Millimeter Wave Diodes for Harmonic Power Generation

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Abstract—**A discussion of the application of point contact, electrically formed semiconductor junctions to harmonic generating applications is presented. Three different combinations of materials are considered. First, the more popular phosphor-bronze point on gallium arsenide combination is discussed. Results with this material combination when used as millimeter wave multipliers are given as a reference point. The combination *n*-GaAs/Cu is then examined. The slope parameter of these diodes shows that the junction is very close to that of a Schottky barrier. The conversion efficiency measured for these diodes shows a 2 to 4 dB improvement over the *n*-GaAs/P-Br diodes. The third combination, and by far the most efficient, was the *n*-GaAs/Zn diode. These are true p-n junctions (as opposed to Schottky barriers) and have measured zero bias cutoff frequencies on the order of 1000 GHz. The efficiency realized with these diodes in doubling from 70 GHz to 140 GHz typically ranged from 20 percent to 30 percent. The highest output power at 140 GHz that was measured was 16 milliwatts.**

Introduction

FOR MANY YEARS varactor diodes, which are nothing more than reverse-biased *p-n* junction diodes [1], have been used to obtain microwave RF energy by harmonic multiplication from some lower radio frequency power source. Theory predicts [2] that a varactor pumped at some fundamental frequency can produce an output at any desired harmonic with 100 percent efficiency. In practice, however, the conversion efficiency decreases very quickly with increasing fundamental frequency and desired harmonic number.

The results which have been obtained to date are actually quite impressive for the frequency range up to and including X band. One supplier reports [3] a 1 to 4 GHz quadrupler with two watts input power and a conversion efficiency of 45 percent minimum, or a 4 to 12 GHz tripler with one watt input power and a conversion efficiency of 30 percent. Another company has reported [4] a device which triples from 11.6 to 34.8 GHz with 0.172 watts input power and an output power of 0.100 watts for a conversion efficiency of 58 percent, or 2.3 dB loss. Recently, an output of 2 mW at 60 GHz has been reported [5] for a tripler from 20 GHz having an efficiency of 2.5 percent. Very little else has been published on varactors applied as harmonic generators for output frequencies in excess of 35 GHz. The frequency cutoff of the commercially available varactor diodes is just too low for efficient operation any further into the millimeter wave region.

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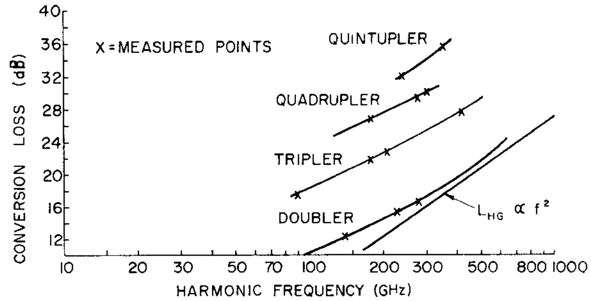

Fig. 1. Harmonic generation conversion loss.

The original development of harmonic generators with millimeter wave output frequencies used the point contact diode as a nonlinear variable resistance element rather then as a variable reactance. Therefore, the devices were limited to a maximum conversion efficiency [6] of $1/n^2$ for generating the *n*th harmonic. This number was reduced further by the circuit losses and the diode parasitic losses. For comparison purposes, Fig. 1 presents a general summary [7] of typical conversion losses achieved by ADTEC with *variable resistance* diode harmonic generation techniques. For all cases these were gallium arsenide devices with electrically "formed" junctions.

Point Contact Rectifiers

It has been known for some time that point contact rectifiers, be they *p-n* junctions, Schottky barrier junctions, or some intermediate type, have a sharp voltage-dependent junction capacitance [8]. When these junctions are reverse biased they can be characterized in the same manner as any varactor diode. There has been initiated at this laboratory a program to determine more precisely the nature of the junction being used so successfully throughout the millimeter wave range as a mixer and as a variable resistance harmonic generator; and to determine, if possible, what modifications in the selection of materials or in the junction forming technique might allow the maximizing of the efficiency and/or power handling capability of the junctions as they may apply to the variable reactance form of harmonic power generation.

All of the sharply breaking I-V curves which have been formed by electrically pulsing the junction with the 60 Hz sweep voltage have followed closely the equation [8]

$$I_f = I_s \left\{ \exp \left[\frac{q}{\eta k T} (V_f - I_f R_s) \right] - 1 \right\}. \quad (1)$$

Here I_f is the forward current, I_s is the saturation current, q is the electronic charge, k is Boltzmann's constant, T is the

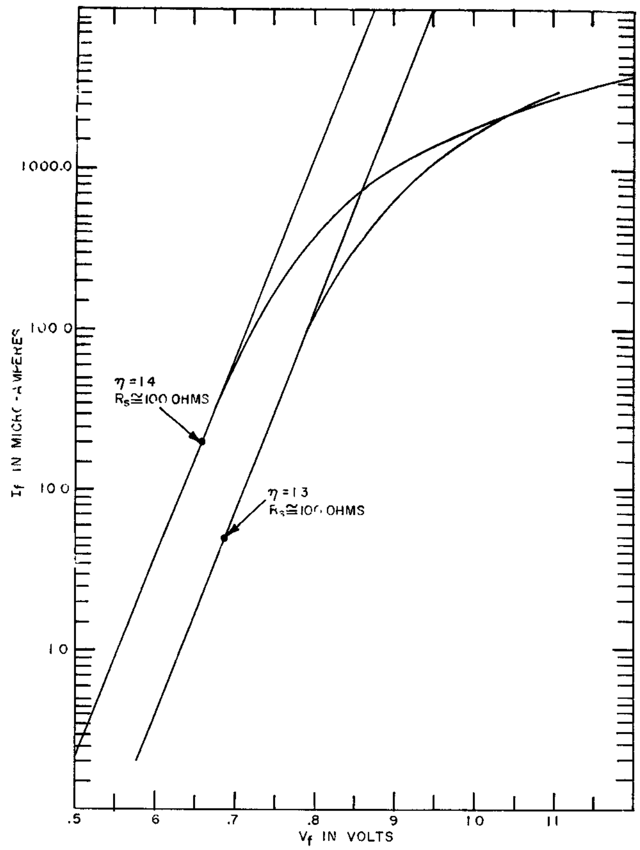

Fig. 2. Voltage-current characteristics of two different, but typical, point contact n-GaAs ($\rho=.015$ Ω-cm) phosphor-bronze diodes.

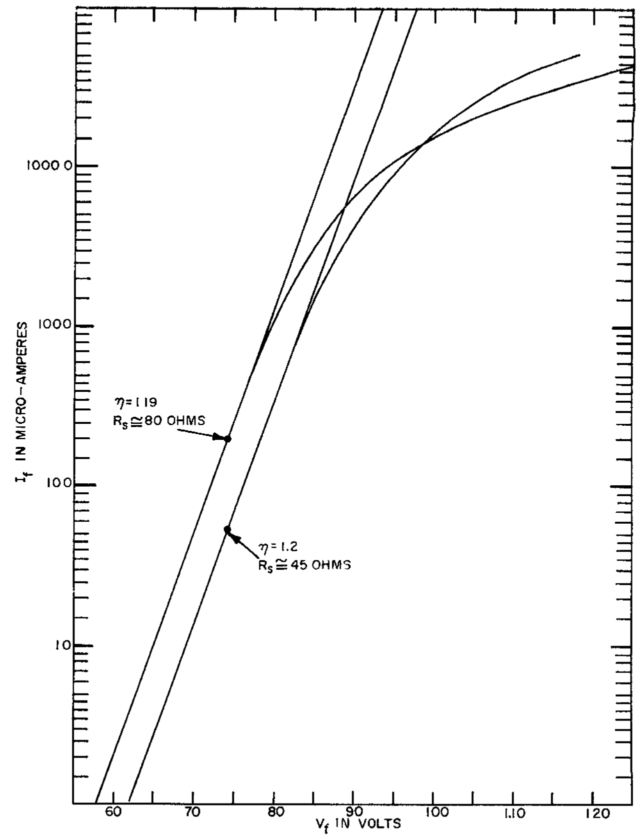

Fig. 3. Voltage-current characteristics of two different, but typical, point contact n-GaAs ($\rho=.015$ Ω-cm) copper diodes.

absolute junction temperature, V_f is the forward (applied) voltage and R_s is the junction spreading resistance. The quantity η is a slope parameter which, for the diodes measured, had values between 1.2 and 1.4. If the junctions were primarily p-n junctions, then the expected value of η would be about 2.0 [9]. If the junctions were ideal Schottky barrier junctions, then η would be equal to 1.0 [10].

The first combination of materials examined was n-GaAs semiconductor with a phosphor-bronze (P-Br) pointed contact. This combination has received the most publicity [7], [11]–[13] and is the one most commonly employed in millimeter wave mixers made from GaAs. Figure 2 shows two typical voltage-current characteristics obtained for GaAs of resistivity $\rho=0.015$ Ω-cm. The junction is formed by electrically overloading the junction with the 60 Hz sweep signal of the I-V curve tracer. The results of Fig. 1 were obtained with diodes typified by the I-V characteristics of Fig. 2. As the slope parameter (η) is on the order of 1.3 to 1.4 for the n-GaAs/P-Br rectifying contact, it would appear that this rectifying contact is predominantly a majority carrier rectifier of the Schottky type. However, the static characteristics of these diodes are not as close to the ideal Schottky characteristic as those reported by Kahng [14]. Kahng reported an η of the order of 1.01 to 1.025 for large area n-GaAs/Au diodes.

In an effort to improve the slope parameter and thereby improve the millimeter wave operation of the devices, pure copper was substituted for the phosphor-bronze. It is believed that, during the forming operation, the contact surfaces of the phosphor-bronze and GaAs are raised to such a temperature that an intimate, metal-semiconductor interface is obtained. This may or may not be attendant with a diffusion of copper [12] from the wire point into the GaAs. The diffusion of copper into the GaAs is not necessary for the formation of the Schottky barrier, since only a true metal-semiconductor interface is needed. In fact, a diffusion of the copper may tend to grade the junction giving less than the extremely abrupt-junction desired. In addition, P-Br is made up of 95 percent Cu+5 percent Sn. Tin (Sn) is a very active donor in GaAs, and a small amount of tin diffusion at the time of forming may also grade the junction and cause an increase in the measured slope parameter. Figure 3 shows two typical voltage-current characteristic curves obtained for GaAs ($\rho=0.015$ Ω-cm) with pure copper wire point. Again the junction was formed by electrical pulsing while the I-V curve is being displayed. While the slope parameter for the P-Br units typically stayed in the range 1.3 to 1.4, η for the copper bonded units rarely deviated from 1.2 ($1.19 \leq \eta \leq 1.21$).

As a harmonic generator, the improvement resulting from the use of Cu contacts was readily seen. Specifically, in the 70 GHz to 140 GHz doubler, an improvement in conversion efficiency of 2 to 4 dB was obtained over that data shown in Fig. 1. The best conversion efficiency measured for the copper-bonded diodes was 8.8 dB. The power handling capability was quite similar to that of the variable resistance devices of Fig. 1 in that the junction would not yield appreciably more than 1 mW of 140 GHz power.

Some few n-GaAs/Cu junctions have been tested as fundamental mixers. The conversion loss of these units was measured and found to be in the range of 5 to 7 dB in converting a 94 GHz signal to a 2 GHz intermediate frequency signal.

Some analytical justification of the above noted results may be made which then can lead one in the direction of improvement. The following calculations are applicable to either the n-GaAs/P-Br devices or the n-GaAs/Cu devices as both had the same basic crystal material. The resistivity of the bulk material used was 0.015 ohm-cm. The spreading resistances, as interpreted from the measured I-V curves, ranged from 40 ohms to 180 ohms with an average figure of about 70 ohms. The reverse breakdown voltage (measured at the 10 micro-ampere conduction point) was 6 to 8 volts. For a uniformly doped semiconductor, the barrier capacitance of an abrupt junction (ideal step junction) depends on the reverse voltage in accordance with the well known equation [10]

$$\frac{C}{A} = \left(\frac{\epsilon q N}{2V_T}\right)^{1/2} \tag{2}$$

where C is the capacitance, A the junction area, ϵ the permittivity, N the donor concentration, and V_T the total voltage across the junction including the diffusion voltage, V_D (i.e., $V_T = V_D - V$). The spreading resistance R_s can be given as

$$R_s = \frac{\rho}{4a}, \tag{3}$$

where ρ is the semiconductor resistivity and a is the effective radius of the point contact.

Using a resistivity value of 0.015 ohm-cm and an R_s of 70 ohms, (2) and (3) allow an estimate for the junction capacitance of approximately 0.002 pF. The cutoff frequency $f_{c0} = (2\pi R_s C)^{-1}$, is calculated to be 1140 GHz at zero bias. This is truly a very high cutoff diode and, according to presently accepted varactor theory, [15], [16] should yield a conversion efficiency (say for a doubler to 140 GHz) of about 80 percent for a conversion loss of 1.0 dB. However, this does not seem to fit the data as shown in Fig. 1.[1] Of course, circuit losses and reflection (mismatch) losses may contribute in a large way to the total loss, but also the phosphor-bronze whisker can exert a rather large stress on the very small point contact. The effect of a large stress applied to a small area junction is to cause the "ideal" current through the small area to increase [17]. For high stress levels the current through the stressed area can become much larger than that through the unstressed area, hence the total diode current is essentially that flowing in the stressed area. There is, then, a very real possibility that the stressed area (the effective area of the subject diode) may be only 20 percent of the total area. This could mean that now an effective shunting capacitance of 0.008 pF must be considered. The effective cutoff frequency is now only 220 GHz and the calculated conversion loss jumps to a figure of the same order of magnitude as has been measured, about 6 dB, as a result of the parasitic capacitance of 0.008 pF.

The figure of 1.0 dB conversion loss is idealistic only in the sense that it represents the minimum possible losses of the model junction in an ideal (lossless) circuit.

A further point that should be noted; namely, that the active junction variable capacitance of 0.002 pF represents in itself a limit in power handling capability. It can be shown [18] that, to a good approximation, the maximum input power P_{in} which can be efficiently transformed to harmonic power can be given, for the abrupt junction, by the equation

$$P_{in} = 0.2 f_1 C_b (V_D - V_b)^2 \tag{4}$$

where f_1 is the input frequency, C_b is the active junction capacitance at the breakdown point, and V_b is the breakdown voltage. This can also be given in terms of the zero bias capacitance C_0 and the breakdown and diffusion voltages by

$$P_{in} = 0.2 f_1 C_0 (V_D - V_b)^{3/2} (V_D)^{1/2}. \tag{5}$$

Using either (4) or (5) and a junction capacitance of 0.002 pF, the value of 0.45 mW is obtained for the maximum input power. Even if the ideal conversion loss were realized, the output power would be insufficient for an application in a solid-state local oscillator. When the diode is overdriven this power level may be increased by taking advantage of the abrupt capacitance change between zero and the diffusion voltage (V_D).

Now if the junction area can be increased but at the same time the parameters again be achieved as have been reported, [12], [19], [20] then more reasonable power levels may be attained. If $R_s = 18$ ohms and $C_0 = 0.01$ pF, then $P_{in} = 2.2$ mW and $f_{c0} = 870$ GHz, which gives a doubler conversion efficiency of about 74 percent or a loss of about 1.3 dB. If a junction capacity of 0.1 pF can be attained and R_s can be reduced to 3 ohms, then even with the f_{c0} at zero bias dropping to 500 GHz, an efficiency of about 59 percent can be calculated, which yields 12.7 mW of output power at 140 GHz.

EPITAXIAL p-n JUNCTIONS

Reduced R_s, increased C_0, and high f_{c0} is attainable through the use of pulse formed p-n junctions. The junction and the forming technique is that proposed by Burrus [20] and consists of pulse forming junctions between an electrolytically pointed zinc (Zn) whisker and epitaxial n-GaAs. The best results to date, in both power handling capability and

[1] This might be an unfair comparison, as the data of Fig. 1 represents diodes operating in the variable resistance mode. However, it has been determined for this class of diodes that the variable resistance mode was indeed more efficient than the variable reactance mode.

efficiency, were obtained with GaAs that had a 4.0 μ epitaxial layer thickness and a carrier concentration of 5.9 E16 donors/cc. The resistivity of the epitaxial layer was 0.0422 Ω-cm and the substrate resistivity was 4.9 E–4 Ω-cm. The diodes made on this material had very sharp reverse breakdown voltages in the range of 16 to 19 volts. Junctions which could be made to yield on the order of 7 dB conversion efficiency (20 percent) with output power at 140 GHz of better than 10 mW could be formed consistently and reproducibly.

The diodes were initially characterized at low frequencies. The capacitance measurements were made at a frequency of 1 MHz on a Boonton (Model 75B) capacitance bridge. The majority of the zero bias capacitance values fell within the range of 0.01 to 0.02 pF. The series resistance R_s was obtained in two ways. First, the deviation from the straight line plot of the $\ln I_f$ vs. V_f was used to estimate R_s; and secondly, the slope of the I-V curve measured in the vicinity of the 10 mA region was used as an estimate of R_s. Relatively good agreement was obtained between the two methods. The values of R_s fell within the range of 10 to 15 ohms. Using the extremities of the grouping for R_s and C_0, the cutoff frequencies are expected to range from 500 GHz to 1500 GHz at zero bias.

Figure 4 presents the I-V characteristic of a typical varactor diode of the n-GaAs/Zn type. The slope parameter of 1.85 corresponds to the value expected for a true p-n junction. The slope parameter was measured for about ten separate junction samples. For all samples, η fell within the range 1.8 to 2.0.

These varactor diodes were all formed in open, crossed guide structures of the type previously used for variable resistance multipliers [7]. The ADTEC M-9838 structure that was used is shown pictorially in Fig. 5. The 0.005 inch thick semiconductor wafer is mounted on a 0.020 inch diameter pin which is inserted and adjusted in the RG-138/U guide by use of the differential screw control. The zinc whisker is mounted on a 0.020 inch diameter whisker carrier which is inserted through the RG-98/U guide and is held in place by the N connector seen in Fig. 5. The contact between the zinc wire and GaAs wafer is made by adjustment of the differential screw, and the junction is pulse formed by pulsing through the N connector. An E-H tuner is used to impedance match the 70 GHz signal through the RG-98/U input to the diode. A TRG bolometer is used to detect the 140 GHz output. The bolometer was calibrated against a water calorimeter at a frequency of 140 GHz. The 70 GHz available power was also measured by use of a water calorimeter.

Figure 6 presents the measured data for eight different diodes. Curves A and B show the variation of conversion loss with peak input power. Curve A is close to the average for the number of diodes formed. Curve B shows a diode with similar efficiency (about 20 percent) with a maximum 140 GHz output of 12 milliwatts of power. There are six other points (marked by X's) which represent the variations that were obtained. The best efficiency of 5.4 dB (about 30

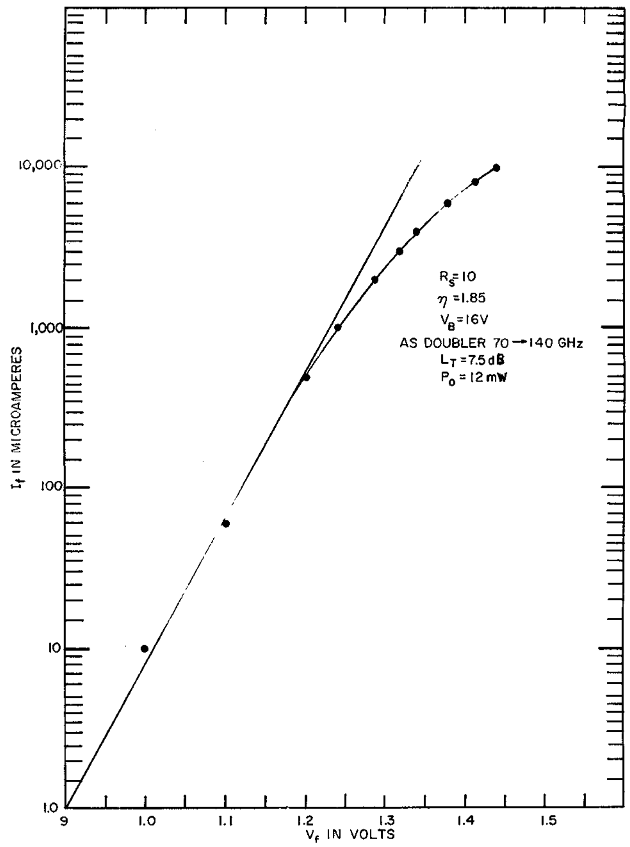

Fig. 4. Voltage-current characteristics of a typical point-contact n-GaAs/Zn varactor diode.

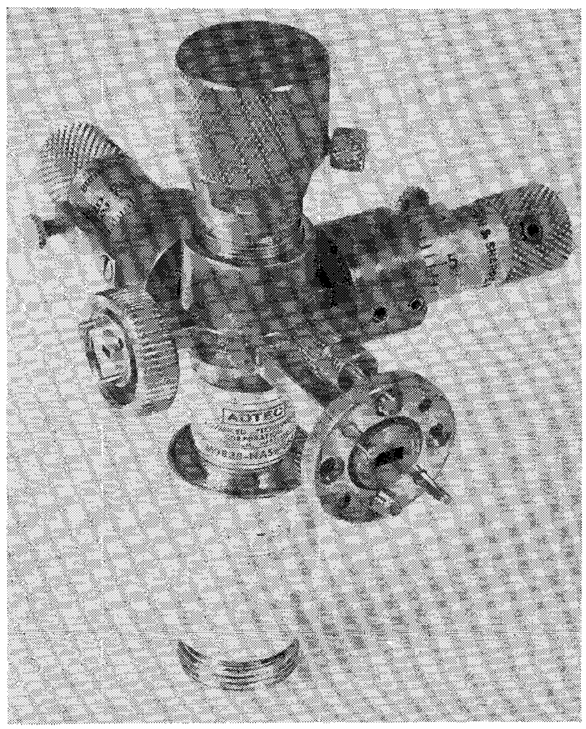

Fig. 5. M-9838 crossed guide varactor multiplier.

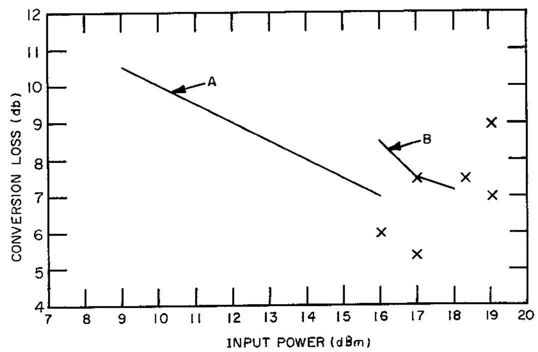

Fig. 6. Conversion loss vs. input power for the 70 GHz to 140 GHz doublers.

percent) occurred with an output power of 11.5 milliwatts and the highest power of 16 milliwatts was obtained with a different diode at an efficiency of 20 percent. The input power shown for each individual point, and the uppermost input power for Curves A and B represent what appeared to be the saturation power for that particular junction. That is, for a small fractional increase in input power, complete dynamic detuning appeared to result with a sharp loss in output power.

Now the calculations previously made can be modified slightly to see just how the above given data fit the predictions. Using a breakdown voltage, $V_B = 16$ volts, a zero bias junction capacitance of $C_0 = 0.015$ pF, an estimated maximum input power of 14 milliwatts is obtained. It has been estimated by Morrison [18] that by slightly driving into the forward region a factor of 3 to 5 times this input power may be realized. Therefore it is expected that this small capacitance of 0.015 pF can accept the level of power as shown in Fig. 6. Using an R_s of 10 ohms, and neglecting the fact that this R_s may vary with reverse bias, a zero bias f_{c0} is estimated to be about 1000 GHz. The doubler efficiency that might be expected (assuming no other losses) would be 78 percent, or 1.1 dB loss. In the crossed waveguide structure used, there was no reduction in height of either waveguide, so a high VSWR existed between the diode and the E-H tuner on the input side and most probably between the diode and the load on the output side. The VSWR between the E-H tuner and the diode on the input side was measured to be between 10 to 1 and 16 to 1. Therefore it would not be unreasonable to assume 1.5 dB loss for the RG-138/U components (sliding short tuners, flange connections and a section of waveguide) and on the order of 3 dB for the E-H tuner, the 2 inches of resonant, RG-87/U waveguide, and a sliding short. This may account for the losses shown in Fig. 6. If this is correct, then by use of a suitable design in reduced height waveguide the varactors herein discussed should give even more output power at 140 GHz, or operate efficiency at even higher frequencies.

It is of interest to calculate the series equivalent input and output resistances into which the guide impedance must transform if one is to attain the quoted efficiencies. The input resistance R_{in} and output resistance R_{out} for the doubler are [16]

$$R_{in} = R_{out} = R_s[1 + (K_1 Q_1)^2]^{1/2}, \tag{6}$$

where Q_1 is the quality factor at the dc bias point for the input frequency. K_1 is the modulation factor; values for K_1 are given in reference [16]. For the abrupt junction $K_1 = 0.286$. For $C_0 = 0.015$ pF, $R_s = 10$ ohms, and an input frequency of 70 GHz, $Q_1 = 30$. Using this data and (6) one obtains $R_{in} = R_{out} = 86$ ohms. This is a very low value of resistance and may present quite a matching problem. To match the relatively high waveguide impedance to such a low value may require the use of a matching transformer which (as noted above) could easily introduce more loss than the diode multiplier itself.

Conclusions

On the basis of the above discussion, it is believed that the use of varactor harmonic generators for the millimeter wave ranges has been proved not only feasible but practical. In particular, the construction of a 70 GHz to 140 GHz doubler with an output of greater than 15 milliwatts has been demonstrated. It is believed that there are yet several ways of obtaining improvement in circuit efficiency and thus obtaining overall multiplier efficiency much closer to the expected diode efficiency. The application of presently well-known techniques for making precision electroformed waveguides to the construction of the varactor diode mounts of reduced height waveguide should provide much better impedance matching to the diodes and should reduce the overall conversion loss. Crystal dimensions should be kept small to minimize the skin-effect losses [21] in the semiconductor. Also, the mount should be designed to minimize the interaction of the tuning and loading elements and hence the losses that are always incurred when harmonic power can propagate back to the source.

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A Nonreciprocal Circular Polarizer

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Abstract—**A nonreciprocal circular polarizer has been developed. This ferrite device converts linear polarization propagating in rectangular waveguide into circular polarization propagating in circular waveguide. The sense, right- or left-hand, of the circular polarization is determined by the direction of a longitudinal magnetic field applied to the ferrite. If one sense of circular polarization, e.g., right-hand, is transmitted, then only left-hand circular polarization can be received.**

Performance data indicate good ellipticity with reasonable loss and VSWR for two models of the circular polarizer, and for two devices—a circulator and a nonreciprocal antenna element—based on the polarizer. The antenna element permits one antenna to be used both to transmit and to receive the reflected circularly polarized signals from a target.

INTRODUCTION

THE USE OF circular polarization at microwave frequencies is dependent upon a device to convert the wave produced by the signal source (klystron, magnetron, etc.) into a circularly polarized wave. Several techniques are available which can be used to design reciprocal transmission-line components that convert linear polarization into circular polarization. There are applications, however, in which it is desired that the component be nonreciprocal. One application for such a polarizer is in a radar system where it is necessary to transmit one sense of circular polarization and to receive the opposite sense of circular polarization. Another application may be found in the construction of a three-port circulator.

Recently, as the outgrowth of a ferrite phase-shifter study by the author, a method for designing a nonreciprocal polarizer was obtained. A section of rectangular waveguide is joined to a section of circular waveguide in such a way that the two have a common longitudinal axis. A ferrite rod of suitable diameter and length is placed along the axis of the rectangular waveguide, with one end protruding into the circular waveguide. A longitudinal magnetic field of appropriate magnitude is then applied to the ferrite rod. If a linearly polarized wave is introduced into the rectangular waveguide, the wave transmitted into the circular waveguide will be circularly polarized, the sense of polarization depending on the direction of the applied magnetic field. A circularaly polarized wave of the opposite sense can be transmitted from the circular to the rectangular waveguide, where it is converted to a linear polarized wave. However, a circularly polarized wave of the same sense will be completely reflected by the rectangular waveguide section. Two models of the circular polarizer were investigated, and the data obtained from these models are presented in this report. The principal quantities studied (ellipticity, VSWR, and insertion loss) are shown as a function of applied magnetic field and of frequency. Additional information is then presented for the two applications previously mentioned.

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