SCHOTTKY-BARRIER DIODE CONVERTERS IN THE SHORT MILLIMETER WAVELENGTHS REGION

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ABSTRACT

A theoretical analysis of upconverters, and an experimental waveguide-type upconverter and downconverter at 120 GHz are described. An upconverter with an output power of 2.5 dBm, and a downconverter with a conversion loss of 9.2±0.7 dB and an RF bandwidth of 35 GHz were obtained.

[I] INTRODUCTION

A guided millimeter-wave (mm-wave) transmission system in Japan, W-40G, has been developed and the field evaluation test is successfully being continued.[1] The W-40G system uses a frequency range of 43-87 GHz. This paper reports the works on n-GaAs Schottky-barrier diode (SBD) upconverters and downconverters beyond that frequency range.

In designing the circuit and diode to be used, theoretical studies concerning the impedance, voltage and current waveforms, and power relation are necessary. An SBD is characterized by two nonlinealities of resistance and of capacitance. As for downconverters, an analysis which takes into consideration these two nonlinealities has been reported.[2] In this analysis, differential equations of voltage and current with respect to time are built and they are solved by means of the Runge-Kutta-Gill method. However, there have been no reports on theoretical works of upconverters using an SBD.

In this paper, first an analysis of SBD upconverters is shown. The analysis is based upon the similar concept to that of the downconverters.[2] Then an experimental upconverter and downconverter in the 120-GHz band are described.

[II] UPCONVERTERS

2.1 Voltage-current relations and differential equations

Fig.1 shows an upconverter circuit. Three circuits are connected to an SBD: a mm-wave circuit, an IF circuit, and a DC circuit. (The mm-wave circuit represents both the local-oscillator circuit and output circuit.) Each circuit has an excitation or signal source: a local oscillator (frequency: f_{LO}), an IF signal source (frequency: f_{IF}), and a DC bias source. Those circuits are separated by three ideal filters, each of which short-circuits for wanted frequencies and opens for unwanted frequencies. Since the diode is capacitive, inductances are connected in the mm-wave and IF circuits to make the impedances be matched to the diode. The inductance in the DC circuit is a choke inductor.

In Fig.1, the voltage-current relation of the SBD is

$$I_T = I_S[\exp(eV_B/\eta kT)-1] + C_o(1-V_B/\phi)^{-\gamma}\, dV_B/dt$$
$$V_T = R_S I_T + V_B. \qquad (1)$$

From voltage-current relations of the SBD and connected circuits, one obtains a set of differential equations with respect to IF phase angle Θ ($\Theta=\Omega t$, $\Omega=2\pi f_{IF}$) as follows:

$$dI_{MM}/d\Theta = [E_{MM}\sin n\Theta - R_{MM}I_{MM} - R_S I_T - V_B - V_{FM}]/(\Omega L_{MM}) \qquad (2)$$
$$dI_{IF}/d\Theta = [E_{IF}\sin\Theta - R_{IF}I_{IF} - R_S I_T - V_B - V_{FI}]/(\Omega L_{IF}) \qquad (3)$$
$$dI_{DC}/d\Theta = [E_{DC} - R_{DC}I_{DC} - R_S I_T - V_B - V_{FD}]/(\Omega L_{DC}) \qquad (4)$$
$$dV_B/d\Theta = [I_{MM} + I_{IF} + I_{DC} - I_S\{\exp(eV_B/\eta kT)-1\}]/(\Omega C_B) \qquad (5)$$

where n is an integer and shows the ratio of f_{LO} to f_{IF}. Each resistance and inductance is assumed to take the same value for all frequencies. This is approximately valid when IF is very low compared to local-oscillator frequency.

MMF short-circuits for $kf_{IF}(k\geq m+1)$ and opens for DC and f_{IF}, $2f_{IF}$, $\cdots$, mf_{IF}. IFF short-circuits for f_{IF}, $2f_{IF}$, $\cdots$, mf_{IF}, and opens for DC and $kf_{IF}(k\geq m+1)$. DCF short-circuits only for DC and opens for other frequencies. Then the voltage drops of filters V_{FM}, V_{FI}, and V_{FD} are

$$V_{FM} = -\sum_{|\ell|\leq m} V_{T\ell}\, e^{j\ell\Omega t},\quad V_{FI} = -\sum_{|\ell|\geq(m+1),\,=0} V_{T\ell}\, e^{j\ell\Omega t},\quad V_{FD} = -\sum_{\ell\neq 0} V_{T\ell}\, e^{j\ell\Omega t} \qquad (6)$$

where $V_{T\ell}$ is the ℓth Fourier expansion component of V_T. mf_{IF} is chosen to be near the cutoff frequency of the waveguide used for the mm-wave circuit.

2.2 Numerical computation

By computing the steady-state solutions of Eqs.(2)-(5) and by their Fourier components with respect to f_{LO}, f_{IF} and f_{OUT}, one can know the voltage-current waveforms, impedances, and input-output power relation of the upconverter. An upper-sideband upconverter is considered here. The output frequency f_{OUT} is the sum of f_{LO} and f_{IF}.

The process of computation is as follows:

(1) Voltage drops of filters After setting the diode parameters (listed in Table 1), source voltages (E_{MM}, E_{IF}, and E_{DC}), resistances and inductances of three external circuits, and the initial values of V_{FM}, V_{FI} and V_{FD}, one computes the steady-state solution of V_T by means of the Runge-Kutta-Gill method. From their Fourier components, more accurate voltage drops of filters are given. Correct V_{FM}, V_{FD} and V_{FD} are obtained by iterating this computation.

(2) Matched impedances In order to utilize the local-oscillator and IF powers effectively, the impedances are necessary to be matched to the diode. For obtaining this matching condition, the resistances and inductances are varied so as to satisfy the following equations:

$$R_{MM} + j\omega L_{MM} = [V_{Tn}/I_{Tn}]^*,\quad R_{IF} + j\Omega L_{IF} = [V_{T1}/I_{T1}]^* \qquad (7)$$

where $I_{T\ell}$ is the ℓth Fourier expansion component of I_T.

(3) Voltage and current waveforms, and power relation By iterating processes (1) and (2), one can obtain the voltage and current waveforms, impedances, and power relation with a sufficient accuracy. The available powers of the local-oscillator and IF source, P_{LO} and P_{IF}, their delivered powers to the diode, P_{LOIN} and P_{IFIN}, and the output power P_{OUT} are

$$P_{LO} = |E_{MM}|^2/8R_{MM},\quad P_{IF} = |E_{IF}|^2/8R_{IF},$$
$$P_{LOIN} = 2Re[V_{Tn}I_{Tn}^*],\quad P_{IFIN} = 2Re[V_{T1}I_{T1}^*], \qquad (8)$$
$$P_{OUT} = -2Re[V_{Tn+1}I_{Tn+1}^*].$$

2.3 Computed result

Computed characteristics for f_{LO}=110 GHz, f_{IF}=11 GHz, and f_{OUT}=121 GHz are shown below. Let us consider the R-1200 rectangular waveguide (frequency: 90-140 GHz; inside dimension: 2.032×1.016 mm²) for the mm-wave circuit. Since the cutoff frequency of this waveguide is 73.7 GHz, m is set at 7 in the computation. The diode parameters used in the computation are listed in Table 1. They were obtained by measurement[3] of n-GaAs SBD's (honeycomb type) placed in waveguide-wafer-type diode holders.

Fig.2 shows computed voltage and current waveforms as a function of IF phase angle. Fig.2(a) is the waveform of V_B (voltage across the barrier). It shows that the voltage waveform is far from sinusoidal. From the maximum reverse voltage, one can know a necessary reverse breakdown voltage of the diode. (The breakdown voltage relates to the impurity concentration and thickness of epitaxial layer.) Fig.2(b) is the current waveform. The current through the barrier resistance (dotted line) is also shown. The current through the barrier resistance folws during half a cycle of IF and the displacement current dominates the other half cycle. From these waveforms one can know the power spectra for various harmonic frequencies. The power spectra are important imformation in designing filters for suppressing spurious interference and in estimating reliability of diodes in practical transmission systems use. Fig.3 is the power spectra. The lower sideband has approximately the same level as the upper sideband.

Fig.4 shows diode impedances for various local-oscillator powers as a function of IF power. The resistances increase gradually with increase in IF power. Fig.5 is the input-output power relation for various local-oscillator powers.

2.4 Experimental result

An upconverter using the R-1200 rectangular waveguide and an n-GaAs honeycomb SBD has been built. An unencapsulated diode is mounted in a waveguide-wafer-type diode holder. The height of the waveguide where the diode is mounted is 0.3 mm. Transition between the reduced and standard waveguides is made by a tapered waveguide. The other side of the waveguide is terminated by a reduced-height waveguide short. The IF coaxial line is cross-coupled to the mm-wave waveguide. The upper-sideband signal is separated from the local-oscillator and lower-sideband powers by a circulator and a cutoff filter. The diode parameters measured[3] at 120 GHz with this waveguide-wafer are listed in Table 1. The series resistance includes RF loss in the IF coaxial line. Breakdown voltage of the diode is 12 V.

Fig.6 shows the input-output power relation of this upconverter. The output power is 2.5 dBm when $P_{LO} = P_{IF} =$ 12.5 dBm.

Thermal loss of the waveguide short and reflection loss are estimated below. VSWR of the short is about 6, and the resulting loss is estimated as 1 dB. VSWR of the diode is 2.5 for both local-oscillator frequency and IF. Therefore, the total reflection loss is estimated as 1.2 dB (including a saturation effect of 0.5 dB). An increase in output power of 2.2 dB is expected when one makes the circuit complete. If one considers these circuit imperfection, the experimental result agrees with the theoretical computation.

[III] DOWNCONVERTERS

An experimental broad-band downconverter is described below. An n-GaAs SBD is mounted in a reduced-height(0.3 mm) R-1200 waveguide-wafer. In this downconverter, lossy dielectric material (epoxy resin with carbonyl iron) is inserted into the coaxial line of IF circuit. The fundamental structure is the same as the previously reported 60-90-GHz downconverter.[4] Since the loss of the inserted material is large in the mm-wave region and is slight in lower frewuencies, it suppresses ripples in frequency response caused by RF reflection within the coaxial line. This downconverter has no special circuits for rejecting the image or other harmonic frequencies.

Fig.7 shows a measured conversion loss as a function of signal frequency. The local-oscillator frequency is varied so that the IF is kept constant (=1.7 GHz). The circuit is fixed within the whole frequency band. The input VSWR for local-oscillator frequency is less than 2.5 and the conversion loss is 9.2 ± 0.7 dB for 90 - 125 GHz.

Since the inserted lossy material degrades the effective diode Q, conversion loss degradation is of interest. The diode Q is 2.9 and 5.1 for the case with and without the lossy material, respectively. The author computed the conversion loss of an image-matched downconverter for various Q's by means of the method described in [2]. (Fig.8) From Fig.8, the increase in conversion loss is about 1.5 dB.

[IV] CONCLUSION

Theoretical and experimental works on Schottky-barrier diode converters in the 120-GHz band have been reported. The voltage and current waveforms, power and impedance relations of upconverters have been made clear by the analysis. Experimentally, an upconverter with an output power of 2.5 dBm and a downconverter with a conversion loss of 9.2 ± 0.7 dB (90-125 GHz) have been obtained.

[V] ACKNOWLEDGMENT

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[VI] REFERENCES

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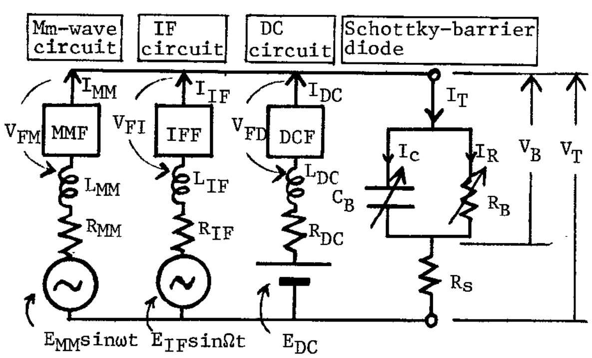


$$I_R = I_S[\exp(eV_B/\eta kT) - 1], \quad I_c = C_B\, dV_B/dt$$

$$I_T = I_R + I_c = I_{MM} + I_{IF} + I_{DC}$$

$$\omega = 2\pi f_{LO}, \quad \Omega = 2\pi f_{IF}, \quad \omega = n\Omega$$

Fig.1 Circuit construction of the upconverter.

Table 1 Diode parameters used in the upconverters.

I_S	Saturation current, 1.4×10^{-14} A
η	Slope factor of current, 1.1
R_S	Series resistance, 17 Ω
C_B	Junction capacitance, $C_B = C_o(1 - V_B/\phi)^{-\gamma}$
C_o	Junction capacitance at zero-bias, 0.022 pF
γ	Slope factor of capacitance, 0.3
ϕ	Diffusion voltage, 0.85 V
e/kT	= 40 [1/V] at room temperature

I_S and η were measured at DC. R_S, C_o, and γ were measured at 120 GHz.

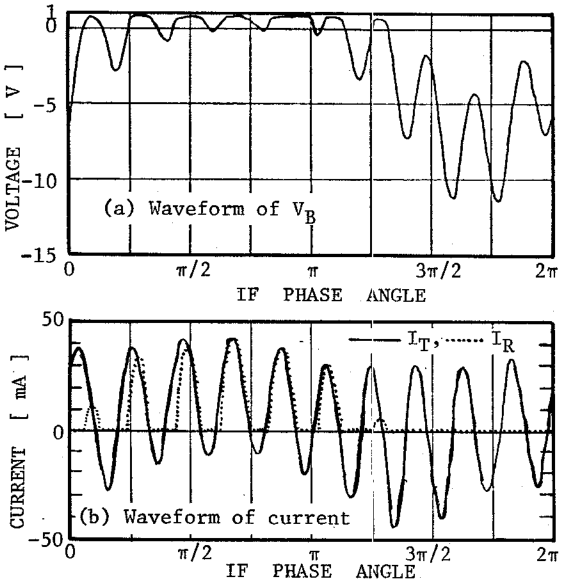


Fig.2 Voltage and current waveforms. $P_{LO}=P_{IF}=12.5$ dBm, $E_{DC}=0$ V, $R_{DC}=300\ \Omega$.

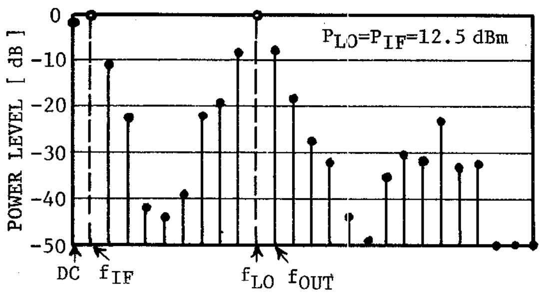
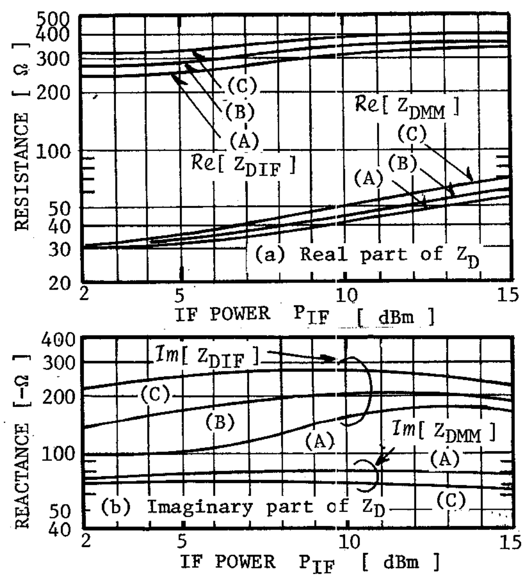


Fig.3 Power spectra. Broken lines show input powers (P_{IF} and P_{LO}) and solid lines show output powers. $P_{LO}=P_{IF}=12.5$ dBm, $E_{DC}=0$ V, and $R_{DC}=300\ \Omega$.



$Z_{DMM} = V_{Tn}/I_{Tn}$, $Z_{DIF} = V_{T1}/I_{T1}$

Fig.4 Diode impedance looked at IF and local-oscillator frequency as a function of IF power P_{IF}. P_{LO} is 14 dBm for (A), 11 dBm for (B), and 8 dBm for (C). $E_{DC}=0$ V, and $R_{DC}=300\ \Omega$.

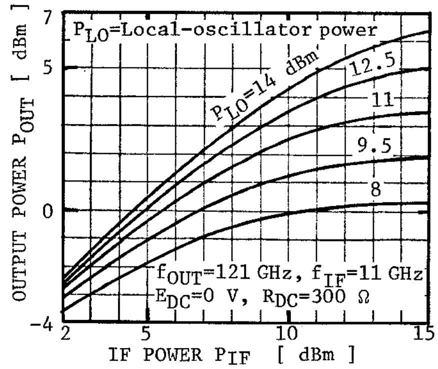


Fig.5 Input and output power relation of the upconverter.

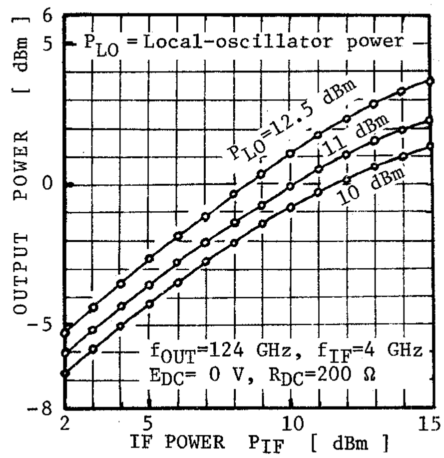


Fig.6 Input and output power relation of an experimental upconverter.

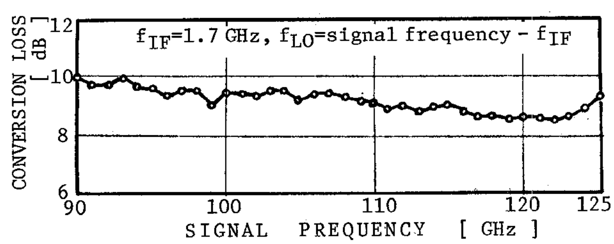


Fig.7 Conversion loss versus signal frequency of an experimental downconverter. Diode junction diameter= 3 μm, bias voltage=0.6 V (forward), and $R_s=30\ \Omega$ (including lossy material).

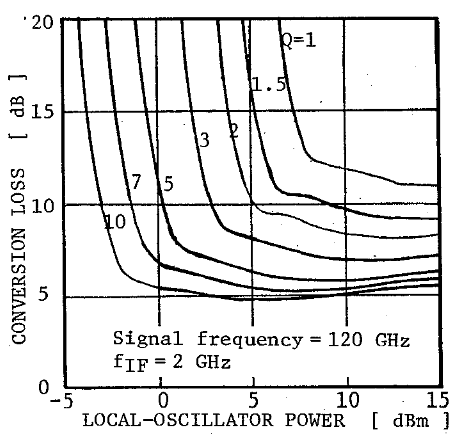


Fig.8 Computed conversion loss of downconverters. $C_o = 0.02$ pF, and R_s is varied according to $Q = 1/(2\pi f_{LO} C_o R_s)$.