Harmonically Pumped Stripline Down-Converter

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***Abstract*—A novel thin-film down-converter which is pumped at a submultiple of the local-oscillator frequency has given a conversion loss which is comparable to the performance of conventional balanced mixers. The converter consists of two stripline filters and two Schottky-barrier diodes which are shunt mounted in a strip transmission line. The conversion loss measured at a signal frequency of 3.5 GHz is 3.2 dB for a pump frequency of 1.7 GHz and 4.9 dB for a pump frequency of 0.85 GHz. The circuit looks attractive for use at millimeter-wave frequencies where stable pump sources with low FM noise are not readily available.**

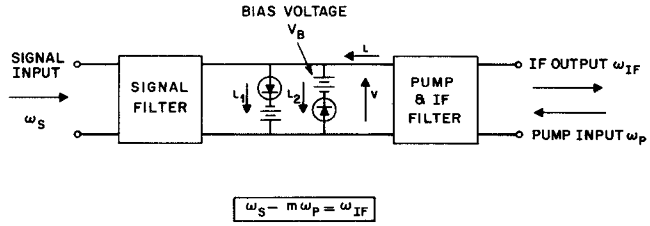

Fig. 1. Block diagram of harmonically pumped down-converter, including signal filter, pump and IF filter, and diode pair with opposite polarities and dc bias.

I. INTRODUCTION

THE PROCESS of frequency conversion and its applications are well known and have been extensively treated in the literature [1]–[7]. The conversion is usually performed by pumping a nonlinear resistive or reactive element embedded in a linear network and extracting the sum or difference frequencies which are generated by the signal and by the pump frequency. The purpose of this paper is to describe a novel thin-film converter which has the following properties.

1) The pump frequency required for efficient up-conversion or down-conversion is a submultiple of that needed in conventional frequency converters.

2) The circuit does not require a dc return path.

3) The separation of the signal and the local-oscillator frequency is readily obtained and the loss in the signal path is small.

The thin-film circuit consists of two strip transmission-line filters and two metal-semiconductor diodes which are shunt mounted in a stripline with opposite polarities as shown in the block diagram of Fig. 1. The strip transmission line is used because the conversion from the hybrid TEM mode to the first-order waveguide mode (longitudinal-section magnetic mode) is substantially reduced compared to the conversion obtained with other transmission-line circuits such as microstrip lines. This approach eliminates noise contributions from undesired bands near harmonics of the pump frequency.

The circuit design has the desired properties that the image frequency is reactively terminated and that the isolation of the pump oscillator is approximately 30 dB which is about 10 dB better than the isolation obtained with conventional circuits. The unit is therefore well suited for use in digital-communication receivers in the microwave and millimeter-wave frequency bands. The converter described herein is serving as a model for similar units being developed for use at higher frequencies. The individual components, the electrical characteristics of the diode pair, and the performance of the down-converter are described in the following paragraphs.

II. DESCRIPTION OF STRIPLINE CIRCUIT

The stripline conductor pattern of a harmonically pumped frequency converter is shown in Fig. 2. The pattern consists of a 50-Ω line section at the signal input, a half-wavelength resonator for the bandpass filter, a five-element low-pass filter, and a 50-Ω line section for the pump input and the IF output. Two Schottky-barrier diodes with opposite polarities are connected to the section between the filters at opposite sides of the stripline conductor. The conductor pattern is deposited on a quartz substrate which is suspended in a rectangular channel as shown in Fig. 3. Coupling to waveguide modes at harmonics of the pump frequency is substantially reduced because of the opposite polarity of the electric fields as indicated in Fig. 3. Undesired waveguide modes can also be suppressed if the slot which supports the substrate in each side wall has an electrical depth which is a quarter wavelength of a harmonic of the pump frequency [8]. The dimensions of the channel, the substrate, and the stripline conductor are given in Fig. 3 for a signal frequency of 3.5 GHz. They can be linearly scaled to higher frequencies using electromagnetic scaling laws [9]. The

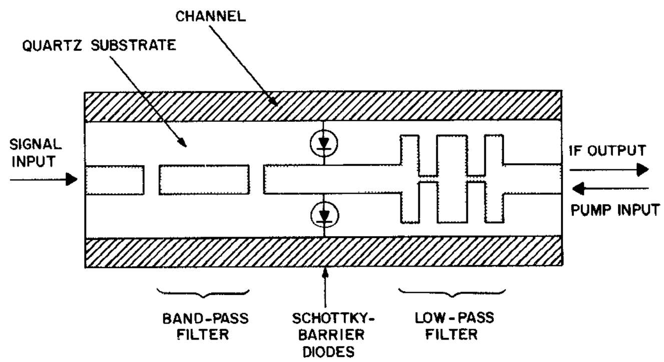

Fig. 2. Microstrip conductor pattern on quartz substrate in a metal channel of harmonically pumped down-converter. The diode pair is shunt mounted to the ground on opposite sides of the strip transmission line.

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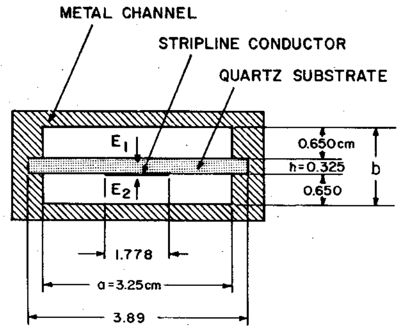

Fig. 3. Cross-sectional view of shielded stripline with symmetrically suspended quartz substrate and stripline conductor.

cutoff frequency for the first-order longitudinal-section magnetic mode for the channel dimensions a and b and a substrate thickness h is given by [10]

$$\omega_2 = \frac{\pi c}{a}\left(1 - \frac{h(\epsilon_r - 1)}{b\epsilon_r}\right)^{1/2} \quad (1)$$

where ϵ_r is the relative dielectric constant of the substrate. The signal frequency must satisfy the condition

$$\omega_1 < \omega_s < \omega_2 \quad (2)$$

where ω_1 is the cutoff frequency of the low-pass stripline filter. This condition insures that there is no signal loss through the low-pass filter and that waveguide modes are suppressed at the signal frequency. The cutoff frequency ω_2 calculated for the channel dimensions given in Fig. 3 with $\epsilon_r = 3.8$ is 4.25 GHz. The measured cutoff frequency of the channel is 4.20 GHz as shown in Fig. 4. The figure also gives the measured transmission loss of the low-pass filter as a function of frequency between 2 and 8 GHz. The usual low-pass characteristics are observed up to 4.2 GHz. Multimoding occurs at higher frequencies as shown by several peaks in the transmission curve which are caused by longitudinal LSM and LSE modes in the channel. The first-order LSM mode is partially suppressed if the mode conversion at a discontinuity is equal, but of opposite phase for the fields surrounding the stripline conductor shown in Fig. 3. This condition is fulfilled if the center conductor is symmetrically located between the top and the bottom plane of the surrounding shield. It is approximately fulfilled if the center conductor is deposited on a dielectric substrate with an appropriate dielectric constant for a fixed set of air gaps.

It should be noted that higher order mixer products are terminated by a complex reactance which is mainly determined by the transmission characteristics of the low-pass filter and the electrical length to the bandpass filter. An optimum conversion loss and noise figure for the converter is obtained by using an appropriate spacing between the diode pair and each filter, and by designing the filters in such a way that the excitation of undesired channel modes for the higher order mixer products is minimized.

A photograph of a harmonically pumped down-converter is shown in Fig. 5. Two Western Electric 497A GaAs Schottky-barrier diodes are used on opposite sides of the

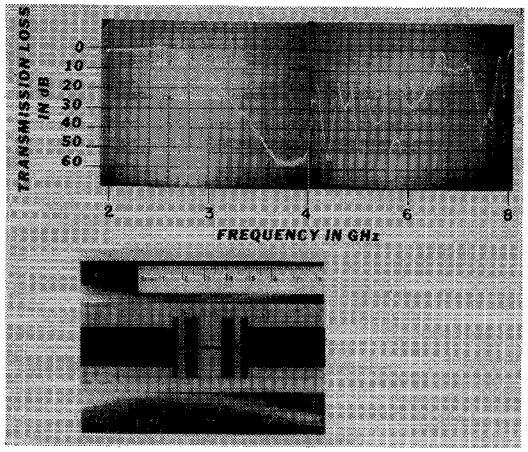

Fig. 4. Transmission loss of seven-element low-pass stripline filter from 2–8 GHz. The transmission spikes above 4 GHz are caused by resonances of the first-order LSM mode.

stripline conductor. The figure also shows the performance of the signal filter and the IF and pump filter measured with a network analyzer. The transmission loss of the signal filter at 3.5 GHz is normalized to zero. Its actual insertion loss at that frequency is 0.2 dB. The cutoff frequency of the low-pass filter is 2.6 GHz and the transmission loss at the signal frequency is 40 dB. The current-voltage characteristics of the diode pair are symmetrical with respect to the origin as shown in Fig. 6. This results in a current waveform which has only odd-order harmonics and a conductance waveform with even-order harmonics. The second feature combined with the low conversion to waveguide modes results in a converter which has a good conversion loss and a low noise figure for subharmonic pumping. The electrical characteristics of the diode pair and the converter characteristics are discussed in the two following paragraphs.

III. ELECTRICAL CHARACTERISTICS OF DIODE PAIR

The current-voltage characteristics of a Schottky-barrier diode can be computed from the thermionic-emission diffusion theory of Crowell and Sze [11], [12]. For a sufficiently small minority carrier injection ratio one obtains for the diode current

$$i = i_s \left\{\exp\left[\frac{q}{nkT}(v - iR_s)\right] - 1\right\} \quad (3)$$

where v is the applied voltage, R_s the diode series resistance, n the idealty factor, and $q/kT = 38.7\ \mathrm{V}^{-1}$ for 300 K. The saturation current i_s is a function of the diode area S, the barrier height ϕ_B, and the modified Richardson constant A^{**}. It is given by

$$i_s = A^{**}ST^2 \exp\left[-\frac{e\phi_B}{mkT}\right] \quad (4)$$

where $\phi_B = kT/e + V_D + \phi_F - \Delta\phi$. V_D is the diffusion voltage, ϕ_F the position of the Fermi level relative to the bottom of the conduction band, and $\Delta\phi$ the image-force lowering of the barrier.

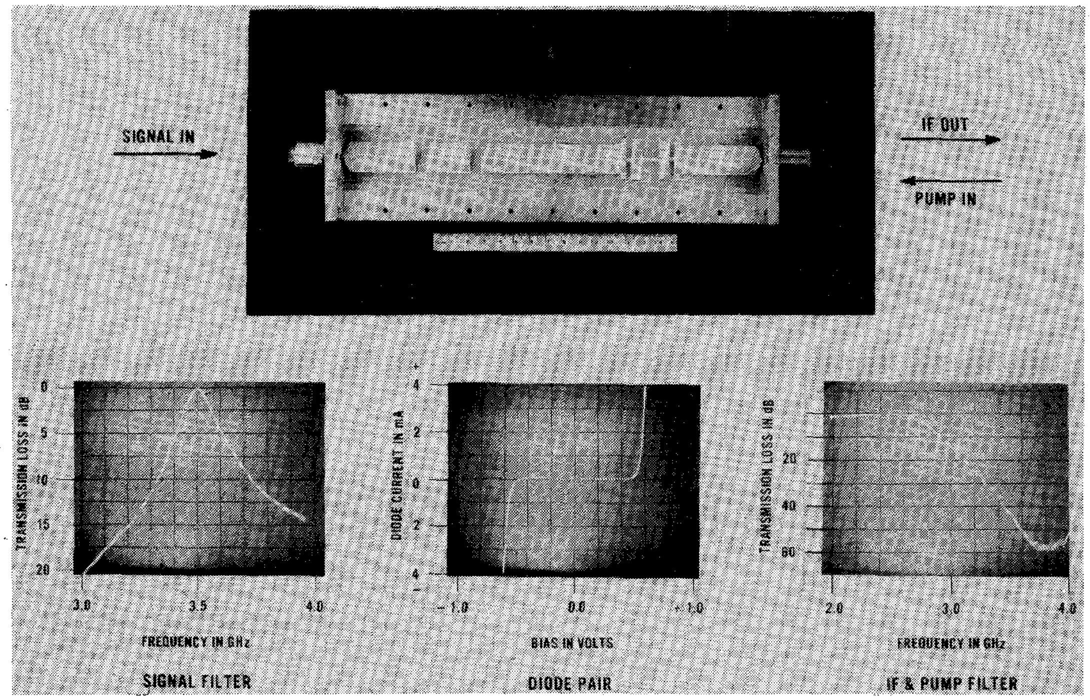

Fig. 5. Photograph of harmonically pumped down-converter showing top view of stripline conductor pattern in a rectangular channel. The characteristics of the bandpass filter, the low-pass filter, and the diode pair are displayed at the bottom of the photograph.

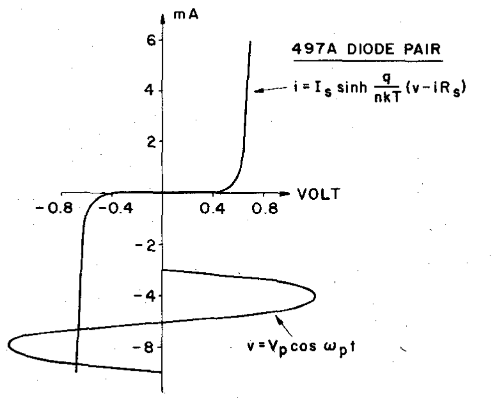

Fig. 6. Current-voltage characteristics of diode pair consisting of two Western Electric 497A Schottky-barrier diodes connected with opposite polarities. Two conducting switching states per RF cycle are obtained if the pair is driven by a sinusoidal pump frequency.

The current flowing through a diode pair shown in Fig. 1 is a function of the applied dc bias V_B, and is given by the sum $i = i_1 + i_2$ where

$$i_1 = i_s \left\{ \exp \frac{q}{nkT} (v - V_B - i_1 R_s) \right\} \tag{5}$$

$$i_2 = -i_s \left\{ \exp \frac{q}{nkT} (-v - V_B + i_2 R_s) \right\}. \tag{6}$$

We assume that the voltage drop $i_1 R_s$ and $i_2 R_s$ is only significant for $i_1 \gg i_2$ or $i_2 \gg i_1$. The resulting current becomes

$$i = 2 i_s \exp \left(-\frac{q V_B}{nkT} \right) \sinh \frac{q}{nkT} (v - i R_s) \tag{7}$$

and for $iR_s \ll v$, which is fulfilled for most practical applications, one obtains

$$i = \frac{I_{sat} \sinh (qv/nkT)}{1 + (q I_{sat} R_s / nkT) \cosh (qv/nkT)} \tag{8}$$

where we define I_{sat} by

$$I_{sat} = 2 i_s \exp (-q V_B / nkT). \tag{9}$$

In order to compute the conversion loss one has to know the conductance di/dv of the diode pair. From (7) one obtains

$$\frac{di}{dv} = \left(\frac{nkT}{q} \frac{1}{(i^2 + I_{sat}^2)^{1/2}} + R_s \right)^{-1}. \tag{10}$$

For $R_s = 0$ the resulting conductance is

$$\frac{di}{dv} = \frac{q I_{sat}}{nkT} \cosh \frac{qv}{nkT}. \tag{11}$$

IV. VOLTAGE PUMPING AND CONVERSION LOSS

Let us assume that the diode pair is pumped with a periodic signal

$$v = V_p \cos \omega_p t. \tag{12}$$

This means that the pumping voltage across the diode is constrained to be sinusoidal, while the current i can have all the possible harmonics. The current through the diode pair and the pair conductance becomes a periodic function which can be computed from the series expansions

$$\cosh (z \cos \theta) = I_0(z) + 2 \sum_{k=1}^{\infty} I_k(z) \cos 2k\theta \tag{13}$$

$$\sinh (z \cos \theta) = 2 \sum_{k=0}^{\infty} I_{2k+1}(z) \cos (2k+1)\theta \quad (14)$$

where I_k is the modified Bessel function of the first kind of order k. Using the abreviation $\alpha = q/nkT$ one obtains from (7), (11), and (12) for $R_s = 0$

$$i = 2I_{\text{sat}} \sum_{k=0}^{\infty} I_{2k+1}(\alpha V_p) \cos (2k+1)\omega_p t \quad (15)$$

$$di/dv = \alpha I_{\text{sat}} I_0(\alpha V_p) + 2\alpha I_{\text{sat}} \sum_{k=1}^{\infty} I_k(\alpha V_p) \cos 2k\omega_p t. \quad (16)$$

As expected, 1) there is no dc current flowing through the diode pair, i.e., the converter does not need a dc return path; 2) the diode-pair current contains only odd-order harmonics; and 3) the pair conductance has only even-order harmonics. Let us write the conductance waveform $g(t) = di/dv$ as follows

$$g(t) = y_0 + 2y_1 \cos 2\omega_p t + 2y_2 \cos 4\omega_p t + \cdots \quad (17)$$

$$y_n = \alpha I_{\text{sat}} I_n(\alpha V_p), \qquad n = 0,1,2,\cdots. \quad (18)$$

The conversion loss L of the down-converter operated at a pump frequency $2\omega_p$ is now given by

$$L = \Phi(Y_{\text{image}}, y_1/y_0, y_2/y_0) \quad (19)$$

where Φ is an irrational function of the image conductance Y_{image} and the first two normalized Fourier coefficients of the conductance waveform. The function Φ is exactly the same as the one which is used for computing the conversion loss of a conventional down-converter operated with a single diode and pumped with a local oscillator frequency which is close to the signal frequency ($\omega_{\text{LO}} = \omega_s \pm \omega_{\text{IF}}$). The properties of the function Φ are extensively treated in the work by Saleh [3]. For the special case $\alpha V_p \gg 1$ and for $Y_{\text{image}} = 0$, Y_{signal}, or ∞ the resulting conversion loss is

$$L(Y_{\text{image}} = 0) = 1 + (2/\alpha V_p)^{1/2} \quad (20)$$

$$L(Y_{\text{image}} = Y_{\text{signal}}) = 2(1 + \sqrt{2}/\alpha V_p) \quad (21)$$

$$L(Y_{\text{image}} = \infty) = 1 + 2/(\alpha V_p)^{1/2}. \quad (22)$$

This means that the minimum conversion loss which can be achieved with an open or short at the image frequency is 0 dB. The minimum conversion loss for a matched image is 3 dB. The minimum conversion loss for a series resistance $R_s \neq 0$ is a function of the ratio ω_s/ω_c where ω_s is the signal frequency and ω_c the cutoff frequency of the diode

$$\omega_c = (R_s C_0)^{-1} \quad (23)$$

where C_0 is the zero-bias capacitance of one single converter diode. Computations of the conversion loss L as a function of ω_s/ω_c have been performed by Dragone [13]. For a Western Electric diode WE 497A with $R_s = 2\ \Omega$ and $C_0 = 0.45$ pF pumped at a signal frequency of 3.5 GHz one obtains $f_c = 177$ GHz or $L = 2.1$ dB. Beam-leaded devices fabricated for use at millimeter-wave frequencies [14] have shown a cutoff frequency of approximately 1000 GHz. The corresponding diode conversion loss of an optimized converter at 50 GHz built with these diodes would be 3.1 dB.

V. PERFORMANCE OF THE STRIPLINE CONVERTER

The measured single-sideband noise figure for the stripline down-converter of Fig. 5 is plotted in Fig. 7 as a function of the signal frequency ω_s for $m = 2$ and $m = 4$. The harmonic integer m is defined by

$$m = \frac{\omega_s \pm \omega_{\text{IF}}}{\omega_p}. \quad (24)$$

The noise figure of the 100-MHz IF amplifier is 1.7 dB. The total single-sideband noise figure including the IF amplifier noise at a signal frequency of 3.455 GHz is 4.9 dB for $m = 2$ and 6.6 dB for $m = 4$. The corresponding conversion loss is 3.2 dB for $m = 2$. This result approaches the theoretically predicted loss of 2.1 dB obtained in the last paragraph. The loss for $m = 4$ is higher because the circuit does not contain a trap at the second subharmonic. The total noise figure for $m = 2$ is 6 dB or better over a bandwidth of 35 MHz which is 1 percent of the signal frequency. The bandwidth for $m = 4$ is much smaller because the circuit was designed for optimized performance at a pump frequency which is the second subharmonic of the conventional local-oscillator frequency. A well-designed harmonic down-converter which is pumped at the fourth subharmonic ($m = 4$) should include a trap at the second subharmonic consisting of an open-ended section of a strip transmission line which is connected to the part of each diode terminal at the stripline side, or an approximately chosen length for the stripline sections between the diode pair and the low-pass and the bandpass filter. The total noise figure as a function of a pump power for $m = 2$ is shown in Fig. 8. A first minimum is obtained at a power of approximately +3 dB. It can be shown that this minimum can be reduced further by using a small bias voltage V_B in series with each diode as shown in Fig. 1. It has also been found that for a down-converter

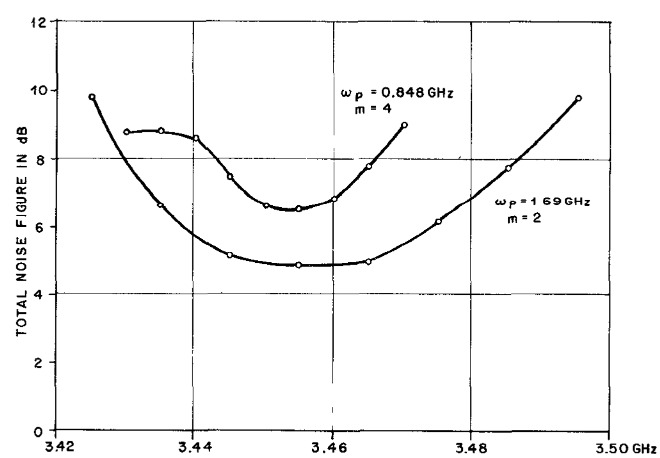

Fig. 7. Single-sideband noise figure including noise of IF amplifier in decibels as a function of signal frequency for harmonically pumped stripline down-converter pumped at the second subharmonic ($m = 2$) and at the fourth subharmonic ($m = 4$). The noise figure of the 100-MHz IF amplifier is 1.7 dB.

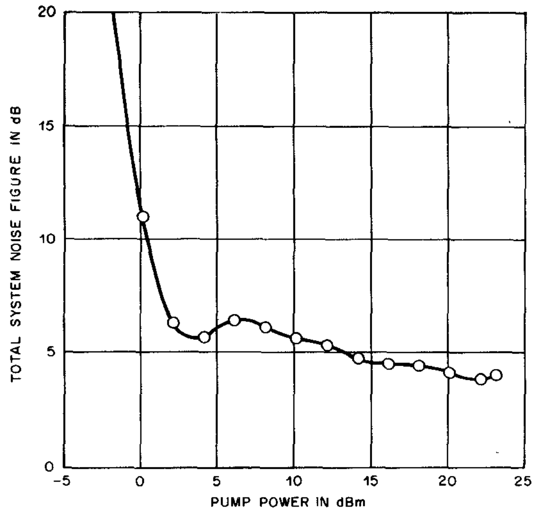

Fig. 8. Total system noise figure as a function of pump power for $m = 2$. The first minimum at +3 dBm can be further reduced using a small bias voltage V_B in series with each diode.

with a much higher signal frequency substantially less pump power is needed to obtain a minimum noise figure for the case $V_B = 0$.

A circuit which is similar to the one shown in Fig. 2 was also built using microstrip transmission-line filters and microstrip line sections. It was found that the noise figure of the microstrip down-converter is approximately 6 dB higher than the noise figure of the corresponding stripline circuit. This effect is not surprising since shielded microstrip circuits show relatively strong coupling to waveguide modes above the cutoff frequency of the shielding enclosure. Coupling to undesired modes can be suppressed by using waffle-iron filters or other traps; however, such a circuit is likely to be more complex and more costly than the simple stripline structure shown in Fig. 2.

VI. CONCLUSIONS

It has been shown that harmonically pumped down-converters with good noise performance can be built with two strip transmission-line filters and two metal-semiconductor diodes which are shunt mounted in a stripline with opposite polarities. The thin-film circuit can be pumped with the second or the fourth subharmonic of the local-oscillator frequency required in conventional down-converters. DC bias and a dc return path for the diodes is not required.

The new harmonically pumped stripline circuit can be readily scaled to higher microwave frequencies and particularly to millimeter-wave frequencies where solid-state oscillators are only available at subharmonics of the local-oscillator frequency. The basic design principles outlined in this paper can also be applied to other converters in the electromagnetic spectrum, such as up-converters, harmonic generators, and parametric amplifiers.

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REFERENCES

[1] C. T. Torrey and C. A. Whitmer, *Crystal Rectifiers* (M.I.T. Radiation Lab. Series), vol. 15. New York: McGraw-Hill, 1948.
[2] C. Dragone, "Amplitude and phase modulations in resistive diode mixers," *Bell. Syst. Tech. J.*, vol. 48, pp. 1967–1998, July–Aug. 1969.
[3] A. A. M. Saleh, *Theory of Resistive Mixers* (Res. Monograph 64). Cambridge, Mass.: M.I.T. Press, 1971.
[4] M. R. Barber, "Noise figure and conversion loss of the Schottky barrier mixer diode," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 629–635, Nov. 1967.
[5] J. W. Gewartowski, "Noise figure for a mixer diode," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, p. 481, May 1971.
[6] C. A. Liechti, "Down-converters using Schottky-barrier diodes," *IEEE Trans. Electron Devices*, vol. ED-17, pp. 975–983, Nov. 1970.
[7] K. M. Johnson, "*X* band integrated circuit mixer with reactively terminated image," *IEEE Trans. Electron Devices (Special Issue on Microwave Integrated Circuits)*, vol. ED-15, pp. 450–459, July 1968.
[8] M. V. Schneider and B. S. Glance, "Suppression of waveguide modes in strip transmission lines," *Proc. IEEE* (Lett.), vol. 62, p. 1184, Aug. 1974.
[9] J. A. Stratton, *Electromagnetic Theory.* New York: McGraw-Hill, 1941, pp. 488–490.
[10] M. V. Schneider, "Millimeter-wave integrated circuits," in *1973 IEEE G-MTT Int. Symp. Digest Tech. Papers* (Univ. Colorado, Boulder), June 4–6, 1973, pp. 16–18.
[11] C. R. Crowell and S. M. Sze, "Current transport in metal-semiconductor barriers," *Solid-State Electron.*, vol. 9, pp. 1035–1048, Nov./Dec. 1966.
[12] S. M. Sze, *Physics of Semiconductor Devices.* New York: Wiley, 1969, pp. 363–409.
[13] C. Dragone, to be published.
[14] A. Y. Cho and W. C. Ballamy, "GaAs planar technology by molecular beam epitaxy," *J. Appl. Phys.*, vol. 46, Feb. 1975.