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Noise in Avalanche Transit-Time Devices

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Abstract—The work performed on noise in avalanche transit-time devices is reviewed and presented in detail. Both theoretical and experimental results on the noise mechanisms and performance of these devices when employed as oscillators, amplifiers, and self-oscillating mixers are included. Suggestions for further studies in this area are also given.

I. Introduction

A. Object of the Review

The inception of every new electron device triggers a detailed study of the various noise mechanisms in it and ways to reduce the noise. The literature on avalanche transit-time devices, which is now six years old, is no exception and it is worthwhile to make a comprehensive review of the status of understanding of noise in these devices. It is hoped that this review does not only have the advantage of consolidating this knowledge and arranging it systematically so as to put the entire field in perspective, but it also reveals unresolved problems and suggests new areas of investigation.

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The importance of noise studies in avalanche transit-time diodes cannot be overstated for two reasons. First, it is generally believed that the noisiness of avalanche diodes may limit their applications and represents their major weakness in comparison with other microwave devices. On the other hand, the large noise generation makes the avalanche diode an attractive noise source for microwave frequencies.

Historically, noise studies in avalanche transit-time diodes began almost as soon as the device became operational. The earliest reported results of measurements of noise in avalanche-diode amplifiers and oscillators were those of DeLoach and Johnston [1] who reported 1) very large amplifier noise figures (50 to 60 dB), 2) reduction of noise figure with an increase in bias current, and 3) very large spectral linewidth (over 100 kHz for

3-dB width). The first theories of noise in avalanche-diode oscillators and amplifiers were both due to Hines [2], [3]. Substantial improvements have been made since, both in device noise performance and in sophistication of theories of noise in these devices.

B. Sources of Noise in Avalanche Diodes

The noise in an avalanche transit-time diode is primarily made up of three parts which are, in the order of their significance: avalanche noise, frequency-converted noise, and thermal noise. Avalanche noise, which is a type of shot noise, is the noise in carrier current generated by the inherently noisy avalanche multiplication process. Avalanche multiplication acts much like a noisy amplifier, not only multiplying the original signal noise by a factor M (called the multiplication factor), but also by adding an appreciable amount of noise to it. This noise addition is best described in terms of the statistical fluctuations of M. To understand the origin of fluctuations in M, the avalanche mechanism must be considered in detail. Following the discussion of Hines [3], consider an avalanche region with a self-sustaining constant current so that each carrier pair produces, on the average, exactly one carrier pair by impact ionization. Let N be the total number of carrier pairs present in the avalanche region on the average. If the history of one carrier pair in time is followed, it is found that its "offsprings" are generated and swept out of the avalanche region at time intervals of τ_x on the average, where τ_x is the mean time interval between successive ionizations due to a single carrier pair. The chain ionization leads to a pulse-train-like current at the output. The total current through the avalanche region is then given by

$$I = Nq_e/\tau_x \tag{1}$$

where q_e equals the electronic charge. This current would appear to be a constant if N is large, and τ_x is very small compared to the period of the frequencies of interest. Now the sources of fluctuations in I are looked for.

First of all fluctuations in M should be expected because each carrier pair has a "probability" of ionization; i.e., the ionization process is not deterministic. In terms of the previously mentioned model, this means that not all chains of ionization are interminable and uniform; some of them terminate (when a carrier pair produces no ionizations before being swept out of the avalanche region) and some branch (when a carrier pair produces more than one ionization), even though on the average there is only one impact ionization per carrier pair. This random beginning and ending of pulse trains causes fluctuations in the output current. Again, since τ_x is only the *average* time interval between ionizations in a single chain, the random fluctuation of this interval would give rise to another source of noise in I.

The second source of noise is frequency-converted noise, which is primarily the low-frequency noise upconverted to the neighborhood of the carrier frequency by beating with the carrier. The sources of this low-frequency noise and its nature will be discussed later in Section III-B. Finally, there is thermal noise generated in the diode, which is very much smaller than the avalanche noise, and has therefore been neglected in all noise analyses to date.

It can be seen that generation recombination noise, diffusion noise, and flicker noise are all missing from the preceding list. In practice they would all be present; however, these have not normally been accounted for in avalanche diodes, because their contribution is expected to be unimportant either from theoretical considerations or from experimental evidence. Generation recombination noise is expected to be small because the transit time of the carriers through the space-charge region is of the order of 10^{-10} s, while the carrier lifetime of excess carriers is of the order of 10^{-6} s even in direct gap semiconductors.

TABLE I

APPLICATIONS OF AVALANCHE TRANSIT-TIME DIODES AND CORRESPONDING CHARACTERIZATIONS OF NOISE PERFORMANCE UTILIZED IN THIS PAPER

Type of Network	Application of Avalanche Diode	One Common Characterization of Noise Performance
Passive one-port	noise generator	spectrum of current fluctuations
Active one-port	oscillator	AM and FM noise spectra
Linear two-port	small-signal amplifier	noise figure
	self-oscillating mixer	noise figure
Nonlinear two-port	large-signal amplifier	AM and FM noise of output

Flicker noise, on the other hand, has mostly been neglected until now on experimental grounds. Early work by Josenhans [4] on X-band avalanche diodes showed no $1/f$ effect in noise close to the carrier, leading him to the observation that "no flicker noise was present in Read oscillators." Ondria and Collinet [5] have also reported the absence of $1/f$ behavior in FM noise spectra close to the carrier frequency, indicating that no flicker noise is present in avalanche diodes at low frequencies. More recently, Ashley and Palka [6] have observed a 3-dB/octave slope in noise spectra close to the carrier in some Ku-band avalanche-diode oscillators with a knee below 5 kHz, although the data are not consistent enough to be conclusive.

Obviously, when the avalanche transit-time diode is used as an amplifier or an oscillator the circuit in which it is embedded also contributes to the total noise. Circuit losses, impedance mismatch in the circuit, and noise in the nonreciprocal element (e.g., circulator) are all known to cause additional noise. However, avalanche diodes are very noisy devices, and it is generally believed that the noise contributions from all sources other than the diode can safely be neglected in estimating the noise behavior.

C. Plan of the Paper

The fact that avalanche transit-time diodes have more than one circuit application makes the work of studying noise more difficult. Table I shows the various applications of an avalanche diode and a corresponding commonly employed measure of noise used to describe noise quantitatively. Of course many other measures of noise are also used; e.g., the noise of a passive one-port may also be measured in terms of an equivalent saturated diode current, noise temperature, an equivalent noise resistor, available noise power, noise ratio, or other parameters. The difficulty arises when the noise behavior of the device in one application has to be correlated with its noise behavior in another application. The noise behavior of avalanche diodes in the various applications will be surveyed.

The plan of this paper is as follows. Noise mechanisms in an avalanche diode are discussed in the next section. Early works on random pulse-type noise due to microplasmas in avalanche breakdown are briefly touched upon. Thereafter, two theories of noise, one due to Tager [7] and McIntyre [8], and the other due to Hines [3] and Gummel and Blue [9] are summarized. Experimental work verifying various aspects of these theories is then summarized. In the third section, noise in avalanche-diode oscillators is considered. Theoretical analyses of both a small- and large-signal nature are reviewed. Experimental results under CW and pulsed conditions on unsynchronized as well as phase-locked oscillators, locked with the fundamental or with the subharmonic frequency, are discussed, as are the effects of the circuit on oscillator noise. Section IV is concerned with the theory of noise in small-signal avalanche-diode amplifiers and its comparison with experimental results is reported. Noise in avalanche-diode mixers is briefly discussed in Section V. Finally, in Section VI, some suggestions are made concerning possible areas of investigation.

II. Noise in Avalanche Diodes

A. Noise in Microplasmas

Pearson and Sawyer [10] reported a current instability related to the onset of avalanche breakdown in a reverse-biased p-n junction. McKay [11] showed that the breakdown current consisted of a train of rectangular pulses of equal amplitude but randomly varying pulse length and repetition rate, and explained this phenomenon by predicting the existence of regions of localized ionization in a reverse-biased silicon p-n junction. Such nonuniform carrier multiplication over the junction area was detected by Chynoweth and McKay [12], and was called a microplasma by Rose [13]. Champlin [14] made detailed experimental studies of this breakdown and deduced that the noise is caused by current fluctuations among stable levels. A simple account of a theory based on a random on-off switch model is given by van der Ziel [15]. Haitz [16] later improved the model and characterized the microplasma by four quantities: 1) an extrapolated breakdown voltage; 2) a series resistance; 3) a turnon probability; and 4) a turnoff probability. A summary of this and some later work is given by Monch [17]. This phenomenon will not be discussed in great detail as the reviews of van der Ziel and Monch cited previously provide an excellent survey of this field, and also because advances in the technology of preparation of p-n junctions have made it possible to make microplasma-free or "uniform" junctions. Good microwave avalanche diodes are usually fabricated with such uniform junctions.

Prior to the use of avalanche diodes as negative resistance devices at microwave frequencies, they were being used, based on the previously stated current fluctuation mechanism, as RF noise sources (up to several hundred MHz), and were commercially available (Penfield [18]) to replace gas discharge tube noise sources. Haitz [19], [20] has discussed at length the design of uniform avalanche diodes (using guard rings) as noise sources and has described their spectrum, amplitude distribution, and temperature dependence.

B. Theory of Avalanche Noise

Tager [7] presented the first theory of current fluctuations in semiconductors under impact ionization and avalanche breakdown conditions. He made the following assumptions in his investigation of the statistical characteristics of the avalanche process.

1) Avalanche breakdown occurs in a plane layer of the semiconductor.

2) A large uniform electric field is applied across this layer.

3) Carriers of both species move with the same saturated velocity, which is independent of the number of ionizations produced by a given carrier.

4) The width of the avalanching layer of the semiconductor is small enough ($<10^{-2}$ cm in silicon) so that the carrier transit time τ_a through it is much shorter than the carrier lifetime, and therefore thermal generation and recombination in the layer are negligible. At the same time the layer width is much larger ($>10^{-5}$ cm in silicon) than the mean free paths so that only the average motion ("drift") of carriers need be considered.

5) The ionization rates (number of electron-hole pairs produced by impact ionization per unit length per carrier) are the same for electrons and holes. If α_e and α_h, the ionization rates for electrons and holes, respectively, are unequal an equivalent ionization rate may be defined as

$$\bar{\alpha} = \frac{\alpha_h - \alpha_e}{\ln \alpha_h - \ln \alpha_e}. \tag{2}$$

This ionization rate is assumed to be uninfluenced by temperature and is an instantaneous function of the electric field.

6) Fluctuations of the flicker-effect-type and thermal fluctuations are neglected.

7) The primary carrier current I_0 entering the avalanching layer contains full shot noise (the mean square noise current equals $2q_eI_0B$, where q_e is the charge of an electron, I_0 the primary current, and B the bandwidth).

8) The primary current is not rapidly time varying; i.e.,

$$\frac{dI_0}{dt} < \frac{I_0}{\tau_a}. \tag{3}$$

With these assumptions, taking into account 1) the fluctuations in the entering primary current, 2) the fluctuations in the multiplication factor M of the avalanche layer, and 3) the depression of current fluctuations due to the space-charge of the moving carriers, Tager obtained the following results.

1) The mean square fluctuations in the multiplication factor M depend upon the ratio of ionization rates of the two types of carriers. When this ratio is unity (equal ionization rates)

$$\overline{\Delta M^2} = (\overline{M})^2(\overline{M} - 1) \tag{4}$$

while for an infinite ratio (only one species of carrier ionizing)

$$\overline{\Delta M^2} = \overline{M}(\overline{M} - 1). \tag{5}$$

2) The mean square value of M is equal to the cube of the average value of M; $\overline{M^2} = (\overline{M})^3$.

3) The spectrum of carrier current leaving the avalanche layer is

$$S_i(\omega) = \frac{2q_eI_0(\overline{M})^3}{1 + \left(\frac{\omega \overline{M} \tau_a}{2}\right)^2} \tag{6}$$

i.e., at low frequency it is just the shot noise multiplied by $(\overline{M})^3$, while at high frequencies it is inversely proportional to the square of the frequency.

Further developments of this theory were primarily due to an interest in the noise properties of avalanche photodiodes. McIntyre [8] derived a general expression for the spectral density of noise generated in uniformly multiplying p-n junctions for any distribution of injected carriers which is valid at frequencies that are low compared to the inverse of the transit time through the avalanche layer. He used the same set of assumptions as Tager, except that unequal ionization rates for holes and electrons and any field profile are permitted. The expression for the spectral density at low frequencies ($f \ll 1/\tau_a$) is given by

$$S_i(\omega)=2q_e\left\{2\left[I_p(0)M^2(0)+I_n(w)M^2(w)+\int_0^w gM^2(x)dx\right]+I_0\left[2\int_0^w \alpha_e M^2(x)dx-M^2(w)\right]\right\} \quad (7)$$

where w is the width of the avalanche layer, $I_p(0)$ is the primary hole current entering at one end ($x=0$) of the avalanche layer, $I_n(w)$ is the primary electron current entering the other end ($x=w$) of the layer, M is the multiplication factor of the avalanche layer which is a function of x because the electric field is a function of x, and g is the rate of thermal or optical generation of carriers in pairs per unit length. While α_e occurs explicitly in the expression, both α_e and α_h are present through M. Also note that the expression is independent of frequency (which is a direct consequence of omitting all time dependence), resulting in a white noise spectrum at low frequencies.

Under the additional assumption that the electric field is uniform over the entire avalanche region, the previous expression reduces to

$$S_i(\omega) = 2q_eI_0M^3\left[1 + A\left(\frac{M-1}{M}\right)^2\right] \quad (8)$$

where

$$A = \frac{\alpha_e - \alpha_h}{\alpha_h}$$

or

$$A = \frac{\alpha_h - \alpha_e}{\alpha_e}$$

when, respectively, holes or electrons alone are injected into the avalanching layer. For the special case of $\alpha_e=\alpha_h$, this reduces to $S_i(\omega)=2q_eI_0M^3$, which is identical with Tager's result at low frequencies.

On the basis of these results McIntyre concluded that for a given M, noise could be reduced if the ionization were caused primarily by the more ionizing species of carriers. McIntyre also estimated the effect of time-dependent mechanisms which introduce frequency dependence in the noise spectrum at high frequencies. If all multiplications are not instantaneous, but instead there is an average time separation τ_x between ionizations caused by a single pair of carriers the high-frequency end of the spectrum will be attenuated by a factor $(1+\omega^2M^2\tau_x^2)^{-1}$. Also, if C is the diode capacitance and R_p the parallel resistance as seen by the diode, the circuit time constants will introduce an additional frequency-dependent attenuation term $(1+\omega^2R_p^2C^2)^{-1}$.

In an avalanche transit-time diode there is a third source of frequency dependence due to the finite transit time in the drift region which causes a phase shift between the high-frequency voltage and current. This problem was considered by Hines [3] in a small-signal fashion; he assumed the noise to be small compared to the dc bias current on which it is superimposed. The diode discussed by Hines differs from Tager's diode in another very important respect; namely, that the diode current is entirely self-sustaining, requiring no injected carriers. Therefore, the results of the two analyses cannot be compared directly. The method of analysis of Hines is based upon the space-charge wave approach of a small-signal analysis given by Gilden and Hines [21] and involves the following assumptions.

1) The diode is separated into an avalanche region and a drift region.

2) All noise is assumed to originate in the avalanche region.

3) All the assumptions of Gilden and Hines' small-signal theory are carried over; namely, the assumptions of saturated drift velocities which are the same for electrons and holes; a thin avalanche region at one side of a high-field region; equal ionization rates for electrons and holes; constant electric field in the avalanche region; the current, electric field, and ionization rate being expressed as a constant dc value plus a small sinusoidal ac variation; negligible thermally generated reverse saturation current; the drift region current entirely due to one species, the majority carriers; no fixed space charge in the drift region; punch-through operation at all times; negligible series resistance and negligible displacement current so that the total carrier current is independent of distance along the diode length.

4) The ionization rate α varies as a power of the electric field E^m.

5) The noise due to statistical variation of the interval τ_x between ionizations in any given chain of ionizations is negligible.

6) Carrier inertial effects are negligible so that the probability of ionization by a given carrier during its transit is constant and consequently the Poisson distribution can be used.

Under these assumptions, Hines found that the mean square value of total noise current is

$$\overline{I_n^2(\omega)} = \frac{2q_eI_0B}{\omega^2\tau_x^2}\left|\frac{R_d}{Z_t^2}\cdot\frac{1}{1-\dfrac{\omega_a^2}{\omega^2}}\cdot\frac{V_a}{2mI_0}\right| \quad (9)$$

where

$$R_d = \frac{l_d}{\theta\omega\epsilon A}\left[\frac{1-\cos\theta}{1-\dfrac{\omega^2}{\omega_a^2}}\right]$$

I_0 is the dc bias current, l_d is the width of the drift region, θ is the transit angle through the drift region at frequency ω, ϵ is the permittivity of the semiconductor material, A is the area of the cross section of the diode, ω_a is the avalanche frequency of the diode, Z_t is the total impedance around the RF loop containing the diode including the load impedance, and V_a is the dc voltage across the avalanche region. Under the special case of low frequencies ($\omega\ll\omega_a$), the above simplifies to[1]

$$\overline{I_n^2(\omega)} = \frac{q_eBC_d^2V_a^2}{2I_0m^2\tau_x^2} \quad (10)$$

where C_d is the depletion capacitance of the entire depletion zone of the diode, showing that the mean square noise current varies inversely with the dc current I_0. This is due to a decrease in avalanche impedance with the increase of current. At high frequency (9) simplifies to

$$\overline{I_n^2(\omega)} = \frac{q_eB}{\left(1+\dfrac{R_L}{R_d}\right)^2}\cdot\frac{C_d^2V_a^2\theta^2}{m^2\tau_x^2(1-\cos\theta)I_0}. \quad (11)$$

For reasons stated earlier, no comparison with Tager's results is made.

Constant and Semichon [22] have described an analysis similar to Hines', and have found expressions for mean square noise voltage and spectral linewidth.

[1] Equation (34) of Hines [3] has an extra factor of 2.

Gummel and Blue [9] have generalized the analysis of Hines by removing some of the assumptions made, in particular the assumptions of an idealized Read structure, equal saturated velocities for electrons and holes, and equal ionization rates for holes and electrons. The one-dimensional model and small-signal analysis are maintained. In addition it is assumed that the conduction current in the diode has full shot noise; this noise is injected into the avalanche region of the diode, and solution of the carrier transport equations then yields the open-circuit voltage fluctuations caused by the shot noise. A rigorous justification for such an approach has been given by Blue [23] for a stationary quasi-linear system. The mean squared voltage $\langle v^2 \rangle$ is calculated analytically for an idealized Read-type diode structure and numerically for a realistic p-n junction diode with a wide avalanche region. The expression for $\langle v^2 \rangle$ shows the following behavior of the mean square noise voltage.

1) For a fixed bias current this voltage is constant at low frequencies, then it increases and attains a maximum at a resonance frequency, and falls approximately at the fourth power of frequency above resonance.

2) At low frequencies (below resonance) $\langle v^2 \rangle$ is inversely proportional to the bias current, the resonance frequency is proportional to the square root of the bias current density, and in the $1/\omega^4$ domain it is approximately directly proportional to the bias current.

These conclusions agree with the experimental observations of Haitz and Voltmer [24], [25] described in the next section.

C. Experimental Results

Tager's result that the mean square value of fluctuations equals M^3 has been experimentally verified by Naqvi *et al.* [26]. They have measured multiplication noise as a function of the multiplication factor and have plotted the spatial variation of both over the cross section of the diode. Their experimental setup consisted of a sharply focused chopped laser beam, scanning the reverse-biased diode junction, and a phase-sensitive lock-in amplifier to measure the avalanche multiplied photocurrent. They found that: 1) multiplication noise at a multiplication of 88 was as high as 37 dB above the full shot noise in the junction current; and 2) agreement with McIntyre's theory suggests that there is no space-charge correlation effect up to a current density of 100 A/cm^2, which was the maximum used in their experiments.

Baertsch [27], [28] made measurements of noise in a silicon avalanche photodiode current as a function of the multiplication factor and found good agreement with McIntyre's theory.

Constant *et al.* [29] have reported experimental studies of radio frequency and microwave noise in avalanching p-n junctions. Their results on the observed variation of the mean square noise current with bias current and frequency are shown in Fig. 1, and show agreement with Hines' theory.

Haitz and Voltmer [24], [25] and Haitz [30] have reported experimental measurements of the spectral density of a silicon avalanche-diode noise voltage, both at audio frequencies (1 kHz to 11 kHz) and at microwave frequencies (3 GHz to 9 GHz), and have verified Hines' theory of noise in Read diodes as modified for p-n junctions. The main results of this experimental study follow.

1) At low frequencies the spectral density varies inversely as the square root of the dc bias current as expected. There is an excess noise at high frequencies due to thermal effects, and an excess noise at low frequencies due to local variations of the breakdown voltage (as evidenced by the fact that the excess noise increases with area and is not reproducible from diode to diode).

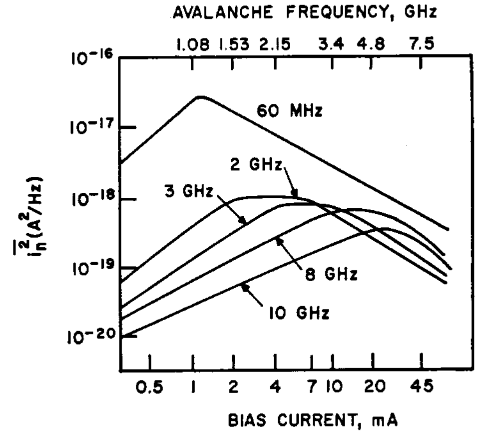

Fig. 1. Mean square noise current of an avalanche diode as a function of bias current and frequency. The avalanche frequency calculated from bias current is also marked on the axis. (Constant *et al.* [29].)

2) The spectral density of the noise voltage is proportional to the breakdown voltage for several different doping profiles of the diode: n$^+$-p, p$^+$-n, and n-p-π-p$^+$.

3) At high frequencies the spectral density varies linearly with bias current for small bias currents (where the avalanche frequency f_a is small), attains a peak, and decreases thereafter as the bias current (and hence f_a) increases.

4) For low bias currents (and hence small f_a), the spectral density of noise shows $1/f^4$ variation with frequency, while at larger bias currents the frequency dependence is much smaller, as expected theoretically.

D. Avalanche-Diode Microwave Noise Generators

Several workers have explored the possibility of using avalanche diodes as microwave noise sources. Such noise sources would have the following advantages over gas-discharge-type noise sources.

1) Much larger noise output, eliminating the need of amplification in many applications.

2) Small size, small weight, low power requirements, and low cost, making it possible to use them for inservice measurement of critical parameters in microwave equipment (Chasek [31]).

3) Possibility of pulse modulation with very narrow pulses (of the order of 1 μs).

The use of flat-topped random pulses of microplasma breakdown in p-n junctions as a source of noise has been mentioned. Minden [32] has carried out some experimental work demonstrating that noise in avalanche diodes is of two distinct types: that associated with microplasma breakdown, and that associated with uniform junction breakdown. He pointed out the following difference between the two. Microplasma breakdown occurs at very low breakdown current (1 to 300 μA), and the noise level as a function of bias current shows several peaks. The uniform junction breakdown noise becomes appreciable at larger reverse bias current and attains a maximum at a value of bias current which is lower than the threshold for coherent microwave oscillations. Minden also found that high-output avalanche-diode oscillators show no microplasma noise, while diodes which generated larger uniform junction noise also generated large microwave output when operated as oscillators.

Val'd Perlov *et al.* [33] described a microwave noise source, verifying some of the predictions of Tager [7]. In particular they found the following.

1) For diodes with breakdown voltages of 10 to 15 V, and at

bias currents of 0.5 to 10 mA, the noise temperature of the source was 10^5 to 10^6°K in the centimeter band, and 10^6 to 10^7°K in the meter band.

2) The long-term stability of noise level was very good, with a temperature coefficient of spectral density of noise power being 0.02 dB/°K.

3) The noise source could be modulated by microsecond pulses.

Tager's result (6) shows that at high frequencies the noise level depends only upon frequency and bias current, and not upon the multiplication factor M. Hence the output is independent of reverse saturation current of the diode. At low frequencies, however, it does depend upon M, and consequently upon reverse saturation current and temperature.

Dalman and Eastman [34] reported the following results of noise measurements on diffused p^+-n-n^+ Si avalanche diodes.

1) The avalanche diode itself is an inherently broad-band noise source and the circuit largely determined the bandwidth of the noise source.

2) Noise temperatures from 15 to 25 dB greater than an argon gas discharge tube (30 to 35 dB over 290°K) are available, depending upon the bandwidth of the diode circuit.

Chadelas *et al.* [35] subsequently suggested an automatic radiometer utilizing an avalanche-diode noise generator, and made two observations.

1) The noise temperature of the source (10^5 to 10^6°K) varies linearly with the diode bias current (1 to 10 mA).

2) The noise source would be usable to Q band (35 GHz).

Haitz and Opp [36] have designed an avalanche-diode noise source integrated in a microstrip-line circuit, and reported the following results with the diodes biased at 30 mA (20- to 35-V breakdown voltage).

1) The noise source had a potential range from dc to 18 GHz.

2) The spectral noise power density was in excess of 30 dB above kT_0 from 1 to 11 GHz, with variations within ± 0.7 dB over this frequency range. The variations are further reduced by tuning out reflections from connectors and adaptors.

3) The source has a very good long-term stability (± 0.1 dB over a 500-h period).

4) The temperature dependence of the spectral power density (measured at 2.5 GHz) was less than -0.002 dB/°C.

5) The bias voltage dependence of the spectral density was better than -0.005 dB/V.

6) Output variations from diode to diode were small.

Bareysha *et al.* [37] discussed in detail the design of a microwave noise generator using diffused Ge avalanche diodes. They have used a circuit model of the noise generator to study the effect of mismatch between the diode and the load upon noise power output, and the bandwidth of the generator. In addition results of experimental measurements of the dependence of noise spectra on bias current, junction capacitance, breakdown voltage, and temperature are also given. Their main findings follow.

1) Noise-power spectral density at a given frequency attains a broad maximum as a function of diode bias current; the higher the frequency, the larger the bias current required for maximum noise power and the lower the magnitude of this maximum. (See Fig. 1 due to Constant *et al.*)

2) The noise-power spectral density remains practically unchanged as the junction capacitance varies.

3) Noise power is slightly dependent on breakdown voltage for large breakdown voltages where Zener current is negligible.

4) The operation of the noise generator is very unstable if the dynamic resistance of the junction is negative, and its output is strongly dependent upon the load, particularly near the oscillation threshold. Therefore, for high-frequency noise generation the breakdown voltage should be kept low so that the threshold oscillation frequency is high.

5) A change in temperature affects the junction impedance and hence the noise power output. Thermal compensation can be achieved by using a thermistor to control the diode bias current.

III. Noise in Avalanche Transit-Time Diode Oscillators

A. Theory of Oscillator Noise

Hines [2] presented the first noise theory for avalanche transit-time diode oscillators. His analysis, which can only be considered as a first-order approximation, is based upon results found in his small-signal analysis presented in Section II-B. Two sets of assumptions are carried over in this work.

1) The assumptions made by Edson [38] in his analysis of the perturbation of an oscillator by thermal noise.

2) The assumptions made by Hines in his analysis of the noise in the avalanche diode (given in Section II-B).

Thereafter, it is assumed that (9) accurately described noise current in an oscillator and that thermal noise in Edson's theory can be directly replaced by this shot noise. Using these assumptions, Hines found expressions for the AM and FM noise.

Obviously, the assumptions made are quite restrictive. Edson analyzed an oscillator consisting of a simple resonant circuit and a nonlinear conductance only. Therefore, only the device conductance is assumed to be voltage dependent and not the susceptance, and the nonlinearity of the active device conductance is described by using a constant s factor, defined as

$$s = \frac{\Delta G}{G} \tag{12}$$

where ΔG is the small-signal conductance, and G is the total conductance of the device.

Within the limitations of the model, Hines found an AM noise spectrum that is white for low-Q circuits, given by

$$N_{AM}(\omega) = \frac{b^2 q_e I_0 R_L}{s^2 + 4Q_L\left(\dfrac{\omega - \omega_0}{\omega_0}\right)^2} \quad \text{W/Hz}$$

and a constant rms frequency deviation

$$\Delta f_{\text{rms}} = \frac{f_0}{Q_L}\sqrt{\frac{b^2 q_e I_0 B R_L}{2P}} \quad \text{Hz}$$

where

$$b^2 = \frac{\tau_d^2 V_a^2 \omega_0^2 C_d^2 (1 - \cos\theta)}{2m^2 \tau_x^2 I_0^2 \theta^2 \left(1 - \dfrac{\omega^2}{\omega_a^2}\right)^2}$$

τ_d is the transit time in the drift region, and the other symbols have the same meaning as in (9).

Inkson [39] published the first large-signal theory of noise generation in avalanche transit-time diode oscillators. He considered Read's model of an avalanche diode; i.e., he assumed a thin avalanche region, equal drift velocities and ionization rates for electrons and holes, and a power law dependence of ionization rate α on electric field, and he used the sharp pulse approximation also first suggested by Read [40]. The "sharp pulse assumption" maintains that the carrier current consists of one sharp pulse of charge per cycle traveling in the drift region at a saturated velocity with only one pulse being present at any time, and the space charge of the avalanche current being nonzero only when a pulse is present in the avalanche region. It is further assumed that the electrons and holes are always in equilibrium with the field, and hence a Poisson distribution is used for the number of ionizations. Inkson then calculated the jitter in pulse amplitude and interpulse interval due to the random process of ionization, and calculated the AM and FM noise spectra therefrom. The analytical expressions obtained are quite complicated and are not reproduced here; however, the following conclusions can be drawn from Inkson's results.

1) As the bias current of the diode is increased, the output of the oscillator rapidly becomes very noisy.

2) A larger area avalanche diode would make the oscillator less noisy (the diode model being one-dimensional, nonuniformities are assumed to be absent).

3) A wider avalanche region in the diode (i.e., appreciable ionization over a larger part of the depletion layer) leads to a lower noise output from the oscillator (although the analysis is not applicable to such diodes).

4) FM noise (rms frequency deviation) varies inversely as the square root of the loaded Q of the microwave cavity (rather than inversely with Q as in Edson's model), so that the device should be coupled to a high-Q cavity.

Ulrich [41] has also found expressions for AM and FM noise spectra of an avalanche transit-time diode oscillator, but in terms of the nonlinearity of the diode impedance rather than the diode material, structure, and operating point parameters as in the case of earlier works. Ulrich used an approach similar to Kurokawa's general analysis [42], modeling the oscillator by a series circuit containing the device (with RF amplitude-dependent impedance), the impedance as seen by the device (which is frequency dependent), and an all-inclusive noise source independent of RF amplitude or frequency. He found that the AM and FM noise spectra are

$$|\Delta A(f)|^2 = \frac{|e|^2}{2A_0^2\left|\left(\frac{\partial Z_d}{\partial A}\right)_{A_0,\omega_0}\right|^2 \sin^2\phi} \tag{13}$$

and

$$|\Delta\omega(f)|^2 = \frac{|e|^2}{2A_0^2\left|\left(\frac{\partial Z_L}{\partial \omega}\right)_{A_0,\omega_0}\right|^2 \sin^2\phi} \tag{14}$$

and their correlation coefficient is

$$C = -\cos\phi \tag{15}$$

where $|e|^2$ is the mean square noise voltage of the noise source previously mentioned, including all fluctuations produced by the device; A and ω are the current amplitude and frequency of oscillation with mean values A_0 and ω_0, respectively; $Z_L = R_L + jX_L$ is the impedance of the load (including circuit) as seen by the diode; $Z_d = R_d + jX_d$ is the impedance of the diode, and

$$\phi = \tan^{-1}\left(\frac{\partial X_L}{\partial\omega}\Big/\frac{\partial R_L}{\partial\omega}\right) - \tan^{-1}\left(\frac{\partial X_d}{\partial A}\Big/\frac{\partial R_d}{\partial A}\right). \tag{16}$$

Two conclusions, both of which have been experimentally verified, can be drawn from the previous analysis concerning the circuit dependence of noise behavior.

1) Only the FM noise depends upon circuit Q, as evidenced by the $\partial Z_L/\partial\omega$ term in (14).

2) A minimum of noise occurs when $\phi = 90°$ which can be obtained by a proper circuit arrangement, and does not require a high-Q cavity.

Experimental results verifying these conclusions are described in a later section.

Vlaardingerbroek [43] found expressions for the output power spectrum and the width of the output spectrum of an avalanche transit-time diode oscillator operating at low and intermediate output levels. He followed the assumptions and method of Hines, discussed in Section II-B, in that the "primary" noise current due to fluctuations in the random avalanche process is related to the noise in the Read diode terminal current; however, nonlinearity is included, as opposed to Hines' small-signal approximations. The output power spectrum is then expressed in terms of the spectrum of the primary noise current.

B. Upconversion of Low-Frequency Noise

The nonlinearity of avalanche diodes, which makes them useful as mixers, introduces another source of noise in avalanche transit-time diode oscillators; namely, upconversion of low-frequency noise to frequencies near the carrier. Experimental as well as theoretical results obtained by Evans and Haddad [44] have shown that upconversion of low-frequency signals to frequencies in the neighborhood of the carrier frequency in an avalanche diode is accompanied by a large gain. This upconversion gain therefore makes low-frequency noise an important contributor to total noise.[2] In addition to thermal noise in the RF circuit, this low-frequency noise could arise from at least two different sources, both of them stronger than the circuit thermal noise.

1) Low-frequency noise (both avalanche and thermal noise with the avalanche noise predominating) generated within the diode.

2) Bias current fluctuations (due to supply fluctuations, thermal noise, or $1/f$ noise) generated in the dc bias circuit.

Goedbloed [45] carried out a theoretical analysis of upconverted noise in an avalanche transit-time diode oscillator using the Read model of the diode (with infinitely thin avalanche region and infinitely high multiplication factor) and a passive single resonant network model for the oscillator circuit. He has shown that if both of the previously mentioned assumptions of the Read model are maintained, there is upconversion of low-frequency noise to AM noise of the oscillator, but not to FM noise. However, if one of these assumptions is discarded, FM noise is enhanced due to upconversion of low-frequency noise. This observation should serve as a warning for caution in model selection before studying noise in such nonlinear devices as avalanche diodes.

Scherer [46] has taken the effect of low-frequency noise into account by calculating the components of AM and FM noise due to fluctuations in the bias current. These fluctuations are assumed to be due to avalanche noise alone, and are estimated using a low-frequency noise equivalent circuit of the avalanche diode first given by Haitz [30] and an impedance representing the bias circuit. The low-frequency noise current, which is calculated using this model, modulates the dc bias current, and is transformed into the high-frequency AM and FM noise using ampli-

[2] The reasons why the downconverted high-frequency noise is not considered are twofold. 1) The high-frequency noise can only be generated in the diode and not in the bias circuit, and 2) it suffers a downconversion loss, consequently it is small.

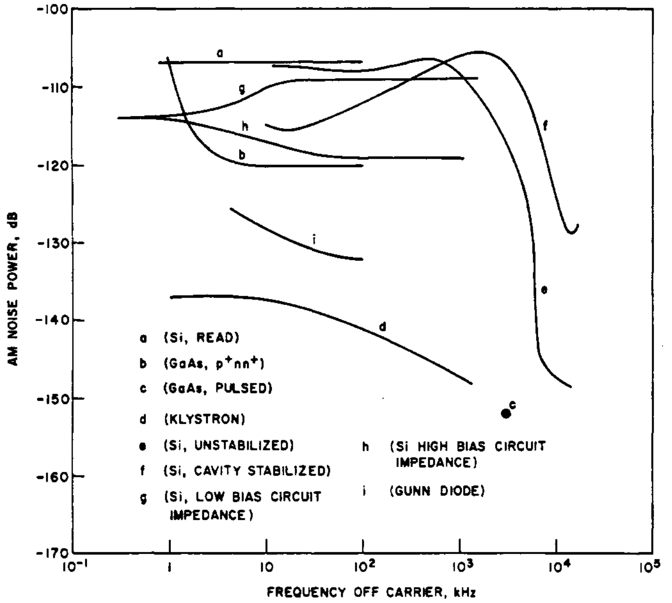

Fig. 2. AM noise spectra of avalanche-diode oscillators. All results have been reduced to double sideband AM noise power to carrier power ratio in a 100-Hz bandwidth. Curves *a* and *b* give noise spectra for a Si Read structure [4] and a GaAs p$^+$-n-n$^+$ structure [57], respectively. Point *c* represents AM noise in a pulsed GaAs diode oscillator [59]. Curves *d* and *i* giving AM noise for an X-13 klystron [5] and a Gunn diode [4] are included for comparison. Curves *e* and *f* show AM noise spectra for a Si diode oscillator with and without stabilization using a transmission cavity [63]. Curves *g* and *h* are AM noise spectra for a Si diode oscillator when the dc biasing circuit impedance was very low and very high, respectively, [46]. Output power, bias current density, and frequency of oscillation are different for the various curves.

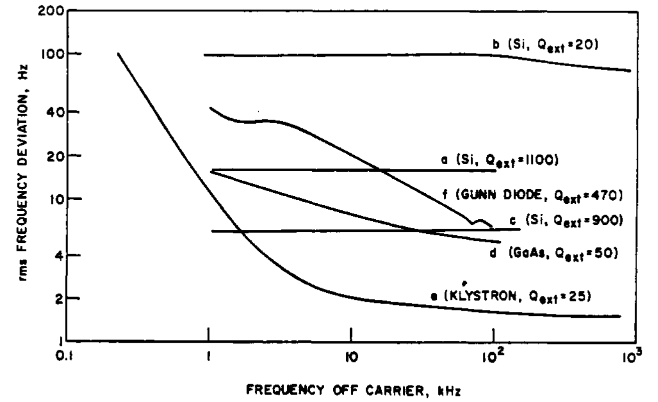

Fig. 3. FM noise of avalanche-diode oscillators. All results have been reduced to double sideband FM noise expressed in rms frequency deviation for a 100-Hz bandwidth. Curve *a* gives the FM noise spectrum for a Si Read diode oscillator with $Q_{ext}=1100$ [4]. Curves *b* and *c* give these spectra for Si p$^+$-n-n$^+$ structures for $Q_{ext}=20$ [67] and $Q_{ext}=900$ [5], respectively. Curve *d* is the FM noise spectrum for a GaAs avalanche-diode oscillator for $Q_{ext}=50$ [57]. Curves *e* and *f* giving FM noise for an X-13 klystron [5] and a Gunn diode [4] are included for comparison.

tude and frequency modulation sensitivities. Using values of avalanche current noise from the computer calculated results of Gummel and Blue and experimentally measured values of modulation sensitivities, he obtained the following.

AM Noise: noise-to-signal ratio $= -108$ dB;
FM Noise: rms frequency deviation $= 10.6$ Hz

in a 100-Hz bandwidth under a typical (given) set of operating conditions for a Si avalanche diode.

C. Measurements of Oscillator Noise

No attempts are made to discuss the techniques of measurement of AM and FM noise in microwave oscillators; a review on this subject appeared elsewhere [47], and some more recent work will simply be referred to [48], [49]. The noise behavior of "typical" avalanche-diode oscillators is shown in Figs. 2 and 3. Measurements of avalanche-diode oscillator noise have been reported by a rather large number of workers, and no attempt is made to catalog all of them. Instead, only those experimental reports that have studied the dependence of noise behavior of avalanche-diode oscillators on various parameters such as diode material, structure, circuit Q, bias current, power saturation, and bias circuit are included.

The first measurements of AM and FM noise in avalanche transit-time diode oscillators were reported by Josenhans [4]. His results on silicon Read-type diodes follow.

1) The FM noise spectra are symmetrical about the carrier to within ± 1 dB (found using a spectrum analyzer).

2) FM noise measurements up to as close as 400 Hz away from the carrier frequency showed no flicker noise effects.

3) The AM noise spectrum is flat and the rms frequency deviation is constant in the frequency range measured (up to 100 kHz away from the carrier frequency).

4) Noise measurements were performed on some avalanche transit-time diodes operated both as amplifiers and oscillators. The noise behavior of the diode used as an oscillator was also estimated using the results of measurements on the diode used as an amplifier. The estimated oscillator noise was considerably lower than the measured oscillator noise, indicating a large-signal behavior of noise sources in oscillator applications.

Cook [50] reported on avalanche-diode oscillators in which AM noise dropped at 2 dB/octave. Goldwasser *et al.* [51] reported on experimental measurements of FM noise of CW avalanche-diode oscillators close to the carrier frequency (2 to 10 kHz away from the carrier) and made two important observations:

1) The FM noise was strongly dependent upon the dc bias current, and for a given diode and circuit, the current could be optimized to reduce the noise sharply.

2) Upon such optimization, the FM noise in Schottky barrier GaAs diode oscillators was much lower (0.7 Hz rms for a 100-Hz bandwidth) than in diffused p-n-n$^+$ Si diodes (80 Hz rms for the same bandwidth). An explanation of the superiority of Schottky barrier diodes was also given by Goldwasser.

Cowley [52] experimentally observed the effect of power saturation on avalanche transit-time diode oscillator noise, and concluded that: 1) the occurrence of power saturation or the increase of bias current beyond the saturation level makes the oscillator very noisy. The value of load resistance R_L should therefore be kept somewhat greater than the value that leads to maximum power to achieve better noise behavior; and 2) when saturation occurs, bias current oscillations can arise in the power supply circuit under certain conditions, and would appear as AM and FM modulations in the output, degrading the oscillator spectrum.

In another communication Cowley *et al.* [53] also reported a large increase in noise due to a very small increase in the dc bias current.

The dependence of FM noise of avalanche transit-time diode oscillators on the external Q of the cavity was studied over a wide range by Harth and Ulrich [54]. They also observed the dependence of rms frequency deviation on dc bias current and the correlation coefficient of the AM and FM noise. Their results can be summarized as follows.

1) The rms frequency deviation varies as $1/Q_{ex}\sqrt{P_{out}}$.

2) The rms frequency deviation is constant in the frequency range 100 Hz to 1 MHz away from the carrier frequency, and the contribution of low-frequency upconverted noise to it is negligible in this frequency range as verified by varying the low-frequency impedance in the diode bias circuit.

3) FM noise increases rapidly with an increase of the dc bias current. In the range of bias current between the onset of oscillation and maximum admissible current, the excess noise temperature over T_0 was between 30 and 50 dB, and varied approximately as the fifth power of current density independently of the circuit Q.

4) The correlation coefficient of FM and AM noise was between 0.8 and 1, indicating a common mechanism for their generation.

Scherer [46] has made detailed observations on the effect of the impedance in the dc bias circuit and the bias current of the diode upon the AM noise of the oscillator and reached the following conclusions.

1) The AM noise spectrum at frequencies close to the carrier (less than 1 kHz away from the carrier) is not affected by the impedance of the bias circuit; for large frequency separation AM noise is increased by lowering the bias circuit impedance. The difference in AM noise between the cases of very small and very large bias circuit impedances (compared to diode impedance) increases as the frequency separation increases to 100 kHz and then becomes constant.

2) Some of the diodes show an excess noise with a $1/f$ dependence.

3) For the high bias-circuit impedance case, the measured noise agrees well with the calculated RF noise, indicating that the upconverted component of AM noise is not significant.

4) Noise performance deteriorates with increasing power output, increasing coupling of the load and increasing bias current.

Ulrich [41] observed the effect of RF circuit impedance variation on AM and FM noise and their correlation, and substantiated his theory [(13)–(15)]. All three equations involve the rate of change of circuit impedance with frequency, which was controlled by weakly coupling a high-Q cavity to the oscillator circuit by a magic tee. Tuning this cavity from below to above the oscillation frequency changes the angle ϕ by 360°. Two maxima of both AM and FM noise occurred when ϕ was 0 and 180°, and two minima occurred when ϕ was 90 and 270°. The correlation coefficient was also maximum in magnitude at the noise maxima and minimum at the minima.

FM noise measurements on Ge avalanche transit-time diode oscillators were first reported by Rulison *et al.* [55]. They found that the rms frequency deviation is constant as a function of frequency separation from the carrier, as for Si diodes. However, for a loaded $Q_{ex}=11$, in a 1-kHz bandwidth, the rms frequency deviation was only 300 Hz. In general, Ge avalanche-diode oscillators showed a 10- to 14-dB improvement in noise-to-carrier ratio over Si diodes operating in the same circuit with the same loaded Q_{ex}. Barber [56] also reported on the FM noise in Ge diode oscillators to be 15 dB lower than in Si diode oscillators in cavities of the same Q_{ext} for frequency separations of 1 kHz to 2 MHz from the carrier frequency. GaAs avalanche transit-time diode oscillators have also been reported, by Baranowski *et al.* [57], to be superior to Si diode oscillators in their noise behavior. Their findings may be summarized as follows.

1) The FM noise sideband-to-carrier ratio for a GaAs diode oscillator was at least 10 dB lower when compared to a good Si diode oscillator operating in the same circuit with the same external Q.

2) The FM noise falls off as separation from the carrier frequency is increased.

3) The AM noise sideband-to-carrier ratios were similar for GaAs and Si avalanche-diode oscillators.

Levine [58], [59] reported measurement of AM noise on vapor-grown GaAs avalanche transit-time diodes operated pulsed at high current densities of up to about 2000 A/cm², and obtained AM noise levels lower than in klystrons and Gunn diodes. The best double sideband AM noise-to-signal ratio was −152 dB in a 100-Hz bandwidth 30 MHz away from the carrier frequency (11.1 GHz) for a 25-V breakdown diode operated at 1940 A/cm². In general, AM noise was found to be lower under conditions of high-bias current density, and GaAs diodes had a noise level 20 dB lower than Si diodes.

Avalanche-diode oscillator noise measurements in terms of parameters other than AM and FM noise have also often been reported. Thus DeLoach and Johnston [1] have measured spectral linewidth, Johnston and Josenhans [60], Scherer [46], and Baranowski *et al.* [57] have measured the noise figures of mixers and receivers using avalanche diodes as local oscillators, while Kramer *et al.* [61] have measured the total noise power spectrum. These results will not be discussed in detail.

D. Noise Reduction by Circuit Techniques

In this section some measurements of noise in avalanche transit-time diode oscillators operated with special circuit arrangements intended to reduce noise will be reviewed. It is not the intention here to review the theory or techniques of injection phase locking or other noise reduction methods; such details may be found in references [62]–[67]. The present discussion is confined to the improvement of noise behavior achieved by various methods, such as cavity stabilization and injection locking; these results are shown in Fig. 4.

The simplest method of reducing the noise of an avalanche transit-time diode oscillator is by frequency stabilization using a high-Q transmission cavity. Gilden [62] reported noise measurements on an avalanche transit-time diode oscillator stabilized with a tunable transmission cavity and made the following observations.

1) Even though the bandwidth of the cavity was 3 MHz, the width of the oscillator output spectrum was reduced from 300 kHz to 2 kHz as observed on a spectrum analyzer. This indicates that the cavity does not merely act as a filter; instead, the diode noise depends strongly upon the frequency dependence of the external circuit reactance as seen by the diode. This fact was further proved by introducing an isolator between the diode mount and the stabilizing cavity, in which case no noise improvement occurred.

2) Measurement of the AM noise of the oscillator, by a mixer crystal and an IF amplifier, showed a reduction of 15 dB in the noise at the output of the IF amplifier.

Ondria and Collinet [5] on the other hand measured FM noise in cavity-stabilized avalanche-diode oscillators. They used a Stalo cavity and reduced the rms frequency deviation of an avalanche-diode oscillator by a factor of 10. Ashley and Searles [63] observed the effect of cavity stabilization on AM noise of an avalanche-diode oscillator as a function of frequency separation from the carrier frequency. They found that for large separations (above 500 kHz) the AM noise is reduced by cavity stabilization, as expected, by an amount that increases with frequency separation. At 10 MHz, the AM noise reduction is approximately 20 dB. However, for small frequency separations (below 500 kHz), AM noise actually increased when cavity stabilization was used.

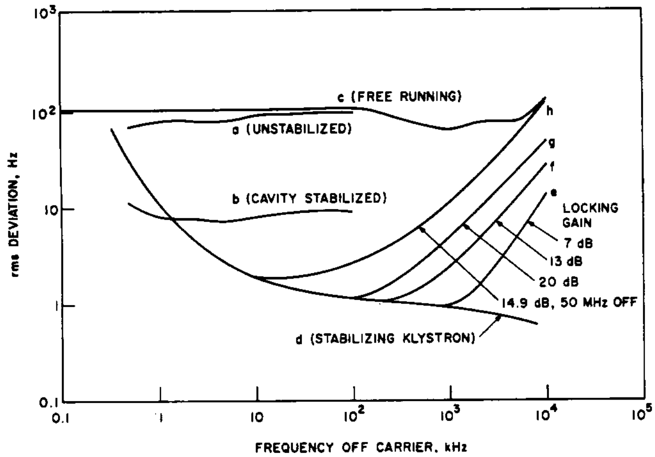

Fig. 4. FM noise reduction by circuit techniques [5]. Curves *a* and *b* are FM noise spectra of an unstabilized and a cavity-stabilized avalanche-diode oscillator. Curve *c* is the FM noise spectrum of another free-running avalanche-diode oscillator which is injection phase locked by a klystron with FM noise spectrum shown by curve *d*. Curves *e*, *f*, and *g* are FM noise spectra of the phase-locked oscillator with locking gains of 7, 13, and 20 dB, respectively, when free-running and klystron frequencies were identical. Curve *h* is the FM noise spectrum for a phase-locking gain of 14.9 dB when the two frequencies were 50 MHz apart. Power output, bias current, and oscillation frequency in cavity-stabilization and phase-locking experiments are different; rms frequency deviation is for one sideband in a 100-Hz bandwidth.

Nagano [64] also measured FM noise in cavity-stabilized oscillators and reported a stabilization factor of 50.

The use of a transmission cavity causes a loss of approximately 6 dB in the signal strength; a method of compensating for this loss has been reported by Ashley and Palka [6]. They used a cavity-stabilized *Ku*-band avalanche-diode oscillator with FM noise of 0.2 Hz rms in a bandwidth of 100 Hz to phase lock another avalanche-diode oscillator, obtaining a locking gain of 10 to 20 dB.

Ondria and Collinet [65], [5] have reported the following results on effects of phase locking on the noise spectra of avalanche transit-time diode oscillators. These results include the experimental work which was also reported by Hines *et al.* [66].

1) For phase locking by a small signal (20 dB below carrier), AM noise is reduced by approximately 3 dB; this effect is not evident from the theory of noise in synchronized oscillators and is attributed to the reduction of FM noise. Consequently, the component of AM noise due to FM to AM conversion is reduced.

2) For larger injected signals (10 dB below the carrier), AM noise spectra show degradation of 1 to 2 dB over that of free-running oscillators, a fact predicted theoretically.

3) In an avalanche-diode oscillator phase locked by a klystron, the FM noise level close to the carrier decreased to the same low level as the locking source, but at frequencies farther from the carrier, FM noise increased and asymptotically approached the noise level of free-running avalanche-diode oscillators.

4) The reduction of FM noise extended farther away from the carrier frequency for smaller phase-locking gain (larger injected signal) and for smaller frequency separation between the free-running frequency and the reference frequency.

Ashley and Palka [67] phased locked an *X*-band avalanche transit-time diode oscillator by a stabilized klystron and measured the AM and FM noise of the oscillator. Two major conclusions from their experiments are: 1) no increase of AM noise due to synchronization was detected, as is predicted by the theory of Kurokawa; and 2) the reduction of FM noise by synchronization is less than that predicted by Kurokawa near the carrier frequency, but more than the predicted value far from it.

A noise loading test for an avalanche transit-time diode oscillator, phase locked by an external frequency modulated signal has been reported by Isobe and Tokida [68].

Perichon [69] has reported measurement of FM noise of an avalanche-diode oscillator injection phase locked by a subharmonic signal, using the third and fourth subharmonics as synchronizing signals. The conclusions are in each case identical to those of Ondria and Collinet obtained with fundamental frequency injection. In addition it is noted that the higher the harmonic ratio, the smaller the bandwidth over which FM noise reduction occurs as a result of synchronization. Stated differently, a smaller phase locking gain is available for the same noise reduction.

Scherer [70] has suggested negative feedback methods for reducing oscillator AM and FM noise output. He has pointed out that dc bias current cannot be used for correction of amplitude and frequency, as it would affect both simultaneously. Instead AM noise can be reduced by using a pin modulator for amplitude correction, and FM noise can be reduced by controlling the frequency using varactor tuning. However, no experimental results using these techniques have been reported.

IV. Noise in Avalanche-Diode Amplifiers

A. Theory of Amplifier Noise

The first small-signal noise analysis of a reflection-type avalanche transit-time diode amplifier was presented by Hines [3]. Neglecting the diode series resistance R_s and assuming that fluctuations in the avalanche current are the only source of noise, he expressed the noise figure as

$$F = 1 + \frac{\overline{I_n^2} R_L}{GkT_0B} \tag{17}$$

where $\overline{I_n^2}$ given in (9) is the mean square noise current in the external circuit due to fluctuations in the avalanche, R_L is the load resistance as seen by the device, k is the Boltzmann constant, G is the amplifier power gain, B is the bandwidth, and T_0 the reference temperature of 290°K. Since an amplifier power gain is given by

$$G = \left| \frac{R_d - R_L}{R_d + R_L} \right|^2 \tag{18}$$

and under high gain conditions ($R_d \approx -R_L$), the noise figure expression simplifies to

$$F = 1 + \frac{q_e V_a / kT}{4m\omega^2 \tau_x^2 \left(1 - \dfrac{\omega_a^2}{\omega^2}\right)}. \tag{19}$$

Using typical values of the parameters, a noise figure of approximately 40 dB is predicted by the analysis. Hines also observed that the carrier current becomes very small over part of the cycle and then builds up to the peak value again by avalanche. Since fluctuations become significant when the total current is small, and are multiplied by avalanche, Hines concluded that: 1) the noise output may be large at higher signal levels (when current minima are smaller); and 2) a diode with large leakage current should be quieter at high signal levels than one with a sharp breakdown characteristic, because the leakage current would limit the minimum current.

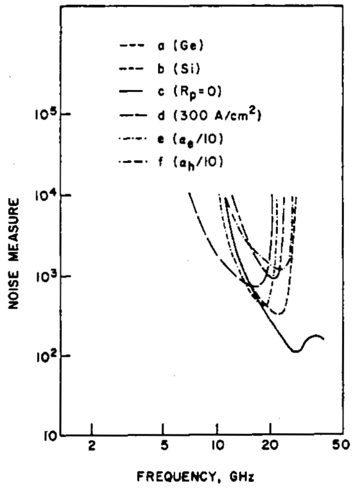

Fig. 5. Optimum noise measure for a p-n avalanche-diode amplifier [9]. Curve *a* gives the noise measure as a function of frequency for a Ge diode with a parasitic resistance of 1 Ω, dc bias current density of 1000 A/cm², and equal electron and hole ionization rates. All other curves are also drawn under the same conditions, except as noted for each curve: *b*, Si diode (unequal ionization rates); *c*, zero parasitic resistance; *d*, 300 A/cm² current density; *e*, electron ionization rate reduced by a factor of 10; and *f*, hole ionization rate reduced by a factor of 10.

Gummel and Blue [9] have used their results of open-circuit mean square noise voltage (described in Section II-B) to calculate the noise measure M of a small-signal avalanche transit-time diode amplifier. The noise measure of a linear two-port amplifier was defined by Haus and Adler [71] as

$$M = \frac{F-1}{1-\dfrac{1}{G}} \tag{20}$$

where F is the noise figure of the amplifier and G its gain, to serve as a figure of merit of amplifiers. The optimum value of this noise measure for a negative conductance amplifier has been found by DeLoach to be

$$M_{\text{opt}} = \frac{\langle v^2 \rangle / B}{4kT(-R_d)} \tag{21}$$

where B is the bandwidth, and R_d the real part of the diode impedance. Gummel and Blue have numerically calculated M_{opt} for an avalanche-diode amplifier as a function of operating frequency, parasitic resistance, diode material, and ratio of electron-to-hole ionization rates. Some of their results are shown in Fig. 5. They have reached the following general conclusions.

1) The noise measure shows a sharp minimum as a function of frequency, the frequency of minimum M_{opt} being higher for lower parasitic resistance and for larger bias current density.

2) The lower the parasitic resistance, the smaller the M_{opt}.

3) The larger the bias current density, the smaller the M_{opt}.

4) Ge avalanche diodes have lower M_{opt} than Si avalanche diodes. In general, M_{opt} is lowest for equal ionization rates for holes and electrons, and deteriorates if either α_e or α_h is reduced.

B. Measurements of Amplifier Noise

Most earlier work reported noise figure measurements on Si avalanche transit-time diode amplifiers. Johnston and Josenhans [60] measured a noise figure of 39 dB at 5.5 GHz for a Read-type structure, Josenhans and Misawa [72] reported a noise figure of 45 dB at 7.5 GHz for a p-i-n structure, and DeLoach and Johnston [1] found the lowest noise figure of 49 dB at 11.5 GHz for a p-n structure. These results should not be directly compared because they were obtained at different frequencies, amplifier gains, and bias current densities. DeLoach and Johnston also found that the noise figure decreased with increasing bias current and with decreasing amplifier gain.

Scherer [73] has reported an *X*-band avalanche-diode amplifier with three cascaded stages which has an oveall gain of 36 dB and a noise figure of 31 dB.

Rulison *et al.* [55] measured the noise figure of *X*-band microwave amplifiers using both p-n and n-p-i-p$^+$ (or Read-type) avalanche diodes fabricated with Ge under high gain conditions, and reported noise figures of 30 ± 1 dB, which is an improvement of approximately 10 dB over the results obtained with comparable Si devices reported earlier by Johnston and Josenhans [60].

Kuno *et al.* [74] have measured noise figures of GaAs avalanche transit-time diode reflection-type amplifiers. They reached a lowest noise figure of 17 dB under high gain conditions, which is lower than any reported using Si or Ge diodes. Two general conclusions can be drawn from their work.

1) The noise figure decreases monotonically with increasing dc bias current of the diode for a constant amplifier gain.

2) For a constant bias current, the noise figure of an amplifier slowly increases with increasing power gain, attains a maximum at a gain somewhere between 10 and 15 dB, and then falls for larger gains.

Noise figure measurements on GaAs avalanche-diode reflection-type amplifiers were also reported by Baranowski *et al.* [57] under high-gain conditions (10 to 30 dB) and 10- to 15-dB improvement was found over similar measurements using Si diodes. They also found a considerable reduction of noise figure with increasing diode bias current.

Typical reflection-type amplifier noise figures reported are shown in Fig. 6 as a function of diode bias current.

Although both degenerate [75] and nondegenerate [76] parametric amplifiers using avalanche transit-time diodes have long been reported, no measurements of noise figures in these amplifiers have been reported. On the other hand, noise figures of sideband amplifiers ("amplifiers" in which oscillations are simultaneously occurring at a nearby frequency) have been reported by Evans and Haddad [44], but will not be discussed here. Noisten [77] has measured amplifier noise in terms of AM and FM noise of output; these results are also not discussed here.

V. Noise in Avalanche-Diode Mixers

Avalanche transit-time diodes have been used as self-oscillating frequency converters in two different modes: that in which the signal is uncorrelated to the "local oscillator" output (the usual mixer application), and that in which the signal is derived from the local oscillator output. While the noisiness of the former is adequately described by the noise figure of the mixer, perhaps a more appropriate characterization of noise performance in the second case is the frequency stability or the minimum detectable signal for the oscillator–mixer combination.

No theoretical results on noise in either type of mixer have been reported so far. The mathematical treatment of noise in such a mixer is difficult for two reasons. First, the noise of the local oscillator is large and cannot be neglected, and second, the local oscillator noise is correlated to the fluctuations in the periodically

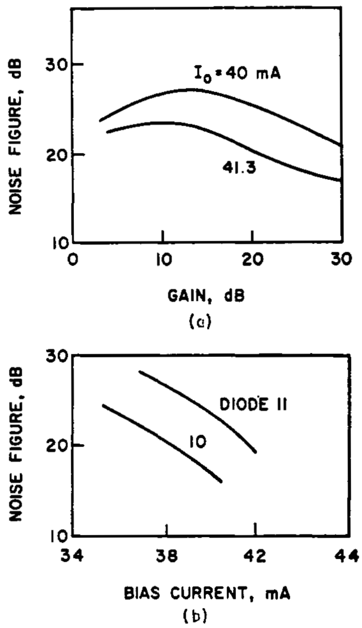

Fig. 6. Single sideband noise figure of GaAs avalanche-diode amplifier at 8.75 GHz [74]. (a) function of amplifier gain. (b) Bias current (for constant gain of 20 dB). Diode diameter is 125 μm.

varying device admittance as they both arise from the same physical mechanism. In addition, a conventional diode mixer noise analysis for a nonlinear conductance or nonlinear reactance type of mixer cannot be simply extended to avalanche-diode mixers, as the conductance and susceptance are both nonlinear and cannot be expressed as functions of voltage independent of frequency (because the *I-V* relationship for the diode is not instantaneous).

Grace [78], who reported on a Si avalanche transit-time diode downconverter (*X* band to 30 MHz) measured a conversion loss of 7 dB, and estimated the noise figure to be approximately 50 dB by measuring the minimum detectable signal power. Evans and Haddad [44] also carried out noise figure measurements on GaAs avalanche diode frequency converters using a noise figure meter, and reported a conversion loss of 6 dB and a noise figure of 55 dB. No later measurements using better diodes, particularly Schottky barrier avalanche diodes, have been reported, and the above figures are poor compared to the Gunn-diode self-oscillating mixers [79].

Measurements of minimum detectable signal on avalanche transit-time diode mixers in doppler radar applications have been carried out [80]. For very short-range radars, reflected signals that are typically 65 dB below the carrier power are detectable 1 Hz away from the carrier frequency.

VI. Conclusions

This exhaustive survey of reported results concerning noise in avalanche transit-time devices has included examination of both theoretical and experimental work on these devices in all of their several applications. Several unexplained experimental results and points of disagreement between experimental work of different workers can be identified. A large number of problems requiring further investigation exist. In particular, experimental and theoretical studies of noise in devices operated in the TRAPATT mode, large-signal noise analysis with a time-dependent multiplication factor, and noise measurements in Schottky-barrier avalanche diodes are some of the possible areas of study. That the work done is not complete is evidenced by the fact that no general set of rules for optimization of the diode structure, material, operating point, and circuit can be stated as yet.

Appendix

Since this paper has been written (in October 1970) several new results in this area have been published. Some of these are summarized below. Naqvi [81] has extended the analysis of McIntyre [8] to higher frequencies by taking into account the finite time required for multiplication. Vlaardingerbroek and Goedbloed [82] have calculated the width of the oscillator output spectrum using a Read model IMPATT diode and taking equal ionization rates for electrons and holes. They reach the conclusion that the p^+-n diode structure leads to a lower noise oscillator than the complementary n^+-p diode structure, which has a smaller avalanche-region width. Sjölund [83] has carried out a numerical large-signal analysis of IMPATT oscillators assuming a rectangular voltage waveform across the diode, and has found that the mean square noise current in the diode is inversely proportional to the ratio $I_{\min}/I_0$, where $I_{\min}$ is the minimum conduction current, and I_0 the dc bias current for the diode. Ulrich and co-workers [84], [85] have derived expressions for AM and FM noise spectra of free-running and synchronized IMPATT oscillators by a method similar to the one used for obtaining (13) and (14) and report good agreement between theoretical and experimental results. Josenhans [86] used a series combination of three Si IMPATT diodes in an oscillator and found the oscillator FM noise to be 30 Hz rms in a 1-kHz bandwidth as compared to 90 Hz rms for single diode oscillators under identical conditions, and ascribed this noise reduction to the accompanying power increase. Earlier, Fukui [87] had also reported an improvement over the average FM noise of individual diode oscillators in an oscillator consisting of eight IMPATT diodes mutually synchronized by a hybrid power combiner. Tatsuguchi *et al.* [88] have reported experimental measurements of the noise measure of a phase-locked IMPATT oscillator as a function of cavity load resistance and oscillator output power. Evans [89] has measured the noise figure of Ge TRAPATT diode amplifiers to be about 120 dB in the stable mode, but only about 60 dB when TRAPATT mode oscillations are occurring simultaneously at a different frequency. The FM noise of Ge TRAPATT oscillators at UHF was earlier reported [90] to be between 8 and 10 Hz rms in a 1-kHz bandwidth and for an external Q of 170 to 350. Claassen [91] has presented an approximate expression for the noise figure of an IMPATT diode amplifier in terms of small-signal parameters which can be calculated as a function of the avalanche-region width l_a, and has compared the noise figures of Si, Ge, and GaAs IMPATT diodes to show that in this respect GaAs is the best and Si the worst of the three materials.

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