

Solid-State Noise Sources at mm-Waves: Theory and Experiment

M.M. Radmanesh
California State University
Northridge, CA
and
J.M. Cadwallader
Hughes Aircraft Co.
Torrance, CA

Introduction

Since the late 1950s, avalanche diodes have been under investigation for noise properties. The first use of avalanche diodes as microwave noise sources was reported from 1966 through 1969.¹⁻³ The publication of a paper on avalanche diode noise sources at short cm- and mm-wavelengths⁴ in 1976 was a milestone in employment of solid-state devices as noise sources at mm-wavelengths. Up to that time, the noise sources reported in the literature had been mounted in coaxial transmission line or stripline and operated only up to and including the X-band. In that paper, a new workable waveguide configuration for the mounting of the avalanche diode was reported. By means of some experimental work, the existing noise theory on avalanche diodes^{5,6} was extrapolated to the newer frequency ranges of mm-waves.

Since that time, there have been numerous theoretical and experimental investigations of the noise performance of avalanche diodes. Nevertheless, no substantial work or result leading to the actual production of noise sources in lieu of gas discharge noise tubes in mm-wave regions has been reported.

In this paper, based on experimental evidence, some workable configurations along with performance results for IMPATT-mounted waveguide cavities in the 26.5 to 75

GHz frequency range will be presented.

Noise Theory

In spite of several simplifications, the studies of available noise^{5,6} yield a fairly accurate description of the avalanche noise source. The simplifications⁶ are that the diode has small transit angles at the measured frequencies and that there are no reactive elements in the circuit external to the diode.

Based on these simplifications, the power spectral density of the available power from an avalanche noise source can be written as

$$W(f) = a^2 \left(\frac{V_b}{I} \right) \frac{\left(\frac{R_L}{[R_{sc} + R_{sp} + R_L]^2} \right)}{(1 - f^2/f_a^2)^2} \quad (1)$$

where

$$f_a = \left[7.6 \frac{I}{AV_b} \right]^{1/2} \quad (2)$$

I = DC current through the diode
 V_b = breakdown voltage
 R_L = load resistance
 R_{sc} = the space charge resistance
 $R_o = \frac{R_{sc}}{(1 - f^2/f_a^2)}$
 R_o = the low frequency space charge resistance

R_{sp} = the spreading resistance
 $= P/2D$
 P = the resistivity of the lightly doped side of the P-N junction, usually the bulk resistivity
 D = the diameter of the breakdown area (A)
 a^2 = a constant dependent on the diode material and geometry

From the noise measurements at low frequencies, it is found that $a^2 = 3.3 \times 10^{-20}$ A/Hz.

While simplification of Equation 1 is probably no longer justified at mm-wave frequencies, measurement of excess noise ratio (ENR) and return loss at these frequencies indicate only limited divergence from the frequency dependence predicted by Equation 1, provided that simplification of Equation 2 is still valid.

According to Equation 1, the spectral power density is independent of frequency for $f \ll f_a$. However, a small frequency dependence arises from the thermal resistance of the diode that is neglected in Equation 1. This frequency dependence is of the order of 1 dB per decade or less.

For frequencies approaching f_a , R_{sc} is the main contribution to the diode resistance since R_{sp} can be ignored. Tuning R_L for maximum power transfer ($R_L = R_{sc} \gg R_{sp}$), $w(f)$ is obtained as

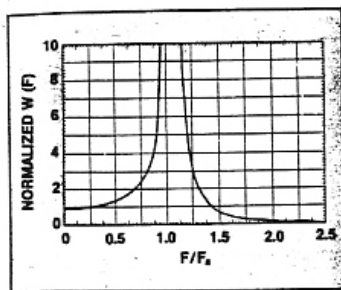


Fig. 1 A power spectrum plot of $W(f)$ vs. f/f_a .

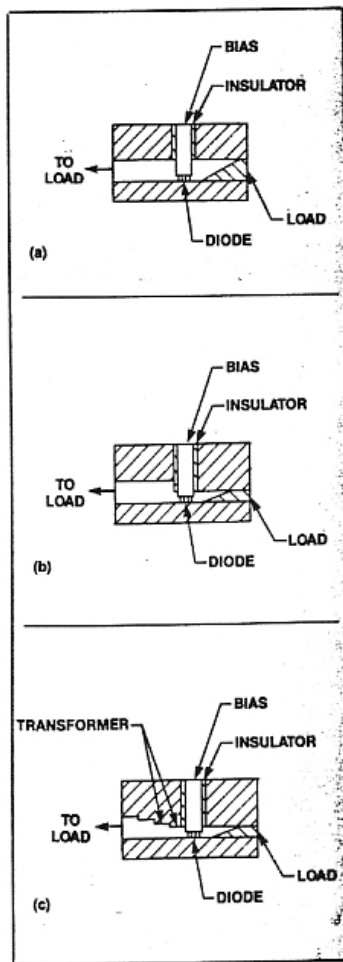


Fig. 2 IMPATT noise source configurations; (a) a full height, full height cavity configuration, (b) a full height, reduced height cavity configuration and (c) a reduced height, reduced height cavity configuration.

$$w(f) = \frac{a^2 v_b^2}{[4 I R_o (1 - f^2/f_a^2)]} \quad (3)$$

For frequencies $f \gg f_a$, the spreading resistance R_{sp} is the predominant contributing factor to the diode resistance. Tuning R_L for maximum power transfer leads to

$$W(f) = a^2 \frac{V_b^2}{[4 I R_{sp} (1 - f^2/f_a^2)]} f \gg f_a \quad (4)$$

Equation 4 predicts an f^{-4} dependence of noise power on frequency.

The ENR from Equation 1, for maximum power transfer across the whole range of frequencies (with $R_L = R_{sc} + R_{sp}$) can be written in dB as

$$\text{ENR} = 10 \log \left\{ \frac{a^2 V_b^2}{[4 I K T_o (R_{sc} + R_{sp})(1 - f^2/f_a^2)]} \right\} \quad (5)$$

where

K = the Boltzman's constant
 T_o = 290°K

Figure 1 shows a plot of normalized $W(f)$ versus f/f_a . As f approaches f_a , $W(f)$ asymptotically approaches infinity, which clearly demonstrates incorrect prediction of actual experimental results. For other values of f/f_a , the plot accurately predicts the diode's behavior in terms of output noise power spectral density.⁴ Since it is desirable to operate in the $f \ll f_a$ region of this plot, the value of f_a is higher and the frequency response of the noise source is flatter. This justifies the reasons for using a high frequency diode in a low frequency cavity since these diodes have higher f_a values.

The breakdown voltage (V_b) of the diode as well as current (I) and diode cross-sectional area (A) play an important role in determining the value of f_a . The cross-sectional area of the diode is inversely proportional to the capacitance value of the diode. Thus, a small capacitance value is preferred since it leads to a higher f_a value.

Aside from increasing the value of DC current (I), which increases the power dissipated in the diode, one

can choose a diode of lower breakdown voltage (a minimum breakdown voltage is 8 to 10 V at present time). This determines the proper choice of the diode that should be made to obtain a reasonably flat noise response.

It should be further noted that Hines' theory,⁵ in spite of its simplifications, yields a fairly accurate description of the avalanche noise power for $f \ll f_a$ and $f \gg f_a$. Around $f = f_a$, Hines' theory is inaccurate since it neglects internal diode losses.

Another problem with Hines' theory is the relationship between the ENR and the avalanche current. From Equation 4, the ENR is inversely proportional to DC current (I), whereas experiments show an increase in ENR with current. This abnormal current-power relationship could be explained by the absence of a guard ring, resulting in excessive noise being produced at higher currents due to nonuniform breakdown. The guard ring is absent in the state-of-the-art mesa structures of modern IMPATT diodes. These structures have a lower junction capacitance, and therefore, are more suitable for accurate noise measurements.⁷

This is as far as the avalanche diode noise theory can predict. However, there is another factor that should be taken into consideration, which is the effect of the cavity configuration in which the diode is placed. Three types of cavity configurations are presented.

mm-Wave Avalanche Diodes vs. Noise Tubes

The current noise tube consists of an argon-filled glass tube that is positioned at an approximate angle of 10° to the broad face of the waveguide. This type of tube produces white noise up to very high frequencies. However, it has several disadvantages, including manufacturing cost and its large, expensive power supply requirement.

The output noise power of several high frequency IMPATT diodes in a lower frequency cavity was investigated using the three types of cavity configurations in the experiments. Each type has a different height for the cavity section and for the tuning

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portion. Figure 2 shows a full-height full-height (FH-FH) cavity configuration, a full-height reduced-height (FH-RH) cavity configuration and a reduced-height reduced-height (RH-RH) cavity configuration.

The position of the load was critical to the output noise power level and flatness because the cavity tended to act as an oscillator in a nonoptimum position of the load. With this and all other configurations, use of a short circuit instead of a load led to unstable operation in which the noise source would generate noise only in a portion of the bandwidth and would oscillate at some frequencies within the band.

The utilized diodes were all half straps with a copper base and diamond pressed in for proper heat sinking. Figure 3a shows a typical packaging process and assembly of mm-wave diodes. The cross section of the final package for a half-strap diode is shown in Figure 3b. As the number of straps on the diode is increased, the overall packaging inductance is reduced, since the inductance of each strap is placed in parallel with the remaining straps. Figure 3c shows the total package inductance versus the number of radial connections.⁸ The half-strap package has the highest inductance at 0.25 nH, whereas a crossed-strap diode package demonstrates the lowest inductance at 0.06 nH. The shunt capacitance of the package is designed such that it is a small fraction of the operating diode capacitance.

Numerous experimental results and similar investigation^{4,8,9} suggest the strong feasibility of the application of avalanche diodes, such as IMPATT diodes, as noise sources in the mm-wave frequencies. Actually, such a solid-state noise source is expected to have several advantages over conventional noise sources, such as temperature-limited thermionic diodes or a gas discharge noise tube. These advantages, summarized in Table 1, make avalanche noise sources, such as IMPATT diodes, good noise sources for all applications with critical restrictions in size, weight, power consumption, reliability, output noise level and bandwidth.

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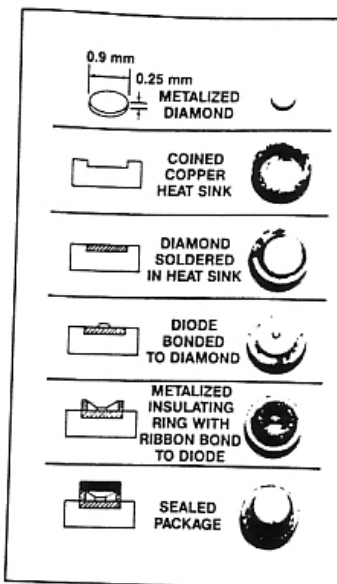


Fig. 3a A typical packaging process and assembly of mm-wave diodes.

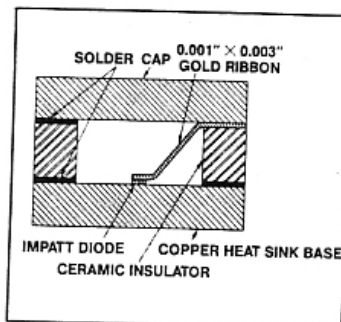


Fig. 3b Cross section of the final package for a half-strap diode.

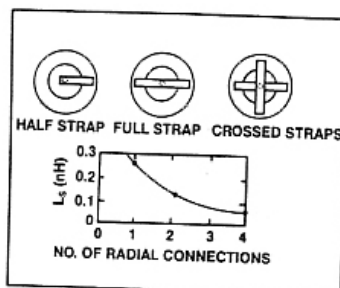


Fig. 3c Variation of total package inductance vs. the number of radial connections.

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TABLE I ADVANTAGES OF SOLID-STATE NOISE SOURCES OVER GAS DISCHARGE TUBES	
Specification	Description
Noise output	ENR value of 30 dB up to and possibly above 110 GHz; can be varied, simplifying a large fraction of noise measurements
Bandwidth	a broadband solid-state noise source with a high value of ENR is quite feasible
Power consumption	input power at 400 mW is sufficient to drive a diode generating noise of 30 dB ENR
Pulsed operation	diodes can be readily pulsed into breakdown with sub-ns rise-and-fall times; no voltage pikes are necessary to trigger the avalanche discharge
Reliability	mean time between failure is expected to exceed the failure time of conventional gas discharge tubes
Temperature Range	expected to operate satisfactorily from -200°C to $+200^{\circ}\text{C}$ with only a small temperature dependence of the noise output*
Size and weight	small size and low weight to be determined by waveguide mount and power supply; can be kept below 45 cm^3

*laboratory test for temperature changes from 0°C to 75°C indicated 0.6 dB change in ENR value

26.5 to 40.0 GHz

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Test Setup and Measurement Procedure

The measuring system, consisting of the noise/gain analyzer, is the heart of the test setup, as shown in Figure 4. In this configuration, a calibrated noise tube is used as a standard noise source to calibrate the system before the actual noise measurement of the IMPATT source can begin. With the help of a local oscillator, the mixer downconverts the noise power to a fixed IF of 100 MHz, which once amplified is fed into the noise/gain analyzer. Next, the IMPATT noise source is routed to the analyzer, replacing the noise tube assembly, where its excess noise ratio (ENR) value is compared to the calibrated source and is displayed on the oscilloscope. Figure 5 shows the internal parts of the RF assembly and the noise source used in this investigation.

The noise analyzer is capable of compensating for the second-stage noise contributions and automatically eliminating them from the actual measured value of the noise figure or noise power. The noise power is expressed in terms of ENR in dB, which can be displayed across the whole band of frequencies of interest.

Experimental Results

Selection of an appropriate diode for flat noise generation is important. Also, the breakdown voltage of the diode, the current (I) and the diode's cross-sectional area (A), play an important role in determining the noise power spectrum of the IMPATT diode.⁴ The two significant factors that must be considered in the design of these IMPATT sources are the noise power level and the noise power spectrum flatness over the whole frequency band.

The noise power of the diode, in terms of ENR in dB, is directly proportional to the DC current. Thus, to obtain a higher ENR value, the DC current may be increased. However, while this might be a sound idea, there are other considerations such as power dissipation and temperature increases that limit this operation. Therefore, it is best to operate the IMPATT source at a relatively low DC current, around 40 mA or below,

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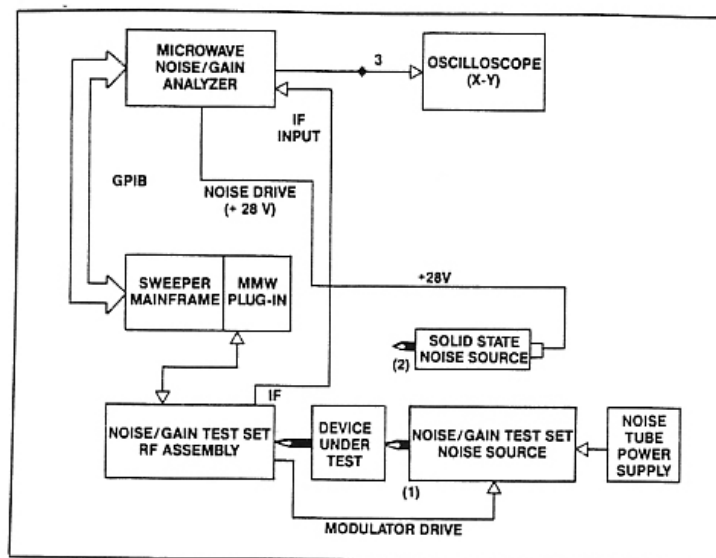


Fig. 4 A schematic diagram of the V-band noise/gain test set.

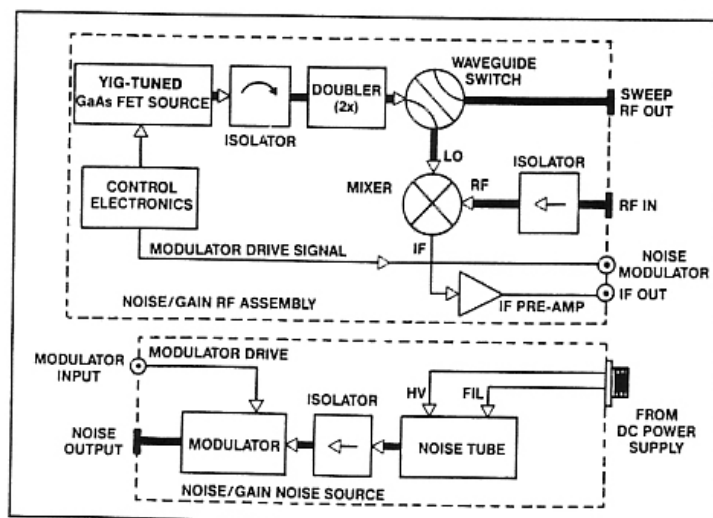


Fig. 5 The internal parts of the RF assembly and noise source.

and select a relatively high frequency diode that will not be excited into oscillation.

The second factor is the flatness of the noise power spectrum, which is inversely proportional to the breakdown voltage (V_b) and cross-sectional area (A) of the diode. Since there is an inverse relationship between the operating frequency of the diode and the breakdown voltage, and the diode capacitance is proportional to the cross-sectional

area of the diode, one would theoretically choose a high frequency diode, $f_a > 100$ GHz, with the lowest possible capacitance, 0.7 to 0.9 pF, to satisfy both requirements.

Among the many diodes tested, only a few proved to be of reasonable value when the power spectrum flatness and the value of the output noise power expressed in terms of ENR were considered.

In the three proposed cavities, the RH-RH configuration proved to be

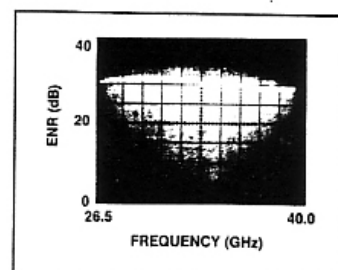


Fig. 6 A photograph of ENR plot in the Ka-band in a RH-RH waveguide cavity mount, where $I_{dc} = 40$ mA.

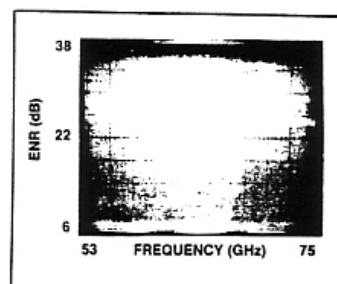


Fig. 7 A photograph of ENR plot over the V-band in a RH-RH cavity mount, where $I_{dc} = 40$ mA.

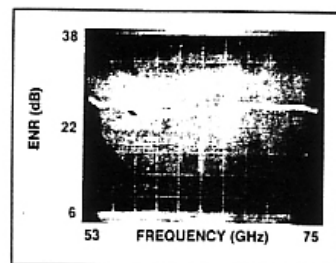


Fig. 8 A photograph of ENR plot over the V-band in a RH-RH cavity mount, where $I_{dc} = 40$ mA.

of great value in generating flat noise spectrum at a relatively high power level. The experimental results can be briefly summarized, as shown in Figures 6, 7 and 8. Figure 6 shows the noise power spectrum plot of the SPD63 IMPATT diode with an ENR of 30 dB and ± 1 dB of flatness in the frequency range of 26.5 to 40 GHz.

All other diodes tested had negative sloping characteristics toward

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the higher edge of the frequency bandwidth. The RH-RH configuration was found to be relatively stable and no oscillation was observed for any position of the load.

For the frequency range from 50 to 75 GHz, two types of diodes were used. Figure 7 shows the noise power spectrum plot of the SPD49 IMPATT diode with an ENR of 26 dB and ± 1 dB of flatness. Using the SPW41 IMPATT diode also produced a very good ENR of 26 dB with good flatness at ± 1 dB, as shown in Figure 8.

A 48-hour stability test was run on an RH-RH configuration with the noise source operating continuously. The effect of thermal drift and overall noise generation stability was studied and the total amount of ENR variation over this period of time was observed to be 0.1 dB or less. This high degree of stability shows a promising future for these devices to operate as stable solid-state noise sources.

Conclusion

This paper presents the noise characteristics of noise sources using IMPATT diodes. Three waveguide mounts have been constructed and tested. Among these three possible waveguide mounts, the RH-RH configuration appears to provide the optimum noise characteristics both in flatness and noise power output.

Experimental investigations on silicon, half strap, single drift IMPATT diodes mounted in a reduced-height waveguide cavity have shown good results in time and temperature stability and have produced very good excess noise ratio, that is, an ENR of 25 to 30 ± 1 dB. The capability to generate such a high ENR is advantageous in device matching, for example, since the output port of this noise source can be followed up with a fixed attenuator of 10 dB or more to achieve an SWR < 1.2 under the ON/OFF conditions of the diode.

Such a solid-state noise source has shown to be superior to the state-of-the-art noise sources, such as a gas discharge noise tube. These advantages can be briefly summarized as higher noise output,

higher reliability, lower power consumption, subns pulsed operation without the use of a modulator, smaller size and lower weight.

As a result of these investigations, noise tubes can be replaced by IMPATT loaded RH-RH waveguides cavity mounts with good stability of operation in time and temperature.^{10,11} By employing noise measurement techniques in the mm-wave range, new experimental results on noise generation have been obtained. These experimental results verify the previously set forth predictions⁴ and demonstrate the fact that mm-wave solid-state noise sources are a reality. ■

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Matthew M. Radmanesh

received his BSEE degree from Pahlavi University in 1978 and his MSEE and his PhD degrees in microwave electronics from the University of Michigan in 1980 and 1984, respectively. From 1979 to 1984, he was a research assistant in the Electron Physics Laboratory at the University of Michigan, where he worked on IMPATTs, PIN diodes and MESFET amplifier design. In 1984, he joined GMI Engineering & Management Institute, where he served as a faculty member until 1987. From 1987 to 1990, he served as senior scientist at Hughes Aircraft Co. and McDonnell Douglas Corp. In 1988, he was awarded the Hughes MPD divisional award for outstanding achievement in mm-wave circuits. He also received a similar award for his work on HERF from McDonnell Douglas Corporation in 1990. Currently, he is a faculty member at the Department of Electrical and Computer Engineering, California State University. His research interests include microwave active circuits, mm-wave devices, circuits and measurement techniques. Radmanesh is a member of Eta Kappa Nu, IEEE and the American Society for Engineering Education.



Joseph M. Cadwallader

received his BSEE from California State University, in 1969. He is a senior staff engineer in the Millimeter-Wave Product Line of Hughes Aircraft Co., Microwave Products Division. He is responsible for the design and development of mm-wave subsystems, instrumentation and special projects spanning the frequency range from 18 to over 200 GHz. He manages the development and manufacture of mm-wave noise sources and noise figure test sets.



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