used a circuit simulator to confirm the conversion loss of the mixer. The result of a harmonic-balance simulator (HP MDS) is shown in Fig. 2. The simulation was performed without the HBT IF amplifier to focus on the rat-race mixer only. The circuit parameters of the rat-race part in Fig. 1, and the dimension of the transmission-lines shown above are used for the simulation. The applied frequencies and the power of the RF port of the mixer are the same values as those in the experiment.

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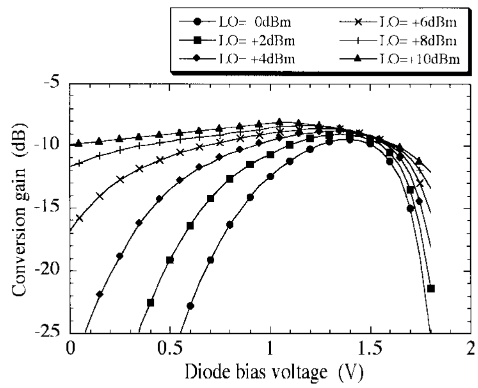
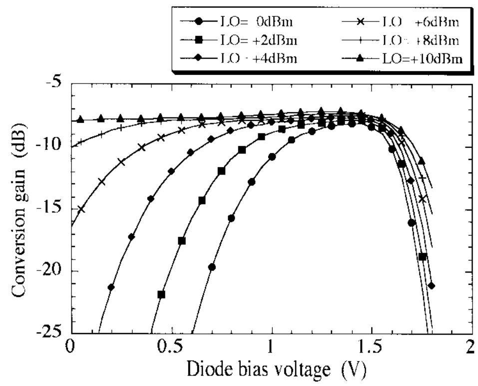


(a)



(b)

Fig. 2. Result of circuit simulation. (a) V-band rat-race mixer. (b) W-band rat-race mixer.

In Fig. 2, the horizontal axis is the dc bias voltage of the mixing diodes, and the vertical axis is the conversion gain. Each trace indicates the LO power from 0 to +10 dBm in 2-dBm steps. Both V- and W-band circuits have the best conversion gain, around -8 dB, under the condition of proper bias voltage, from around 1.2 to 1.6 V. The larger LO power provides a better conversion gain at the lower or higher bias voltage region. Therefore, the results show that the conversion gain is not influenced by the change of the LO power under the proper SBD bias condition. Generally, the low-power LO is advantageous for a MMIC system in the millimeter-wave frequency range, therefore, the importance of the diode bias is confirmed from this circuit simulation. Incidentally, the simulation of the isolation characteristics is very difficult because of the stray devices. Therefore, we show the measured result only for the V- and the W-bands.

III. Measured Performance

The integrated circuits (IC's) are fabricated on a 4-in GaAs wafer [1]. An HBT with $f_T = 50$ GHz and $f_{\rm MAX} = 50$ GHz uses an AlGaAs/GaAs system. The SBD is realized at the collector layer with a cutoff frequency of $F_c = 1.3$ THz. The size of the diode is 2.1 μm $\times$ 5 μm for the W-band mixer [1]. For the V-band mixer, we designed two chips with small diodes (2.1 μm $\times$ 5 μm) and large diodes (2.1 μm $\times$ 10 μm). Fig. 3 shows the photograph of the V-band down-converter. The pattern of the W-band converter is similar to the V-band one.

The summary of the measured results is shown in Table I. Figs. 4 and 5 show the conversion gain and the LO-RF leakage of the V-band down converter, respectively. The V-band down-converter with the large diodes (V-Band 2) has a 7.1-dB conversion gain and -29-dB LO–RF leakage. We compared it to the down-converter with the small diode (V-Band 1). In the case of using the small diodes, the leakage is degraded to -22 dB, due to the impedance mismatch of the rat-race circuit. However, the conversion gain of V-Band 1 is 6.7 dB, which is almost the same as that of the down-converter with the large diodes. Therefore, the large diodes are better for this frequency than the small diodes. However, for the W-band frequency, the small diodes are better when comparing the conversion gain [1].

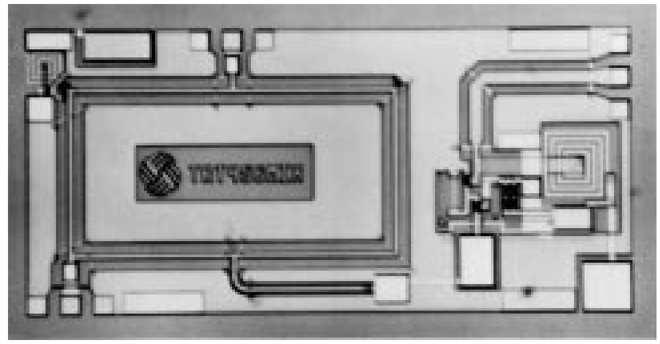


Fig. 3. Photograph of the V-band down-converter. Lower left: LO signal. Upper left: dc bias. Top: RF signal. Right: IF signal. Chip size: 1.0 mm $\times$ 2.0 mm.

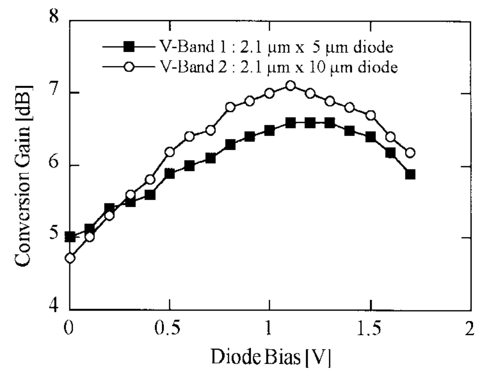


Fig. 4. Measured diode bias versus conversion gain (V-band).

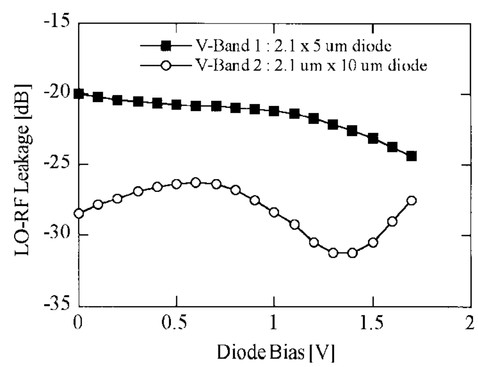


Fig. 5. Measured diode bias versus leakage (V-band).

The HBT IF amplifier has a 14.5-dB gain at the IF frequency of 1 GHz. The conversion gain of the rat-race part, calculated from the total gain 6.7 dB, and the gain of the IF amplifier is -7.8 dB. It is almost the same as that in Fig. 2(b). In addition, the shapes of the lines in Fig. 2(a) and in Fig. 4 are similar. From a comparison of these figures, the actual LO level is estimated to be between 8–10 dBm. The LO level and RF level in the V-band were also measured using the spectrum analyzer and the harmonic mixer, therefore, there might be a measuring error of the power. These results show the effectiveness of the circuit simulation that is shown in Fig. 2, and the suitable action of the actual MMIC's. The conversion gain of the W-band down-converter (W-Band 2; IF signal connected at point P in Fig. 1) is 8.0 dB. Therefore, the rat-race circuit without the IF amplifier has a -6.5-dB conversion gain. We also measured another design (W-Band 1; IF signal connected at point Q in Fig. 1), and found its conversion gain to be 7.7 dB. This is a comparable value within measurement errors. The rat-race circuit without the IF amplifier has a -6.8-dB conversion gain. These values are close to the estimated value shown in Fig. 2(a). We think the errors mainly arise from the power measurement of the millimeter-wave signal performed using a spectrum analyzer with a harmonics mixer. The leakage from LO to RF of W-Band 1 and W-Band 2 are -24 and -25 dB, respectively. In conclusion, we can use either point P or Q in Fig. 1 as an IF signal connecting point under a proper diode bias.

As compared to that of the W-band down-converters, the conversion gain of the V-band down-converters is slightly lower. At first, we considered this to be due to the conductive loss of the CPW of the rat-race circuit, because the length of the CPW for V-band down-converters is 1.67 times longer than that for W-band down-converters. However, Fig. 2 shows that there is no significant difference. We think that the difference comes from the error of the power measurement in the millimeter-wave range.

IV. Conclusion

We have described the millimeter-wave diode down-converters with an HBT amplifier. The combination of high cutoff SBD's and HBT's works very well as a high-frequency down-converter. This combination can be used for the integration of other circuits such as an HBT oscillator [7], [8]. In addition, HBT's have the ability of power handling, so an LO amplifier using HBT's might be a good choice for the frequency converters. We believe that the device combination can be used for many applications in this frequency range.

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A Switchable Multi-Sector Antenna for Indoor Wireless LAN Systems in the 60-GHz Band

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***Abstract*—A switchable multi-sector antenna for indoor wireless local-area network (LAN) systems in the 60-GHz band has been proposed. The antenna has a pyramidal configuration. Each isosceles-triangular surface of the pyramid has been inclined 30° from the vertical axis in order to cover an appropriate elevation angle range. This antenna excites a right-handed circularly polarized wave to suppress unwanted multipath delayed waves. The low-loss curved microstrip-line feeding has been introduced at the junction between antenna feed lines and monolithic microwave integrated circuit (MMIC) amplifiers at the bottoms of the pyramid. Using this antenna, the terminal receiver for indoor wireless LAN systems in the 60-GHz band has been developed.**

***Index Terms*—Curved microstrip lines, millimeter-wave LAN's, multi-sector antenna, patch antennas.**

I. Introduction

Recently, demand for high-speed and large-capacity wireless local-area network (LAN) systems is growing. Millimeter-wave wireless LAN's are expected to achieve a data transmission rate as high as 156 Mb/s, which is compatible with asynchronous transfer mode (ATM) cable networks.

In Japan, the millimeter-wave band between 59.0–60.0-GHz band has been allocated for use in developmental experiments for millimeter-wave wireless LAN systems [1]. The effectiveness of the circular polarization and directive antennas to suppress the unwanted multipath delayed waves [2], and the reflection and transmission coefficients of typical structures in modern offices [3] have been evaluated. These results indicate that the use of circular polarization can reduce the influence of single-bounce multipath reflected waves experiencing single-bounce reflections, which are the main contributors to deteriorating transmission quality. Shadowing caused by human bodies is another important issue to be considered. The effects of shadowing to millimeter waves were discussed in [4]. One of solutions to this problem is the implementation of macroscopic diversity, in which each remote terminal (RT) can communicate with

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