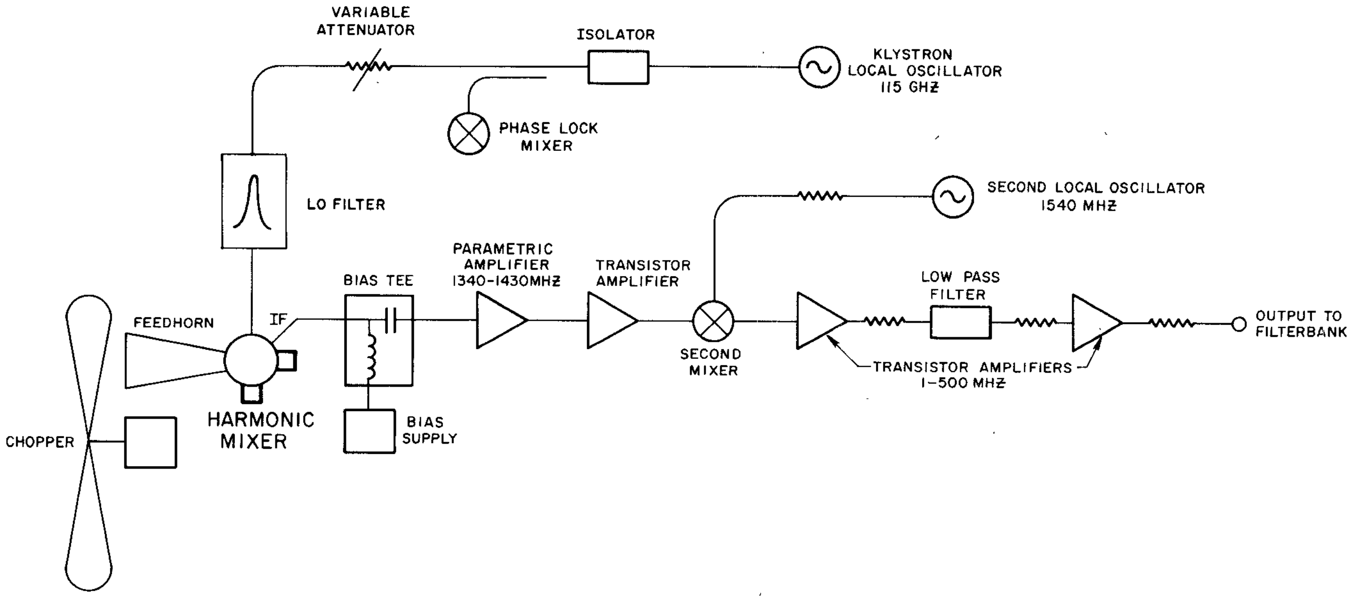

Fig. 2. Block diagram of a 230-GHz radiometer system.

where

T_{AMB} ambient temperature of mixer = 294 K;
L_{INPUT} loss of input waveguide (power input/power reaching mixer);
T_E effective temperature of diode;
L_M double-sideband conversion (RF to IF power) loss of the mixer;
T_{IF} IF system temperature = 75 K.

The loss in the input waveguide L_{INPUT} is estimated to be 1.2 (0.8 dB). This waveguide includes the feedhorn, about 1 cm of standard waveguide, and a flange. We have measured a loss of 2.6 dB for a 2-cm section of RG 139/U waveguide and one flange; this number undoubtedly varies considerably from one specimen of this waveguide to another.

The measured system noise temperature is 6000 K. From (3) we calculate that the mixer conversion loss is 10.3 (10.1 dB).

Conclusion

The double-sideband system noise temperature of 6000 K reported here represents a considerable advance over previous systems at this frequency employing harmonic mixers [3], [4] and is comparable to the performance of a system utilizing a fundamental mixer [1], [2]. The improved mixer performance is primarily a result of the low values of the diode parasitics. The results reported in this paper support the theoretical conclusion of Meredith and Warner [6] that the frequency conversion efficiency of a second-harmonic mixer is not greatly inferior to that of a fundamental mixer.

Acknowledgment

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References

[1] M. V. Schneider and G. T. Wrixon, "Development and testing of a receiver at 230 GHz," in *1974 IEEE Int. Microwave Symp., Digest of Technical Papers*, pp. 120–122, June 1974.
[2] G. T. Wrixon, "Low-noise diodes and mixers for the 1–2-mm wavelength region," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1159–1165, Dec. 1974.
[3] M. Cohn, F. L. Wentworth, and J. L. Wiltse, "High sensitivity 100- to 300-Gc radiometers," *Proc. IEEE*, vol. 51, pp. 1227–1232, Sept. 1963.
[4] W. A. Johnson, T. T. Mori, and F. I. Shimabukuro, "Design, development, and initial measurements of a 1.4-mm radiometric system," *IEEE Trans. Antennas Propagat.*, vol. AP-18, pp. 512–514, July 1970.
[5] R. Ulrich, K. F. Renk, and L. Genzel, "Tunable submillimeter interferometers of the Fabry–Perot type," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 363–371, Sept. 1963.
[6] R. Meredith and F. L. Warner, "Superheterodyne radiometers for use at 70 Gc and 140 Gc," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 397–411, Sept. 1963.
[7] W. W. Mumford and E. H. Scheibe, *Noise Performance Factors in Communication Systems.* Dedham: Horizon House-Microwave, 1968.

High-Efficiency Frequency Multiplication with GaAs Avalanche Diodes

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***Abstract*—GaAs avalanche diodes for frequency multiplication at millimeter wavelengths have been investigated. The GaAs diode design is described and compared with that of Si diodes. Experimental results obtained in the optimum circuit are presented. Frequency multiplication from 4 to 32 GHz with 6-dB conversion loss (400 to 100 mW) and 1.5-W dc bias power was achieved. A temperature dependence of the output power was measured to be less than 1 dB over the −40 to +60°C range.**

Introduction

Frequency multiplication using an avalanche diode enables millimeter-wave generation from a lower frequency signal, using a circuit similar to that of a varactor multiplier but with better overall performances principally in high-order multiplication (typically by a factor of 10). This device, first proposed in 1969 [1], uses a particular type of avalanche diode. After having extensively studied Si devices [2], [4] and having obtained very promising results, it became theoretically apparent that GaAs may have certain advantages. Thus we decided to study the possibilities of GaAs devices in the same area. With Si diodes the following performance was obtained at 35 GHz: 640-mW output power and 7-dB conversion loss with a multiplication factor of 10. It was also pointed out that frequency multiplication could have a

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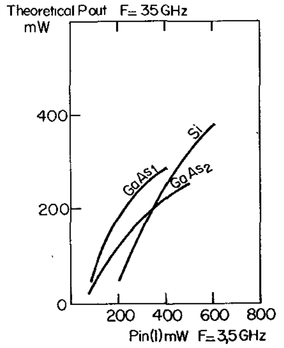

Fig. 1. Theoretical output power as a function of input power in multiplication by 10 for a Si diode and two GaAs diodes of different area (case 1, $S = 0.25 \cdot 10^{-4}$ cm^2, $J = 800$ A $\cdot$ cm^{-2}; case 2: $S = 0.4 \cdot 10^{-4}$ cm^2, $J = 625$ A $\cdot$ cm^{-2}) at a temperature of 100°C with a transit angle of 0.75 rad.

lower noise, a larger bandwidth, and a higher output power than direct generation [2]. Recently, it has been demonstrated that these diodes could be competitive with step-recovery varactor diodes in a *Ku*-band tripler application by obtaining only 1-dB conversion loss at input power of 100 mW [5].

GaAs Diode Design

The principle of the avalanche diode multiplier depends on the highly nonlinear relation between the generation of carriers and the electric field applied to the diode. Because of the cumulative aspect of the avalanche phenomenon which introduces a delay between the current and the voltage, this device acts essentially as a nonlinear inductance. In order to take full advantage of the possibilities of avalanche diodes, the study has been mainly concerned with high-order multiplication (about 10), the output power being in the millimeter-wave range (26–40 GHz).

Previous attempts have demonstrated the inability of analytical methods to correctly treat this process because of the complexity of the phenomenon. Thus we have used exclusively the techniques of numerical calculations. The one-dimensional model is described elsewhere [6]. For reasons of economy, we do not use the full simulation program but a model with two zones without idlers.

The computer analysis of this theoretical model has led to the definition of the component and the characteristics of the multiplier either for Si or GaAs by selecting the appropriate physical parameters. For the ionization rates, we have used the expression $\alpha = A \exp(-B/E)^2$ where $A = 2.25.10^7$ and $B = 7.1.10^5$ V/m, and for the saturation velocity a value of $0.55.10^7$ cm/s for the electrons at 200°C. The influence of the different parameters of the device (such as doping level, drift region thickness, area, current density) can therefore be determined for a given input power and input and output frequencies. The study was limited to flat profile devices. Previous studies have shown that two characteristics of the material have an important influence. Firstly, on the basis of the relationship between the ionization rate and the electric field at very high fields (particularly the second derivative of the ionization rate), GaAs presents significant advantages over Si. Secondly, on the basis of the rise time of the conduction current which generates the high-frequency components, it seems that Si is preferable. Such qualitative reasoning does not permit a conclusive choice to be made and computer simulation is therefore necessary.

Fig. 1 shows such a comparison with one type of Si diode and two types of GaAs diode. In case 1 for GaAs the area of the diode is optimum and the dc power is 80 percent of that of the Si diode. In case 2 the area and the dc power are the same as the Si case. It can be seen that for a low input power such as 300 mW at 3.5 GHz (which is the value for our specific application) and for a multiplication by 10, GaAs is slightly better than Si particularly for case 1. The optimum parameters of the diode are (case 1): avalanche zone thickness of 0.55 μm with a doping density of 2.10^{16} cm^{-3}; an area S close to $0.25.10^{-4}$ cm^2 (diameter 55 μm); a drift zone thickness ($w - \delta$) of 0.15 μm; and a current density J_0 of 800 A $\cdot$ cm^{-2} at 100°C junction temperature. It can be seen that for GaAs the results are better for the smaller area device (case 1) even for smaller equivalent currents. This has two advantages: the dc power is lower (efficiency higher) and the reliability is better (lower temperature). However, it is clear from the figure that if the input power increases to 500 mW, Si is similar in performance to GaAs.

Technology

The realization of these diodes has presented numerous problems. Firstly, we needed devices where very high electric fields can exist at the epitaxial layer/substrate interface without risk of burnout or premature breakdown. This has been possible only by growing an n^+ buffer layer in the epitaxial process. Therefore, since a very short drift region is needed, the substrate/active layer transition is required to be very abrupt in order that parasitic oscillations be avoided. Another problem is the measurement of the epitaxial layer doping density and thickness prior to diode fabrication. The n-layer thickness should be controlled with a high degree of precision because it is the most critical dimension. The precision needed is about 0.05 μm which is of the same order as that of the high-efficiency *X*-band IMPATT diodes which are currently made in the laboratory [7].

The technology itself is very similar to that of IMPATT diodes. The diameter of the diodes is of the same order as one of the diodes of a quadrimesa IMPATT structure. RF bias sputtered Pt Schottky barriers are used as an active contact on the n-layer as well as for the back contact on the substrate (forward bias). In order to decrease the series resistance, the substrate is thinned by mechanical abrasion and then by chemical treatment to 20 μm. The correct diameter of the diode is obtained by chemical etching. Metallized contacts on both sides of the diodes are thickened in order to facilitate the soldering of the active contact to the pillar of the package and the thermocompression bonding of a gold wire to form the back contact. We have chosen a small screw package (MET CERAM type 60 7070) to ensure good electrical behavior around 35 GHz and to be compatible with the millimeter circuit dimensions.

Experimental Measurements in Microwave Circuits

The microwave circuits used are essentially of the coaxial–waveguide transition type similar to that used for the Si diodes. This circuit has to satisfy the following conditions.

1) The input power should be absorbed by the diode; thus a matching circuit is needed.

2) The output power must not be reinjected into the input circuit; thus a strong decoupling between input and output is needed.

3) The impedance seen by the diode at the output frequency has to be optimum, and the coupling from the diode to the output circuit should be as good as possible.

In the mount, the input power and the bias current are supplied to the diode through a coaxial line, and the output power produced by the diode is transmitted to the load via a rectangular waveguide. The diode is placed at the extremity of the coaxial

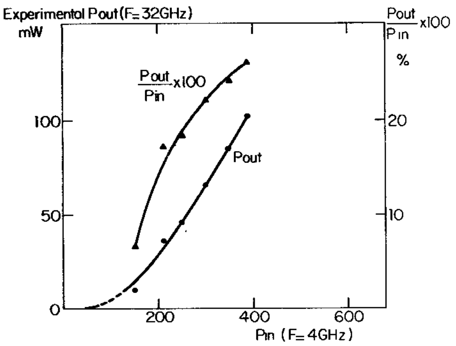

Fig. 2. Best experimental result for a GaAs diode in output power and conversion efficiency as a function of the input power in multiplication by 8 with a dc input power of 1.5 W.

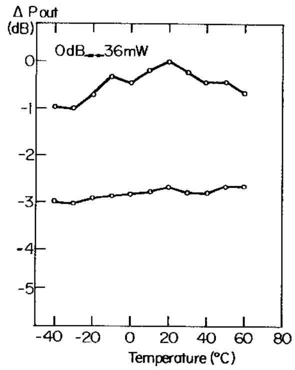

Fig. 3. Temperature dependence of the output power for two GaAs avalanche diodes in multiplication by 8 in the range −40–+60°C.

line opposite to the input (the other side of the waveguide and in the middle of the largest side of the waveguide). The coupling between this coaxial line and the waveguide is facilitated by a ridged waveguide which allows second and third harmonics to be tuned in the waveguide by means of the short circuit. Recent computer calculations have shown the importance of such a tuning control (a reactance of about $-j50\ \Omega$ is needed at the second and third harmonics viewed from the diode).

Four batches were made, and the last gave the best results which were 100 mW of output power at 32 GHz with 400 mW of input power at 4 GHz corresponding to a conversion loss of 6 dB with a dc input power of 1.5 W (Fig. 2). We have verified that this multiplication does not add noise to the input signal but only reproduces the total noise (AM + FM) with a multiplication of the frequencies in the spectrum. From a temperature stability point of view, less than 1-dB variation of output power was measured from −40 to +60°C (Fig. 3). Most of the diodes from this batch gave less than 10-dB conversion loss under the same input conditions. These results are qualitatively in agreement with the preceding computer calculations, but we think that the doping level of these diodes was too high (3.10^{16} cm^{-3} instead of 2.10^{16} cm^{-3}) and that the diameter was too large (70 μm instead of 55 μm). The greatest divergence is in the current density which is much lower experimentally than predicted.

A more versatile mount with variable tuning possibilities at the second and third harmonics is being constructed in order to improve the performance and the reproducibility. A correlation between measured impedances (seen by the diode) with those predicted by the computer will also be possible. The first experimental results obtained with high-harmonic multiplication (by 32) are encouraging because 9-dB conversion loss was obtained at 32 GHz of output frequency.

Summary and Conclusion

We think that frequency multiplication is an attractive solution for the achievement of stable output power at high frequencies (for example, *Ka* band) since stable oscillators are available at lower frequencies (lower than 4 GHz). With this idea in mind, we have chosen the avalanche multiplication process because it is capable of giving high efficiencies (6-dB conversion losses) for high multiplication orders and medium input powers with a very low sensitivity to temperature variations.

It has been shown both theoretically and experimentally that GaAs is at least as good as Si in the conditions mentioned previously. It has been demonstrated that layers which include n^+ buffer layers allow GaAs diodes to support a very high field in a reliable manner because the working temperature is very low (80°C).

References

[1] E. Constant, E. Allamando, and A. Semichon, "Transit time operation of an avalanche diode driven by subharmonic signal and its application to frequency multiplication," *Proc. IEEE*, vol. 58, pp. 483–484, 1970.
[2] G. Salmer, M. Chive, P. A. Rolland, and J. Michel, "A comparison between direct generation and frequency multiplication using avalanche diodes," *J. Phys. D.: Appl. Phys.*, vol. 6, pp. 40–43, 1973.
[3] P. A. Rolland, G. Salmer, A. Derycke, and J. Michel, "Very high rank avalanche diode frequency multiplier," *Proc. IEEE*, vol. 61, pp. 1757–1758, 1973.
[4] P. A. Rolland, E. Constant, A. Derycke, and J. Michel, "Multiplication de fréquence par diode à avalanche en ondes millimétriques," *Acta Electronica*, vol. 17, no. 2, pp. 213–228, 1974.
[5] P. A. Rolland, Thèse de doctorat d'état, to be published.
[6] P. A. Rolland, J. L. Vaterkowski, E. Constant, and G. Salmer, "New modes of operation for avalanche diodes: Frequency multiplication and upconversion," this issue, pp. 768–775.
[7] A. Farrayre, B. Kramer, and A. Mircéa, "High efficiency avalanche diodes at *Ku* band," Int. Symp. on GaAs, Deauville, Sept. 1974.

Low-Loss Broad-Band EHF Circulator

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***Abstract*—A waveguide circulator design is reported that has resulted in a structurally rugged, thermally stable circulator with exceptional RF performance. With this design, insertion loss of less than 0.1 dB, more than 20-dB isolation, and VSWR less than 1.2:1 have been achieved, each over 7 GHz of bandwidth from 27 to 34 GHz and 31 to 38 GHz.**

Introduction

The standard-height waveguide design reported here uses a double turnstile junction, which was previously identified by Owen and Barnes [1] in their explanation of circulator operation, and optimally combines RF broad-band and low-loss performance, parts simplicity, ruggedness, and temperature stability in one unit. Specifically, the following characteristics are true.

1) No epoxies or adhesives of any kind are used since all cylindrical parts are self-indexing. The result is a rugged mechanical design suitable for space applications.

2) Thermal stability was achieved by use of ferrite material (TT2-111) with low $4\pi M_s$ versus temperature variation, by junction design allowing operation with ferrites biased well into saturation and by use of high-quality rare-earth permanent magnets.

3) Two turnstile junctions separated by thin reflecting septum allow use of standard-height waveguide.

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