frequencies of f_+ and f_-. The results show that if the conductance looking to the right from AA' in Fig. 2 is designed to be from 1.3 to 1.5 times larger for the f_- mode than for the f_+ mode, the unwanted oscillations in the f_- mode can be suppressed efficiently by the use of the cavity C within the limit of the bias current of about 60 mA. An output power of at least 50 mW is expected for the f_+ mode.

In the present oscillator, electronic tuning is also available by means of the varactor diode in the cavity C. Only slight variation in output power was caused by the varactor tuning, because in f_+ mode operation the variation of the conductance looking to the right from AA' in Fig. 2 is small when the bias voltage applied to the varactor diode is increased.

IV. EXPERIMENTAL RESULTS

The values of the circuit parameters used in the experimental MIC oscillator as shown in Fig. 1 are given in Table I. In this oscillator, single-mode oscillation in the f_+ mode was obtained for output power below 50 mW, as expected from the analysis in Section III. The varactor tuning range of, at most, 50 MHz was also attained with a sensitivity of 2 MHz/V, and the output power change was less than 7 percent for a tuning range of 30 MHz in the typical oscillator ($f_A = 9.8$ GHz). The mechanical tuning range of 450 MHz was achieved with the tuning screw. The oscillation frequency was tuned to 10.525 ± 5 MHz. The oscillation built up at as low an input power as 0.8 W. The input power giving an output power of 30 mW was as low as 1.5 W. A high frequency stability of 10 ppm/°C was obtained over the temperature range from −20° to 60°C because the variation of the resonant frequency of the cavity B is compensated through TiO_2. The rms frequency deviation in a bandwidth of 1 Hz and the single-sideband AM noise-to-carrier ratio in a bandwidth of 1 Hz were as low as 2 Hz and −148 dB, respectively, at the modulation frequency of 1.4 kHz.

In order to investigate the degree of stabilization due to the cavity B, many germanium avalanche diodes having different admittance values were embedded by turns in two kinds of oscillators: 1) an oscillator with cavities A, B, and C, and 2) an oscillator with a cavity A only. In both oscillators, the dimension of the cavity A is the same and the tuning screw is not inserted. The admittances of both oscillators embedded with the same avalanche diode are adjusted so as to build up oscillation at the same bias current. The oscillation frequencies were measured in both oscillators. The result is shown in Fig. 4. The stabilization factor due to the cavity B is characterized by the quantity S defined as

$$S = 1 \Big/ \frac{\partial f}{\partial f_A}$$

where the variation of f_B is ignored [1], [2]. It is seen from Fig. 4 that S is about 5 at about 9.8 GHz of f_A in the present MIC oscillators.

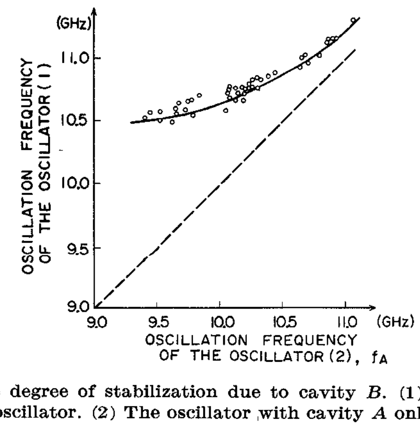

Fig. 4. The degree of stabilization due to cavity B. (1) The present oscillator. (2) The oscillator with cavity A only.

V. CONCLUSION

A single-mode oscillation with high stability in an MIC oscillator has been obtained by coupling a third varactor-embedded low-Q cavity to a conventional coupled-cavity oscillator. It has been confirmed theoretically and experimentally that the third cavity can serve not only for suppressing an unwanted mode but also for varactor tuning with little variation of the output power.

The advantage of using a germanium avalanche diode in the present MIC oscillator is fully exhibited in low-noise [6] and low-input-power operation.

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Avalanche Diode Noise Sources at Short Centimeter and Millimeter Wavelengths

NIGEL J. KEEN

***Abstract*—Semiconductor noise sources for microwave frequencies have been constructed using commercial avalanche diodes in waveguide mounts. For the diodes and waveguide configurations reported here the upper usable frequency is approximately 40 GHz.**

The measurements are in limited agreement with previous predictions. It is possible that a reduction in package and diode parasitics would improve this agreement, and raise appreciably the upper usable frequency of such noise sources.

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INTRODUCTION

Since first reports of the use of avalanche diodes as microwave noise sources [1]–[4], they have replaced noise tubes in a large number of applications [5]–[7]. Up to the present, the noise sources reported in the literature have been mounted in coaxial line or stripline, and operate only up to X band. Up to these frequencies, Haitz and Voltmer [8] confirm the predictions of Hines [9], that this noise power spectral density is approximately constant below the avalanche frequency (f_a) and decreases as $(1 - f^2/f_a^2)^{-2}$ above f_a, and that $f_a \sim I^{1/2}$ (where I is the avalanche current).

In order to raise appreciably the upper usable frequency, it is necessary to mount the diode in waveguide. In the experiments reported here excess noise was measured from 18 to 40 GHz, using commercial packaged diodes and standard waveguides.

EXPERIMENTAL RESULTS

Two similar waveguide diode mounts were employed, in R 220 (WR-42) for the frequency range 18–26.5 GHz and in R 320 (WR-28) for the frequency range 26.5–40 GHz. Both mounts used a tapered ridge section to the diode. Fig. 1 shows schematically the construction of the mounts. The diodes are Mullard silicon avalanche diodes type VX 6542, with breakdown at approximately 22 V. Diode excess noise ratio (ENR) is determined by comparison with the quoted value for the plasma noise tube. The experimental results for numerous diodes are shown in Fig. 2, at a constant current of 55 mA. The effects of current variation on excess noise and return loss are shown in Fig. 3. The diode mounts were situated between a matched load and an isolator, to obtain an ENR which varied as monotonically as possible over the total waveguide band.

In order to determine the absolute noise power output at frequencies above f_a, a sliding short circuit replaced the matched load in the

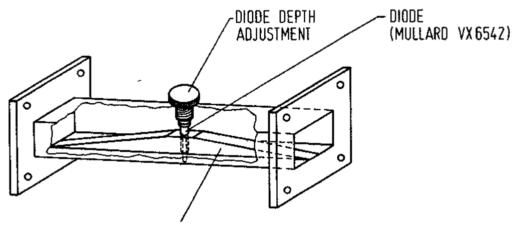

Fig. 1. Construction of waveguide mounts for VX 6542 avalanche diodes: $I = 55$ mA. Ridge width is $0.33A$ dimension. B dimension reduced to $B/3$ at diode. Taper length $\approx 4 \times$ midband λ_g.

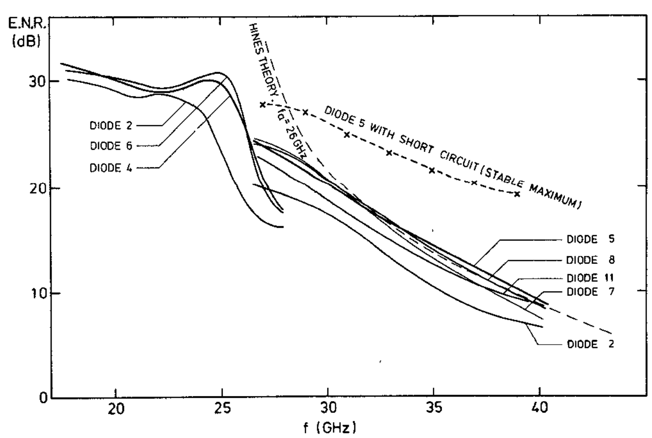

Fig. 2. Excess noise due to various avalanche diodes: $I = 55$ mA. Measurements of maximum stable ENR, using sliding short circuit behind the diode, are indicated by crosses.

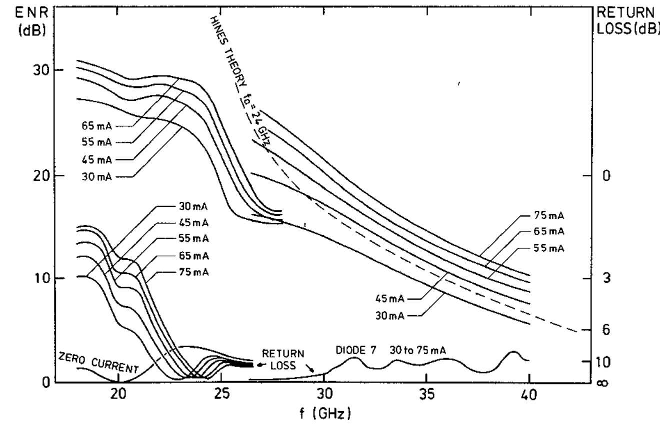

Fig. 3. The effects of current variation on excess noise and return loss diodes 2 (18–26.5 GHz) and 11 (26.5–40 GHz).

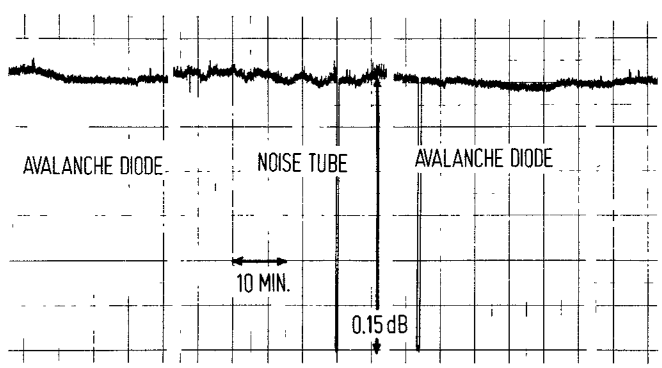

Fig. 4. Comparison of the noise outputs of avalanche and gas-discharge noise sources as a function of time.

R 320 band and was adjusted to permit the maximum stable noise power transfer from the diode to the measuring system. This output was adjusted to be stable with time, and to display no rapid discontinuities in ENR with frequency. Under these conditions, the noise output had a 3-dB width of between 0.5 and 1 GHz—depending on the diode. As would be expected, anomalously high and unstable noise outputs (>40-dB ENR) were obtained for some critical positions of the adjustable short circuit, as was observed by Bareysha *et al.* [4]. The onset of oscillation was invariably associated with temporal instabilities in noise output and large variations in average noise output with frequency. Maximum stable ENR was determined across the R 320 band, a different setting of the sliding short circuit being required at each frequency. These values are shown as crosses in Fig. 2.

The variation of ENR with temperature was not constant. Where the ENR is strongly frequency dependent (23–28 GHz), variations up to 0.08 dB (°C)$^{-1}$ have been observed, whereas above and below this frequency range, the maximum observed variation was 0.03 dB (°C)$^{-1}$.

Earlier comparisons between noise diodes and noise tubes at 2.7 GHz [6] have revealed small-scale variations in ENR with time from commercial noise tubes, which do not appear to occur with noise diodes. These small-scale variations have been confirmed at 22 and 28 GHz, and do not appear to be due to poor current regulation of the noise tube. The variations are usually <0.005 dB and always <0.01 dB, so that they are insignificant for most experimental purposes. Fig. 4 shows comparisons of subsequent runs with a commercial noise tube and a semiconductor noise source at 22 GHz: the noise diode output was attenuated to give an ENR identical to that from the noise tube.

DISCUSSION

The spectral density of available power from an avalanche noise source is

$$W(f) = \beta^2(V_b^2/I)(1 - f^2/f_a^2)^{-2}(R_L/[R_{SC} + R_{SP} + R_L]^2) \quad (1)$$

which is derived from Hines' theory, with some simplifications, by Haitz and Voltmer. V_b is the breakdown voltage, R_L is the load resistance, $R_{SC} = R_{SC}^0(1 - f^2/f_a^2)^{-1}$, and R_{SC}^0 is the low-frequency space-charge resistance, R_{SP} is the spreading resistance, and β^2 is a constant, dependent on diode material and geometry. For maximum power transfer across the whole range of frequencies $R_L = R_{SC} + R_{SP}$. Hence the excess noise ratio (ENR), expressed in decibels, is

$$10 \log_{10} \beta^2 V_b^2/4IkT_0(R_{SC} + R_{SP})(1 - f^2/f_a^2)^2. \quad (2)$$

The simplifications of Haitz and Voltmer are 1) that the diode has small transit angles at the measured frequencies, and 2) that there are no reactive elements in the circuit external to the diode. While simplification 1) is probably no longer justified at frequencies around 40 GHz, measurements of ENR and return loss at these frequencies indicate only limited divergence from the frequency dependence predicted by (1), provided that simplification 2) is still valid.

The ENR values in Figs. 3 and 4 appear to agree with the $(1 - f^2/f_a^2)^{-2}$ dependence predicted by Hines, at frequencies above 30 GHz: at frequencies near f_a the ENR departs from Hines' theory. From the definition of f_a from Haitz and Voltmer

$$f_a^2 = 7.6I/V_b \cdot A \text{ GHz}^2 \quad (3)$$

for silicon diodes, where A is the breakdown area in square centimeters. For $V_b = 22$ V, and $f_a = 25$ GHz, the diameter of the breakdown area is 65 μm, which is in good agreement with the 50 μm (typical) value provided by the manufacturer, particularly in view of the fact that there is no guard ring around the avalanche region.

At identical frequencies there is a considerable discrepance bytween the noise measurements in the two waveguide sizes: this is probably due to waveguide and mount impedance dissimilarities. This discrepancy appears to be confirmed by the measurements of return loss, where a moderately low diode admittance is measured in the R 320 mount, while the admittance in the R 220 mount varies appreciably—appearing to go through a minimum at 23–24 GHz, and rising rapidly as the frequency is further decreased. Comparison of return loss measurements with those of Haitz and Voltmer suggest that this admittance minimum corresponds to the avalanche frequency, which is qualitatively in agreement with the impedance calculations of Gummel and Scharfetter [10].

The maximum stable values of ENR with an adjustable short circuit permit the resistive term $R_{SC} + R_{SP}$ to be determined. In the absence of additional internal losses and reactive parasitics, a value of 10–20 Ω is realistic. However, using the value of $\beta^2 = 3.3 \times 10^{-20}$ $A \cdot Hz^{-1}$ [8], resistance values of 195 Ω at 35 GHz and 130 Ω at 39 GHz were obtained. A further disagreement with Hines' theory is the relationship between ENR and avalanche current. From (1), the power spectral density is inversely proportional to I, whereas experiment shows an increase in ENR with current: this anomalous current relationship could be explained by the absence of a guard ring at these high current densities, resulting in excessive noise being produced at higher currents, due to nonuniform breakdown.

CONCLUSIONS

Noise sources using avalanche diodes in waveguide mounts have been constructed and tested in the laboratory. As a result of these investigations, noise tubes in 22- and 35-GHz radiometers are being replaced by waveguide-mounted avalanche diodes.

The ENR of Mullard VX 6542 silicon avalanche diodes between 18 and 40 GHz shows limited agreement with the theory of Hines, although it appears necessary to improve diode construction, and perhaps mount design, in order to increase the maximum usable frequency of solid-state noise sources appreciably above 40 GHz.

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