Use of Microwave Noise Sources
Application Note

Introduction

Noise sources are the element in a microwave RF system that make it possible to accurately measure the noise figure of the receiver or its components. The requirements of a device used for making such noise figure measurements include broad bandwidth inherent in the active element, stability, ease of operation, and long life. When the gas discharge tube is mounted and terminated normally, it presents a “white signal” of constant intensity over a bandwidth limited only by the system or mount. In general, the range of usefulness of these noise sources permits measurements of noise figures from about 2 to 30dB. Existing mountings provide a useful frequency range of approximately 100MHz to 220GHz.

The noise tube and/or noise source should meet the following general requirements:

- When not operating, it should present a low insertion loss and VSWR to the system.
- When operating, it should provide an adequate signal level.
- Its output should be frequency independent, or at least known, over the prescribed bandwidth.
- Its output should exhibit minimum spurious oscillations.

Definitions and Basic Discussion

Noise Source Tube or Noise Tube - An electron tube filled with a rare gas (generally argon, neon, or a mixture) and operated in a positive column discharge mode at currents normally from 35 to 250mA.

Noise Source or Noise Generator - A noise tube mounted in an appropriate waveguide or coaxial mount.

Noise Power - The available noise power from a noise source tube is essentially kT_eB power coupled to the waveguide from the positive column of the discharge, where k is Boltzmann’s constant, T_e is the effective electron temperature of the discharge, and B is the bandwidth. To some extent, T_e can be estimated by the method of von Engel and Steenbeck.(1)

In microwave power measurements, consideration is given to the noise temperature, T_n, which when multiplied by k gives the power per unit bandwidth of a noise source. T_n is determined by comparison of the noise source against a thermal load.(2) Appropriate corrections must be made if the noise of the tube only is desired. Though T_n is often considered equal to T_e, such an approximation has been shown to have limited usefulness and the noise temperature of an individual noise tube or complete noise source should be measured rather than calculated for accurate results.(3)

Excess Noise Ratio {ENR or (Nr-1)} - The most important characteristic in microwave measurements, the excess noise ratio, is the ratio of the difference between the operating and non-operating temperatures to the non-operating temperature (the latter of which is assumed to be 290K). (Nr-1) is this ratio expressed in dB as

$$(Nr-1) = 10x\log_{10}\left[\frac{T_n - 290K}{290K}\right]$$

At common pressures and operating currents, (Nr-1) for an argon noise tube is approximately 15.5dB and for neon is approximately 18.0dB. The exact value for any noise source is influenced by the tube radius and pressure and, to some degree, by current.(4) The available noise from any given tube-mount combination depends as much on the characteristic of the mount and the method of coupling the tube into the mount as on any tube parameter.

Noise Figure {F} and Y-Factor {Y} - The noise figure of any network is defined as the ratio of signal to noise at the input to the signal to noise at the output(5,6) as

$$F = \frac{S_i / N_i}{S_o / N_o}$$

For calculation purposes, the input signal generated by the gas discharge noise source can be rewritten as $S_i = [S_i + N_i] - N_i$. The total input when the noise source is ON is $[S_i + N_i] = kT_nB$ as defined for noise power. When the noise source is turned OFF, the input is thermal noise of $N_i = kT_oB$ where T_o is the operational temperature (290K). Therefore, $S_i = k[T_n - T_o]B$.

Again, for calculation purposes, the signal output of the device can be rewritten as $S_o = [S_o + N_o] - N_o$. In this case, $P_{ON} = [S_o + N_o]/B$ is the noise tube ON condition and $P_{OFF} = N_o/B$ is the noise tube OFF condition. Therefore, $S_o = [P_{ON} - P_{OFF}] \times B$ and $N_o = P_{OFF} \times B$.

Substituting into the noise figure equation above yields

$$F = \frac{k[T_n - T_o]B \big/ kT_oB}{P_{ON} - P_{OFF} \big/ P_{OFF}} = \left[\frac{T_n - 290K}{290K}\right]\left[\frac{P_{OFF}}{P_{ON} - P_{OFF}}\right]$$

The Y-factor is defined as Y = P_{ON} /P_{OFF}. The quantity in the second pair of brackets of the noise figure equation above can be expressed in terms of Y as

$$\frac{P_{OFF}}{P_{ON} - P_{OFF}} = \frac{1}{P_{ON} \big/ P_{OFF} - 1} = \frac{1}{Y - 1}$$

Substituting this relation into the noise figure equation yields

$$F = \left[\frac{T_n - 290K}{290K}\right]\left[\frac{1}{Y - 1}\right]$$

or, expressed in dB,

$$F = 10x\log_{10}\left[\frac{T_n - 290K}{290K}\right] - 10x\log_{10}[Y - 1]$$

$$F = (Nr - 1) - 10x\log_{10}[Y - 1]$$

The last equation states that the noise figure of the system in dB is simply the excess noise ratio of the noise source, in dB, minus the value of (Y-1), in dB, as determined from a (Y) to (Y-1) logarithmic conversion. We now have the noise figure of the receiver defined in terms of all known quantities.

Types of Operation

DC operation of filamentary cathode noise tubes - The DC supply in Figure 1 is fed to the tube through an inductance, L, and current limiting resistances, R_1 and R_2. Upon closing the starting switch, SW, current flows through the inductance, resistance R_2, and the filamentary cathode. When the switch is opened, the collapse of the magnetic field in L provides a high voltage spike that ionizes the gas in the tube and establishes the discharge from anode to cathode. The anode current is then limited by R_1. SW must be capable of fast break operation and withstanding the high peak voltage developed. The DC supply must be capable of supplying the rated current at voltages greater than the tube drop.

The alternate configuration in Figure 2 uses a DC supply with a potential greater than the starting voltage to eliminate the need for the inductor and switch of Figure 1.

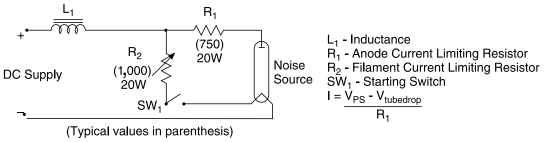

Figure 1 - Circuit for DC operation of filamentary cathode tubes.

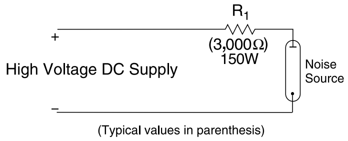

Figure 2 - Typical circuit for high voltage DC operation of noise tubes.

Pulse operation of hollow cathode noise tubes - These tubes are capable of operating for hundreds of millions of starts. Primary parameters are pulse width, pulse current, and pulse repetition rate. The circuit in Figure 3 uses a high voltage transistor Q driven into saturation. The diode is added to help ensure discharge turn-off.

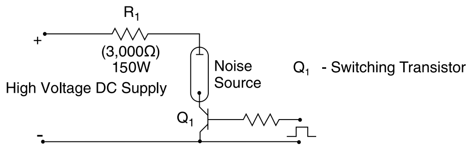

Figure 3 - Simple circuit for pulse operation of noise tubes.

The circuit in Figure 4 adds current regulation via feedback through a second transistor, Q_2.(7) The resistor R_1 reduces the power that the high voltage transistor Q_1, driven here in active mode, dissipates but it must be is sufficiently small in value to avoid saturating Q_1.

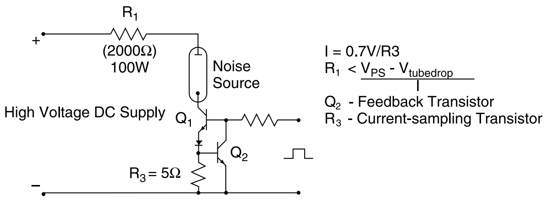

Figure 4 - Circuit for pulse operation of noise tubes with current regulation.

DC or pulse operation of indirectly-heated cathode noise tubes - These tubes may be operated by the circuit in Figure 1 modified to include a continuous filament voltage (often 6.3Vac). The circuits in Figures 2 through 4 may be used without modification.

Grounded anode operation - For all previous methods of operation and cathode types, the polarity can be reversed when desirable so the anode may be operated grounded. In the circuit in Figure 1, under reversed polarity conditions, the inductor L would be moved to the cathode side as would the limiting resistor R_1. Similar modifications would be made to the circuits in Figures 2 through 4 with the NPN transistors replaced with PNP transistors.

The advantage of operating with a grounded anode is that the anode potential is distributed along the length of the tube by the metal tube holder of the mount which results in a 10-50% decrease in the starting voltage depending upon the particular tube type and mounting arrangement.

AC operation of noise tubes with dual filamentary cathodes - When operation directly from an AC source is desired and AC modulation of the noise is not objectionable, the circuit of Figure 5 is suitable. Transformer T must provide sufficient voltage to strike the discharge. L may be included in the transformer as leakage reactance, but should be of a size to limit the average tube current to the specified value. SW can be eliminated if the secondary voltage of T is made high enough to provide a cold start without filament preheat.

Operation of a single-ended tube in this circuit will result in excessive anode heating with probable failure of the anode seal.

Operational Parameters

DC operation of filamentary cathode noise tubes - In the circuits of Figures 1 and 2, these tubes generally require 700-2,500V starting spikes, operate at anode currents of 50-250mA DC, and exhibit tube drops on the order of 40-150Vdc. Their life under conditions of essentially continuous operation, with only occasional starts, is generally in excess of 8,000 hours and may be as high as 20,000 hours. Their life under pulse conditions is short. The circuits in Figures 3 and 4 can also be used for DC operation.

Pulse operation of hollow cathode noise tubes - In the circuits of Figures 3 and 4, these tubes usually require starting spikes of 700-3,000V, operate at peak currents from 75-175mA, and have tube drops of 100-250V. Under pulse conditions with duty cycles of up to 50%, their life is typically 2,000-5,000 hours. In general, under intermittent DC conditions, they have adequate life of at least 500-1,000 hours.

DC or pulse operation of indirectly-heated cathode noise tubes - In the circuits of Figures 1 through 4, these tubes can be operated with very long life under either DC or pulse conditions. This particular cathode assembly utilizes an electrostatic shield around the cathode resulting in minimum ion bombardment of the active cathode surface area. The coated area is such that the maximum current density for any tube of this type is ultra-conservative. These tubes generally require starting pulses on the order of 500-2,000V, operate typically from 35-200mA DC or 50-150mA peak pulse, and have tube drops from 40-200V. Under intermittent DC conditions, life is generally in excess of 10,000 hours and may be as high as 50,000 hours. Under pulse conditions, at duty cycles up to 50%, their life is typically 3,000-7,000 hours.

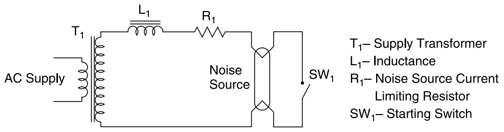

Figure 5 - Circuit for AC operation of noise tubes with dual filamentary cathodes.

Grounded anode operation - As mentioned previously, grounded anode operation reduces all starting voltage requirements.

AC operation of noise tubes with dual filamentary cathodes - In the circuit of Figure 5 driven by 60-400Hz sine waves, these tubes generally require starting voltages on the order of 1,000-2,500Vac, operate at currents of 100-250mA AC, and exhibit tube drops on the order of 40-150Vac. Typical life under 60Hz conditions is 100-1,000 hours, depending on the circuit parameters.

Ionization Time

Because of the presence of the rare gas, there is a finite time required for the discharge to become stable in any gas discharge noise tube. In argon-filled tubes, the discharge will normally become stable in 50-150ms after the completion of the starting spike. For neon, these times are on the order of 80-300ms.

These times may be modified drastically by the drive circuit, however. If there is appreciable ringing in the circuit, or if the supply voltage is only slightly greater than the tube operating voltage at the rated current, the time for a tube to establish a stable discharge may be much longer. In general, by proper circuit design, these indicated times can be attained for any of the types of operation mentioned above.

The ionization time is an important factor in making pulsed noise figure measurements (discussed later in this application note).

Deionization Tiime

Again, because of the presence of the rare gases, these tubes have finite deionization times. In argon at 200mA current and 20 Torr pressure, the deionization times are on the order of 70-300ms, depending on tube diameter. In neon at the same current and pressure, deionization times are normally 150-500ms. These deionization times can be improved by the application of a slight negative voltage when the tube is being turned off, in a pulse application for example. Deionization times generally increase with current.

Microwave Characteristics

General considerations - The level of the ENR that can be attained from any noise source is determined by the available ENR from the noise tube itself and by the coupling of the noise tube in the mount. The available ENR from the noise tube is determined principally by the type of fill gas, the gas pressure, and, to some small extent, by the tube current. The coupling in the mount is determined by the insertion angle of the tube through the mount, by the type of gas fill, and by the ratio of the tube diameter to the maximum guide dimension.(8) The coupling is also affected by the gas pressure and the tube current. The mounting is so important that the success with which any combination of noise tube, mount, and termination meets the general requirements at the end of the Introduction section of this note depends as much on the mounting method as on any other single feature.

Mounting methods - The most common methods and their relative advantages and disadvantages include:

- 0° to 30° E-plane insertion
  Advantages include extremely broad bandwidth (within the tolerances of the ENR specified for tube-and-mount, this style of mounting yields a frequency independent noise source), very low VSWR, very low non-operating insertion loss, and high operating insertion loss (therefore, very little reduction in the available ENR(9) from the noise source itself). Disadvantages include relatively large size, high voltage starting spike, and relatively high tube drop.
- 90° E-plane insertion, transmission-type
  Advantages include fair VSWR, very small size, low voltage starting spike, low tube drop, and low non-operating insertion loss. Disadvantages include low operating insertion loss (therefore, appreciable reduction in the available ENR), and relatively narrow bandwidth (~10-20%).
- 90° E-plane insertion, shorted-type
  Advantages include small size, low voltage starting spike, low tube drop, and high operating insertion loss (therefore, negligible reduction in the available ENR). Disadvantages include poor VSWR and very narrow bandwidth (~5-10%).
- 90° H-plane insertion, transmission-type
  Advantages include low non-operating insertion loss, fairly small size, good non-operating VSWR, and moderate voltage starting spike and tube drop. Disadvantages include poor operating VSWR, low operating insertion loss (with a resultant reduction in the available ENR), and very narrow bandwidth.
- Coaxial, helix-coupled
  Advantages include permitting the use of noise tubes originally designed for waveguide bands down into the UHF region, relatively broad bandwidth, good operating insertion loss, relatively good operating VSWR, and fair non-operating insertion loss and VSWR in the prescribed bands. Disadvantages include relatively large size, high voltage starting spike, and relatively high tube drop.
- Coaxial, direct-coupled
  The advantages and disadvantages of this type are the same as for the helix coupling except that the direct coupling approach, with the toroidal cross section tube family used in this approach, presents much lower non-operating insertion loss than the helix coupling approach. Since these types are almost all transmission types used directly in front of the receiver, the low non-operating insertion loss yields two advantages. First, there is less attenuation of the incoming signal during system operation and, secondly, there is no correction necessary to the available ENR as a result of significant non-operating loss.(10)

Comparative noise measurements - Comparative noise measurements are made by High Energy Devices in a test system shown schematically in Figure 6. Since these measurements depend ultimately on the stability of the gain set (which can be checked by visual observation of the output meter over a period of time long compared with the measurement time), the tolerances to which High energy Devices' ENR specifications are written are at least five times greater than the system capability.

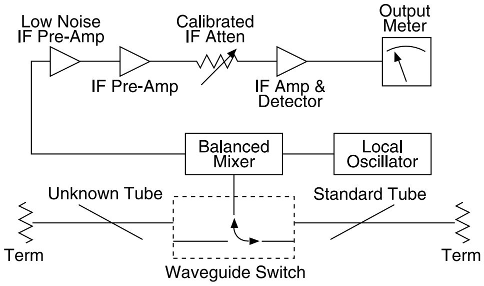

Figure 6 - Schematic diagram of set-up for measuring ENR.

System noise figure measurements - Noise figure has been summarized completely by Mumford and Scheibe(11) and reviewed in the Definitions and Basic Discussion earlier in this application note. Our discussion here will be concerned only with precautions to be taken with pulsed noise sources in making noise figure measurements.

The voltage and current curves of Figure 7 show typical pulsed tube performance as a function of time. The voltage across the tube rises to a very high value, at which point the tube breaks down. The voltage then falls to almost zero and, eventually, stabilizes at the tube drop after several tens of microseconds. The current usually stabilizes faster than the tube drop.

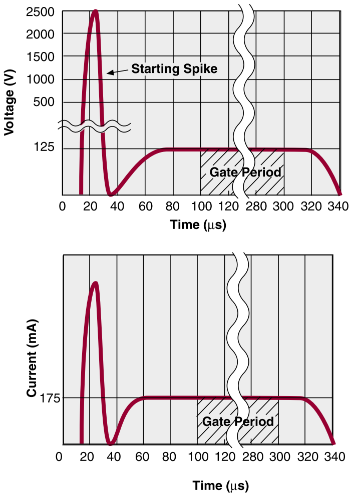

Figure 7 - Typical voltage and current waveforms for TD72 pulse type noise tube (argon filled).

If the "on" time of the receiver gating period starts too soon, there will be a fraction of the total gate period during which the noise power will not have the rated noise output of the tube at the given current because the tube drop, and consequently the field in the positive column, will not have been stabilized. Whenever possible, therefore, the total gating period should be long, ideally a few hundred microseconds, and the initiation of the gating period should be delayed as long as possible following the high voltage starting spike.

Another consideration is that the gating period during which the receiver looks at the cold, non-operating, noise source should be as long as possible after the main transmitter pulse (for a unit being used in the transmitter arm through a directional coupler) so that the lapsed time definitely is long compared with the deionization time of the tube.

Finally, use of a noise source for which there is the smallest possible difference between the operating and non-operating match is important when the noise source is the element being viewed as the cold reference for the system.

Variations with tube current - Since a change in current causes a slight change in tube drop, and thereby a slight change in the field in the positive column, there is a small correction to the ENR of a tube as a result of an actual change in the effective electron temperature. Further, there is an additional small change to the available ENR from the tube-in-mount as a result of the changing insertion loss caused by the change in current.

- Noise vs. current
  For most noise tubes, there is a decrease in ENR with current of 0.003-0.005dB/mA.
- Tube drop vs. current
  For most noise tubes, the tube drop tends to decrease about 0.13-0.26V/mA.
- Insertion loss vs. current
  Nominal values of operating and non-operating insertion loss for argon noise tubes in specific waveguide mounts are given in Table 1. Also, the tube-to-tube variations of operating insertion loss for typical operating insertion loss values of <20dB, 20-30dB, and >30dB are ±0.2-0.6dB, ±0.4-1.0dB, and ±1.0-3.0dB, respectively.

Table 1
Cold and Hot Insertion Loss for Argon Noise Sources

Band	Types (TD)	Mount & Meas't Freq (GHz)	Typical Insertion Loss (dB)					
			I = 0	125	150	175	200	250mA DC
S	12,38	WR-284, 10°E; 3.3	0.12	12.3	13.5	14.0	14.5	15.1
C	10,39	WR-187, 10°E; 5.5	0.11	14.8	16.9	17.3	18.8	20.8
J	10,39	WR-137, 10°E; 7.0	0.16	20.4	22.8	23.8	25.4	28.1
X	40	WR-90, 10°E; 9.0	0.18	18.2	20.8	22.8	24.4	26.0
X	11,72	WR-90, 10°E; 9.0	0.06	23.2	25.7	27.6	29.5	32.2
Ku	18,41	WR-62, 10°E; 16.0	0.07	32.0	37.9	44.1	51.0	54.5
K	13,42	WR-42, 10°E; 24.0	0.10	25.8	31.7	37.8	44.0	57.5

Application and General Operating Notes

Determination of the noise figure - This is the basic use of noise sources; for either a single component or an entire system. This determination stems from the relation: (F) = (Nr-1) - (Y-1), where (F) is the system noise figure, (Nr-1) is the ENR of the noise generator, and (Y) is the output meter reading; all quantities in parentheses being in dB and $Y = 10^{[(Y)/10]}$. See the Definitions and Basic Discussion for more detail.

Noise sources are the basic component of noise figure test sets. They are also used as built-in receiver monitors in radar systems directly in the receiver and/or antenna arms as depicted in Figure 8.

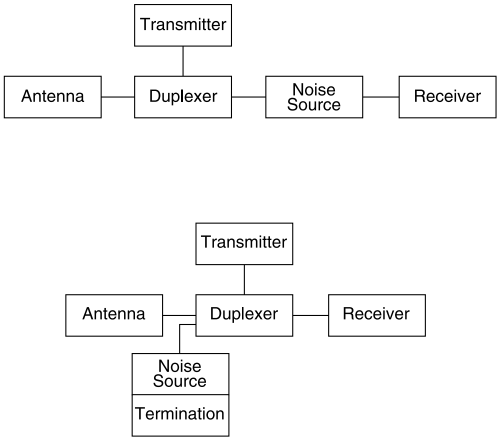

Figure 8 - Block diagrams of noise sources in (A) the receiver arm and (B) the antenna arm of a radar system.

Polarity - Since all noise sources are polarized devices, except those specifically designed for AC operation, they should never be operated in reverse. Under conditions of reverse operation, the life will be extremely short with failure due to anode seal breakage as the result of excessive heating.

Ambient temperatures - All rare gas filled noise tubes can be operated over a temperature range of -55°C to +125°C. Some noise sources cannot be operated over this entire range because built-in shorting plates or terminations may present temperature-dependent characteristics.

Life - The life of a noise tube depends principally upon the type of cathode, the mode of operation (CW or pulse), and the gas pressure. Under CW conditions, the indirectly heated cathodes exhibit extremely long life because their surface area is such that the current density is ultra-conservative. Similarly, the filamentary cathodes are conservatively rated with respect to current density.

Under pulse conditions, again the indirectly-heated cathodes have very long life for two reasons. The first is the lower starting spike required in a tube with this style cathode and the resulting drastically reduced ion bombardment of the cathode during the starting spike. The second is the conservative design with respect to the current density. The hollow cathodes exhibit good life under pulse conditions because the design of these cathodes causes the cathode coating which is sputtered during the starting spike to be re-deposited on another part of the cathode between pulses. Filamentary cathodes typically last only a few hundred thousand discharges of normal starting spikes. In a typical pulsed noise figure setup operating at a rate of 500 pps, one hundred thousand pulses are achieved in less than one hour. Therefore, this type cathode definitely is not recommended for pulse operation.

The principal mode of failure of gas discharge noise tubes is loss of cathode coating with its consequent increase in tube drop and starting voltage. The second failure mode is gas pressure reduction with its consequent change in tube drop and ENR.

Fortunately, the changes in tube drop and starting voltage occur long before there is any significant change in gas pressure. If the starting voltage increases by 20% or if the tube drop increases by 10%, end-of-life may be considered as having been reached. Within this period of time, negligible change in the ENR will have taken place.

For noise tubes with filamentary or indirectly-heated cathodes - For argon-filled noise tubes with indirectly-heated cathodes, the life is in excess of 10,000 hours and may be as long as 50,000 hours when operated DC. The life drops to 3,000-7,000 hours when pulse operated.

For argon-filled noise tubes with filamentary cathodes, the life is in excess of 8,000 hours and may be as long as 20,000 hours when operated DC.

Neon-filled noise tubes with either type of cathode have roughly half the life of similarly constructed and operated argon-filled noise tubes.

For pulse-operated noise tubes with hollow cathodes - For argon-filled noise tubes, the life is typically 2,000-5,000 hours. For neon-filled noise tubes, the life is typically 1,000-2,000 hours.

For AC tubes with dual filamentary cathodes - Though usually rated for 100 hours of operation under 60-400Hz conditions, the life is typically on the order of 500-1,000 hours with as little as 0.05-0.10dB change in the ENR.

Notes:

(1) A. Von Engel and M. Steenbeck, *Electrische Gasentadungen*, Springer, Berlin, vol. 2, p. 86; 1939.

(2) J. S. Wells, et al, “Measurement of effective temperature of microwave noise sources”, *IEEE Trans on Instr and Meast*, vol. IM-13, No. 1, pp. 17-28; Mar 1964.

(3) K. W. Olsen, “Measured noise temperature vs theoretical noise temperature for gas discharge noise sources”, *IEEE Trans Micro Th and Tech*, Vol. MTT-16, No. 9; Sept 1968.

(4) *Ibid.*

(5) C. K. S. Miller, C. W. Daywit, and M. G. Arthur, “Noise standards, measurements, and receiver noise definitions”, Proc *IEEE*, Vol. 55, No. 6, pp. 865-877; Jun 1967.

(6) W. W. Mumford and E. H. Scheibe, *Noise Performance Factors in Communications Systems*, Chapters VI-VIII, Horizon House, Dedham, Mass.; 1968.

(7) R. B. Bartlow, et al, “Increased analytical precision in the hollow cathode discharge source by improved discharge current control”, *Anal Chem*, Sept 1991.

(8) H. Johnson and K. R. deRemer, “Gaseous discharge super high frequency noise sources”, *Proc IRE*, vol. 39, pp. 908-917; Aug 1951.

(9) W. D. White and J. G. Greene, “On the effective noise temperature of gas discharge noise generators”, *IRE Corres*, pp. 939, Mar 1956.

(10) *Ibid.*

(11) Mumford and Scheibe, *loc. cit.*

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