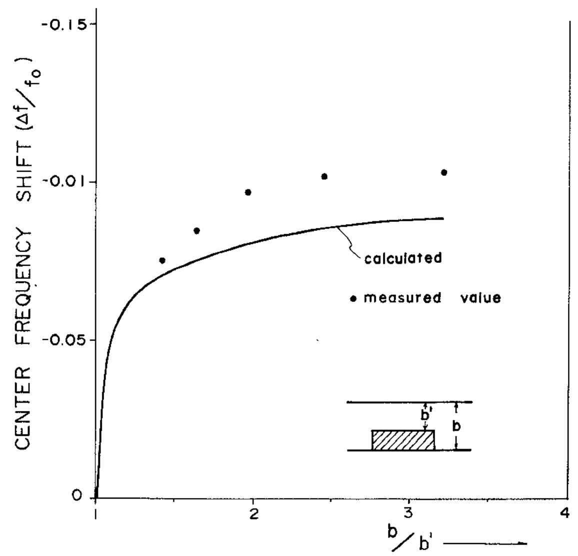

Fig. 4. Comparison of calculated and measured frequency shift of a half-wavelength line resonator due to reactances at discontinuities.

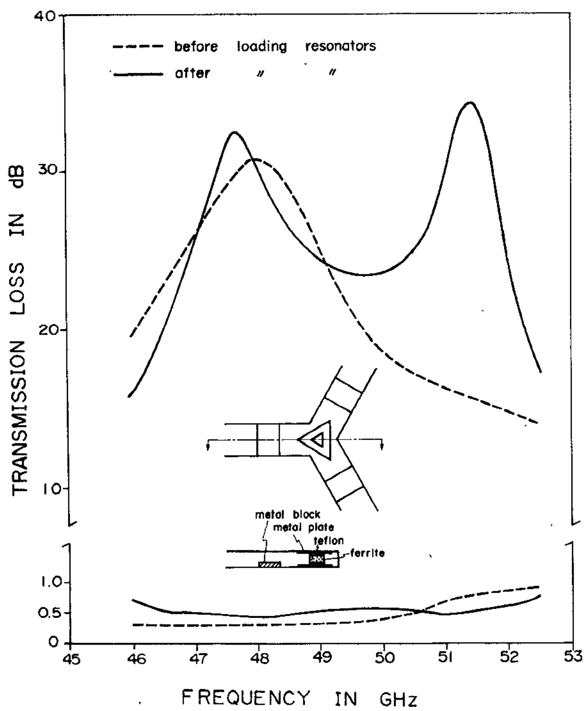

Fig. 5. Construction and characteristics of a circulator with half-wavelength line resonators.

are shown in Fig. 5 by broken lines. The bandwidth over which the isolation loss is greater than 20 dB is 3.5 GHz. The forward loss is 0.3 dB at the center frequency. The center frequency is 48 GHz and is determined by the resonance frequency of the triangular ferrite post. By assuming open circuit boundary conditions at the ferrite surfaces, the resonance frequency is given as follows [11], [12]:

$$f = \frac{1}{2(\epsilon\mu)^{1/2}} \left[\left(\frac{4}{3a}\right)^2 (m^2 + mn + n^2) + \left(\frac{p}{L}\right)^2 \right]^{1/2} \qquad (20)$$

where a is the length of the side of the triangle, L is the height of the ferrite post, and m, n, and p are integers. Experimental results from many frequency bands indicate that the operation mode of the present circulator is given by $m = 1$, $n = -1$, and $p = 1$ [12]. The measured center frequency is higher by 20 percent than the calculated frequency.

Fig. 2 shows the input admittance of the circulator before loading resonators looking 5.8 mm away from the junction center. Although the locus is distorted from that of an ideal resonator, the higher frequency part of the locus well represents a series resonance property. This part may be matched to the locus of parallel resonance of the half-wavelength line resonator.

Transmission losses after loading of resonators are shown in Fig. 5 by solid lines. The bandwidth is increased from 3.5 to 5.5 GHz. Forward loss is increased by 0.3 dB. The resonators are epoxy resin mounted 5.8 mm from the junction center. The external $Q\,(Q_e)$ of the resonators was chosen to be 2.2. Since the input impedance of the circulator before loading of resonators is distorted from that of an ideal resonator, the center frequency and the external Q of the resonators and the distance from the junction center to the resonators are determined experimentally to obtain the widest bandwidth.

V. CONCLUSION

Half-wavelength line resonators are employed to increase the bandwidth of a 50-GHz Y circulator. The bandwidth was successfully increased from 3.5 to 5.5 GHz. The resonator will be effective to increase the bandwidth of circulator with an inphase eigenexcitation resonator.

ACKNOWLEDGMENT

The author wishes to thank S. Kitazume, Y. Sakakihara, and Y. Kasuga for supplying a 50-GHz Y circulator and M. Yada for helpful discussions. He also wishes to thank Dr. H. Kaneko and Dr. M. Sugiyama for their encouragement and guidance.

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Low-Noise Down Converter and High-Efficiency Up Converter for Transmitter–Receiver Applications in the 60–86-GHz Region

NOBORU KANMURI, MEMBER, IEEE, MASAMI AKAIKE, HARUHIKO KATO, SUSUMU KITAZUME, HIDEKI KOBAYASHI, MEMBER, IEEE, AND HIROYUKI ISHIHARA

***Abstract*—Design and performance of a low-noise down converter and a high-efficiency up converter for transmitter–receiver applications in the frequency range of 60–86 GHz are described in this short paper. The receiver and the transmitter are used in a**

Manuscript received May 6, 1974; revised August 30, 1974.
N. Kanmuri, M. Akaike, and H. Kato are with the Yokosuka Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Yokosuka, Japan.
S. Kitazume, H. Kobayashi, and H. Ishihara are with the Millimeter-Wave and Video Communications Development Laboratory, Nippon Electric Company, Yokohama, Japan.

guided millimeter-wave transmission system "W-40G."

A wafer-type GaAs Schottky-barrier diode is used in both units. The diode mount consists of a semiconductor wafer and a whisker which are mounted in a waveguide circuit. The IF terminal is a coaxial line section which is connected to the whisker.

The conversion loss of the up and down converters using the new wafer is 7.5 and 5.5 dB, respectively. The bandwidth of the frequency converters is approximately ±10 percent in the frequency region of 60–86 GHz.

I. INTRODUCTION

The Electrical Communication Laboratory, Nippon Telegraph & Telephone Public Corporation (NTT), is carrying forward a scheme of putting the guided millimeter-wave transmission system "W-40G" to practical use. The W-40G system is capable of relaying approximately 300 000 two-way telephone channels by means of both go and return 26-millimeter-wave carriers in a frequency band of 43–87 GHz. A transmitter–receiver to be used in the W-40G system has been designed and manufactured based upon the results of overall relay experimentation performed in 1970 with the 50-GHz all solid-state 4-phase phase-shift keyed (PSK) repeater, and with the adoption of improved performances and technology advanced thereafter.

The design and characteristics of the low-noise down converter and high-efficiency up converter that constitute an essential part of the transmitter–receiver are described in this short paper. Results obtained on a series of experiments performed on a low-frequency model (microwave-frequency band) are also discussed. Linear scaling of the low-frequency model to millimeter-wave frequencies was used to obtain optimized millimeter-wave circuits. An entirely new wafer-type diode was also developed using frequency scaling. The new wafer-type diode is a GaAs Schottky-barrier diode. Two types of diodes were fabricated. They are almost the same except that the capacity and junction diameter of the GaAs Schottky-barrier diodes are different. Experimental results on the performance of each diode are described together with a discussion of the characteristics of up and down converters using these diodes.

II. WAFER-TYPE DIODE

In the millimeter-wave frequency band it is difficult to obtain broad-band characteristics by means of a pill-type diode package which is generally used in the microwave frequency band. For this reason the wafer-type diodes, which are directly built in the waveguide, are widely used today [3]–[6].

This type of diode is assembled by mounting a semiconductor pellet in a waveguide circuit using a whisker as an electrical contact. The whisker is used as part of the impedance match to the waveguide [7].

Problems often occur when using this technique for impedance matching due to the small size and controlling the dimensional accuracy of the whisker (wire diameter is 0.02 mm; length is 0.2–0.3 mm). For this reason, inconsistency in impedance matching results. It has been reported that the frequency bandwidth of the wafer-type diode depends in a large measure upon parasitic reactance of the whisker built in the waveguide [7]. In this case, the waveguide including parasitic reactance is matched to the impedance of the diode at full RF power. Because of the complexity of the waveguide circuit, it is difficult to design a matching circuit from the input side of the waveguide to the diode. Also when realizing the design of the matching circuit, special consideration must be given to eliminate inconsistency in the size and shape of the whiskers.

This emphasizes the need for developing a circuit that ensures matching over a sufficiently broad frequency band and which is simple in configuration. In undertaking the design two matching circuits are connected in tandem from the input side of the waveguide to the diode and experimentally tested. One circuit is a waveguide–coaxial transition and the other is a matching circuit from the coaxial circuit to the diode. With this technique the power transmitted from the input side of the waveguide is fed to the coaxial circuit which uses the whisker as a center conductor for the waveguide–coaxial transition, and the power sent from the coaxial circuit is matched to the diode to make frequency conversion possible. If it is assumed that the whisker is composed of two such circuits as described, the configuration of the whisker contributes to increased efficiency of the waveguide–coaxial transition. Therefore if the design of the circuit is so made to obtain a satisfactory waveguide–coaxial transition over a broad frequency band using the whisker configuration, it will be possible to achieve impedance matching even if there is a slight inconsistency in the configuration of the whisker.

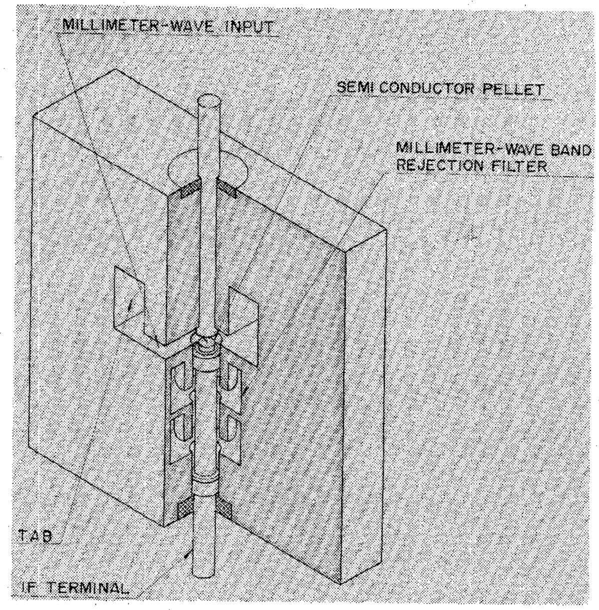

Fig. 1. Wafer-type diode.

Difficulty was anticipated in obtaining size accuracy in the millimeter-wave band. From this and cost considerations it appeared advantageous to use frequency scaling. Thus initial designs were conducted in the 4–8-GHz region for the waveguide–coaxial transition and the band-rejection filter in the coaxial circuit, and the results were frequency scaled to 60 and 86 GHz to obtain the design data of the wafer diode.

A. Whisker

The whisker cannot be discussed without studying the shape, magnitude of impedance in the waveguide, and mechanical and thermal stability. Experimentally, two types of whiskers were compared, the double-turn type (bent in an S shape) and the single-turn type. Impedance-matching tests in the millimeter-wave frequency band indicated that the single-turn type which had smaller impedance yielded better results. However, it was found that the double-turn type possessed higher stability against mechanical and thermal shocks.

For the preceding reason it was decided to use the double-turn-type whisker. In an experiment using the WRJ-620 waveguide in the 60-GHz frequency band, a whisker of about 0.3 mm in length was employed.

B. Waveguide–Coaxial Transition

A simplified view of the wafer diode is shown in Fig. 1. The RF power transmitted from the impedance transformed flat rectangular waveguide is fed to the millimeter-wave input terminal of the wafer-type diode. The height of the millimeter-wave input waveguide is the same as that of the flat rectangular waveguide. This waveguide circuit can be considered a waveguide–coaxial hybrid consisting of an H-plane waveguide, two conjugate waveguides, and a coaxial terminal.

Let two conjugated waveguides be the two tabs. Frequency scaling is conducted on the two-tab waveguide. According to the experiment conducted by this frequency scaling, it has been found that matching frequency is lowered by increasing the length of the tabs.

The result of the measurements made on the characteristics (return loss) of the waveguide–coaxial transition without tabs in the 4–8-GHz frequency band is shown in Fig. 2 with dotted lines [1]. Note, however, that no diode is inserted in this case and both ends of the coaxial section are terminated.

The result of the measurement made on the characteristics (return loss) of the waveguide–coaxial transition with tabs in the 4–8-GHz frequency range is also shown in Fig. 2 with solid lines [2]. The impedance characteristics with the diode inserted in the millimeter-wave frequency band are shown in Fig. 3. From Fig. 2

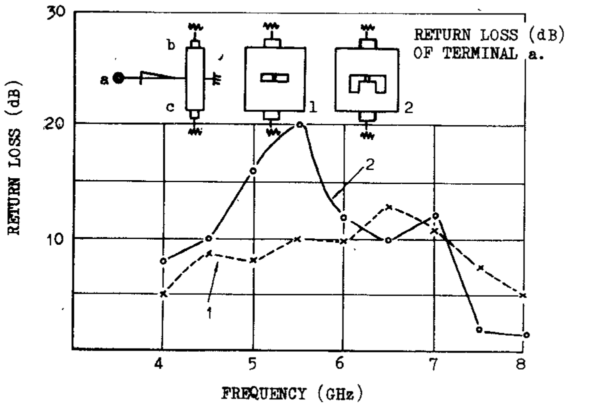

Fig. 2. Return loss (decibels) of waveguide-coaxial transition (with and without tabs).

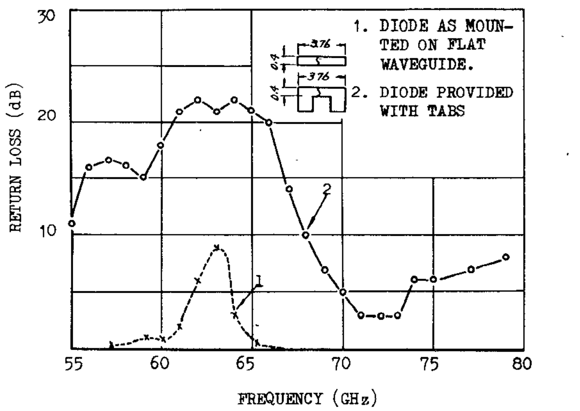

Fig. 3. Input impedances of wafer diode in the 60-GHz band (with and without tabs).

it is apparent that the matching frequency has migrated to a lower frequency band due to the provision of the tabs. Also from Fig. 3 it is obvious that the wafer diode with the tabs ensures impedance matching over a broad range in the millimeter-wave frequency band. The impedance matching in the millimeter-wave frequency range gives a better result because the diode performance characteristics are not subjected to frequency scaling.

C. Coaxial Circuit

If the cutoff frequency is 96 GHz, then to prevent unwanted mode propagation it is necessary to hold the diameter of the center conductor to less than 0.6 mm when the impedance is at 50 Ω. In this case the transmission loss would be 0.025 dB/mm. In order to avoid millimeter-wave power leaking to the IF terminal, a millimeter-wave band-rejection filter is used, of either a low-pass or a band-rejection type. To achieve a circuit configuration that permits broadening of the operating frequency band for the frequency converter, it is more advantageous to make use of a circuit which minimizes migration of a shorting position due to the frequency. Because of this it has been decided to employ a band-rejection-type filter using reentrant resonator cavities in the experiment. The result of the experimental tests on performance in the 4–8-GHz frequency band and the results scaled to the millimeter-wave frequency region are shown in Fig. 4. Judging from this result, the manufacturing error is estimated to be within 0.05 mm. The short-circuiting position of this band-rejection filter will shift by about 0.24 mm within the 10-GHz frequency range centered at 60 GHz. This is 1/20 of a wavelength, and the bandwidth limitation is smaller than that of other circuits.

D. Waveguide Impedance Transformer

The waveguide circuit of the frequency converter consists of a waveguide impedance transformer, a wafer diode, and a waveguide-shorting section. The waveguide impedance transformer is a $\lambda/4$

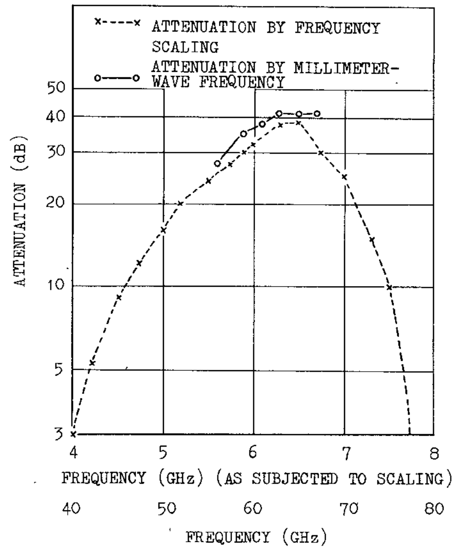

Fig. 4. Attenuation of coaxial choke consisting of two reentrant resonator cavities which eliminate the leakage of both the RF and local-oscillator signals to the IF terminal.

2-stage transformer having an impedance ratio of 4.8 and Chebyshev characteristics.

As described previously, the result of an extensive study on the millimeter-wave impedance-matching circuit of the wafer diode was given in two cases; one using the waveguide–coaxial transition and the other using the diode-matching circuit (coaxial circuit).

As the wafer diode was designed for use in a broad frequency range, highly stable operation could be ensured. Better still, the types of diodes used could be reduced in number thus making manufacture easier.

III. RELATION BETWEEN DIODE JUNCTION DIAMETER AND CONVERSION LOSS

A series of experiments were conducted on the aforementioned wafer diodes of various junction diameters. The diodes used were GaAs Schottky-barrier point-contacted diodes of planar design [8].

A. Conversion Loss of Diode for the Down Converter

In the down converter the smaller the ratio of conversion loss to noise, the lower the noise figure of the receiver. A schematic diagram of the equivalent circuit for the diode is shown in Fig. 5 [6].

Conversion loss may increase due to the effects of barrier capacity (Cj) and series resistance (Rs). There is a certain limit to reducing the Cj and Rs. The relationship between the junction diameter of the diode for the down converter and conversion loss was checked. The measured result at 60 GHz is shown in Fig. 6. It was found that conversion loss was lowest with diodes having a junction diameter of 3–3.5 μm. That is to say, the smaller the junction diameter, the greater the conversion loss due to an increase of Rs. On the other hand, the larger the junction diameter, the greater the conversion loss due to an increase of Cj.

B. Conversion Loss of Diode for the Up Converter

For the up converter it is important to have a small conversion loss and a large conversion output. Furthermore, since input power is relatively large, it is essential that reliability be evaluated fully. The relationship between the transmitted output power from the up converter and the series resistance Rs of the diode is shown in Fig. 7.

If the junction diameter is increased and series resistance is reduced, conversion loss can be minimized. However, since frequency-band characteristics may be limited by an increase of Cj, care should be used when undertaking the design of the matching circuits on the millimeter-wave side and IF side. The chips used in the wafers have an array of approximately 7-μm-diam junctions. Conversion loss in this case is 7–7.5 dB.

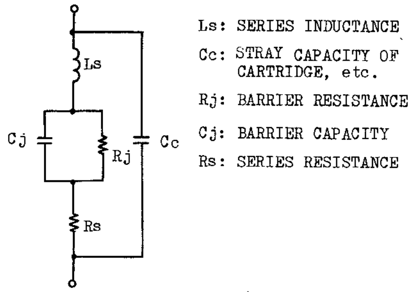

Fig. 5. Equivalent circuit of the diode.

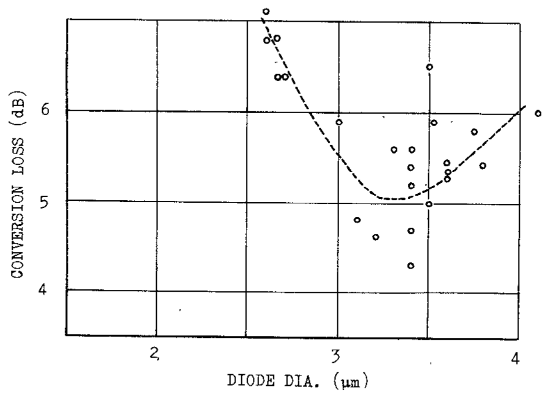

Fig. 6. Conversion loss versus diode junction diameter of the down converter at 60 GHz.

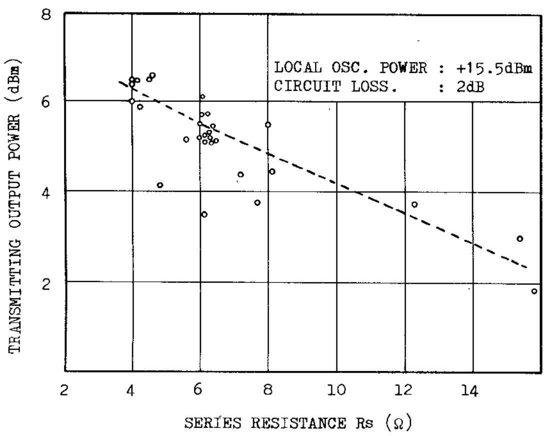

Fig. 7. Output power versus series resistance of the up converter at 60 GHz.

IV. DOWN CONVERTER

The down converter is a single mixer employing the wafer-type diode. This unit is used with an additional bandpass filter (BPF) as shown in Fig. 8. The frequency band of the BPF is ±400 MHz of RF signal frequency. The local power is fed to the BPF and reflected to the circulator; the local power and RF-signal power are combined and led to the down converter. The image-frequency power of the down converter is fed to the termination and terminated.

Two down converters were developed, one in the frequency range of 60 GHz and the other at 80 GHz. The 80-GHz-band down converter is mainly described in the following.

The down converter and the receiving IF amplifier are combined as shown in Fig. 9. The amplifier is constructed with four stages of transistors 2SC-1268 [Nippon Electric Company (NEC)] and its gain is approximately 32 dB. With a local-oscillator power of several milliwatts and without dc bias, conversion loss was measured to be 5.5 dB centered at 80 GHz as shown in Fig. 10. The down converter is operative in a bandwidth of approximately ±10 percent

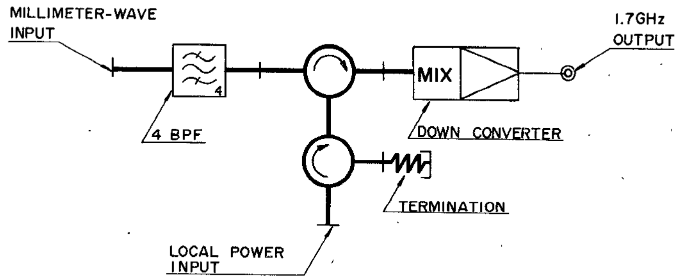

Fig. 8. Block diagram of the down converter.

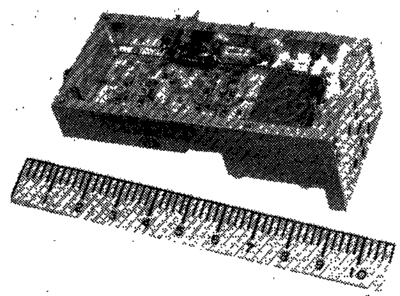

Fig. 9. The down converter connected with the receiving IF amplifier.

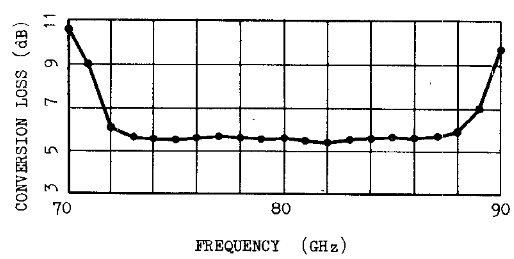

Fig. 10. Conversion loss versus frequency of the down converter.

of 80 GHz, i.e., from 72 to 88 GHz. Therefore it was found that the frequency band of 60–86 GHz could be covered by employing two different types of diodes. In the system under consideration it is advantageous to use a broad-band down converter to cover the many carriers in the millimeter-wave frequency range. The amplitude deviation versus output frequency is within ±0.5 dB, as shown in Fig. 11, over the IF frequency range from 1.3 to 2.1 GHz.

Fig. 12 shows the single-sideband noise figure of the down converter at 86 GHz to be 8.6 dB, which includes the 3.1-dB noise figure of the 1.7-GHz IF amplifier. From the result of this measurement, the noise figure of the down converter is essentially due to the conversion loss, and hence the noise ratio is close to unity.

The overall receiver noise figure of the single-sideband transmitter–receiver is 10.7 dB at 86.35 GHz, which includes a transmission-loss contribution of 2.1 dB from input circuits consisting of a circulator, bandpass filter, isolator, etc.

V. UP CONVERTER

The structure of the up converter is nearly the same as that of the down converter. It is also a single mixer employing a GaAs Schottky-barrier diode of approximately 7-μm junction diameter. The amplitude characteristics versus frequency of the up converter is similar to that of the down converter. The output power of the up converter versus IF-input power is shown in Fig. 13. The conversion loss, when the local-oscillator power is 19 dBm and the output-signal power is 11.5 dBm, is 7.5 dB on condition that the output-signal power is 1 dB compressed against the IF-input power. Consequently, the output-signal power of the up converter becomes +11.5 dBm when the local-oscillator power is +19 dBm.

The local-oscillator power is supplied from a negative-resistance IMPATT amplifier followed by an IMPATT oscillator with a resonant cavity for frequency stabilization. The diode used for this oscillator

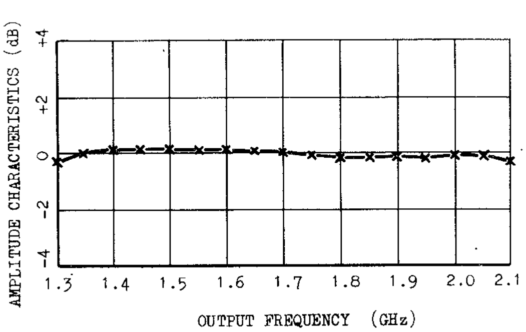

Fig. 11. Amplitude characteristics versus frequency of an 86/1.7-GHz-frequency down converter (F_0 = 86.35 GHz).

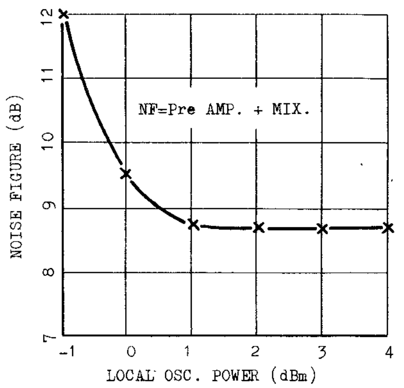

Fig. 12. Noise figure versus local-oscillator power of an 86/1.7-GHz-frequency down converter (F_0 = 86.35 GHz).

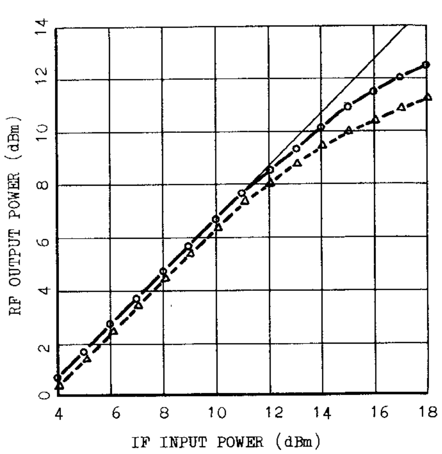

Fig. 13. Output power versus IF-input power of a 1.7/86-GHz-frequency up converter (F_0 = 86.35 GHz). Local-oscillator power levels are +19 dBm (O—O) and +17 dBm (Δ---Δ).

is a single-drift Si IMPATT diode of p^+-n-n^+ structure, and it is mounted in the waveguide. The output-signal power of the transmitter–receiver is +9 dBm, reduced from 11.5 dBm by the insertion loss of the output circuitry of 2.5 dB. This output circuitry is composed of a circulator, a BPF, an isolator, a directional coupler, etc.

VI. CONCLUSIONS

The design, construction, and performance characteristics of down and up converters in the frequency range of 60–86 GHz developed for the W-40G guided millimeter-wave transmission system have been described herein. The greatest feature of these converters is that impedance matching has been done over a broad millimeter-wave frequency band.

It is clear that it would be advantageous to use broad-band down and up converters in the W-40G system comprising many carriers at a millimeter-wave frequency range.

In view of various design difficulties encountered such as the problem of small size as required in the millimeter-wave frequency band, the difficulty of obtaining high mechanical accuracy, and lack of measuring accuracy, frequency scaling was utilized for the development. This frequency scaling produced satisfactory results.

With regard to the diode for use in the down converter, experimental data which give the junction diameter for minimizing conversion loss have been reported.

In the case of the diode for the up converter, experimental data indicate that the optimum junction diameter for this diode can be estimated from conversion loss, output power, and bandpass characteristics. Further study and evaluation of these diodes must be made, however, to assure acceptable performance from a reliability standpoint.

ACKNOWLEDGMENT

The authors wish to thank Dr. K. Miyauchi of the Yokosuka Electrical Communication Laboratory, NTT, and T. Kuroda of NEC, for their continuing guidance and suggestions. They also wish to thank H. Watanabe and his group of the Semiconductor Division of NEC for producing and experimenting on the diodes.

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Millimeter-Wave Receivers and Their Applications in Radio Astronomy

T. G. PHILLIPS AND K. B. JEFFERTS

(Invited Short Paper)

***Abstract*—Millimeter-wave receivers are discussed from the point of view of applications to line astronomy. A heterodyne-bolometer system is described which has a noise temperature of 300 K at 230 GHz.**

INTRODUCTION

Millimeter-wave astronomy has made considerable progress in the last few years due to the effectiveness of the 36-ft National Radio Astronomy Observatory (NRAO) antenna at Kitt Peak and the extension of radio-receiver techniques into the millimeter band. We expect that this progress will continue into the submillimeter band.

Manuscript received April 26, 1974; revised August 28, 1974.
T. G. Phillips is with Queen Mary College, University of London, London, England. He is on leave at Bell Laboratories, Murray Hill, N. J. 07974.
K. B. Jefferts is with Bell Laboratories, Murray Hill, N. J. 07974.