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COVER FEATURE
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Noise-Related Technologies Climb Toward THz Territory

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Noise sources and noise analyzers are essential tools for testing and calibrating a wide variety of radar, communication and test systems. They are also vital for characterizing individual components and chip-scale electronic devices. At frequencies from MHz to THz, broadband noise sources are needed to measure the noise performance of amplifiers and receivers. They provide signals for testing digital radios and networks and they frequently support built-in test functions in radars and radiometric receivers. Amplified noise sources are commonly used as jamming signals in electronic countermeasures and emerging applications include gas and material composition detectors and broadband imaging systems.

At mmWave and sub-THz frequencies, electronic noise sources typically use an active device combined with a matching circuit and an attenuator or an isolator to match the output port to a standard impedance or waveguide type. In their most common configuration, electronic noise sources provide two calibrated noise power levels for measuring the performance of receivers and various other types of components and systems. A "hot" noise level is generated when the active device is turned on, while a "cold" noise level is produced when the active device is off.

An ideal noise source generates Gaussian random noise over a flat frequency spectrum with a negligible output mismatch to the reference termination.[1-6] Many coaxial and waveguide noise sources are available for mmWave frequencies with many reaching 110 GHz. A summary of representative noise sources from a variety of manufacturers is shown in ***Table 1***.

At higher frequencies, fewer options exist. Fortunately, waveguide noise sources are now increasingly being offered at frequencies ex-

TABLE 1
MMWAVE NOISE SOURCES

Manufacturer	Model	Frequency (GHz)	ENR (dB)	VSWR	Interface
Elva-1	ISSN-03	220 to 330	26 to 55	N/A	WR-03 waveguide
Eravant	STZ-22427410-03-IT2	220 to 270	7 to 13	1.6:1	WR-03 waveguide
Keysight	Q347B	33 to 50	9 to 17	1.5:1	WR-22 waveguide
NoiseCom	NC 3210M	2 to 110	>15	1.6:1	1.0 mm coaxial
NoiseWave	NW75G110-W	75 to 110	>15	1.6:1	WR-10 waveguide
VDI	WR5.1NS	140 to 220	8.5	N/A	WR-5.1 waveguide

Fig. 1 **Eravant noise source.**

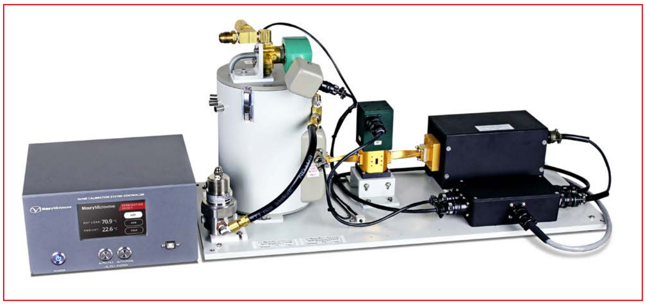

Fig. 2 **Noise calibration system with reference termination immersed in liquid nitrogen. *Source:* Maury Microwave.**

Fig. 3 **Thermal noise source with conical mmWave absorber. *Source:* TK Instruments Ltd.**

ceeding 200 GHz. ***Figure 1*** shows a noise source from Eravant that operates to 270 GHz. Electronic noise sources are commonly used with signal analyzers to perform noise figure measurements. Important specifications include excess noise ratio (ENR) flatness and output return loss. Isolators are often included to improve the output match and stabilize the noise output level.

THERMAL NOISE SOURCES

Thermal radiation sources have been used for calibration since Max Planck presented his theory of heat radiation in 1900. At mmWave and THz frequencies, matched terminations are often cooled with liquid nitrogen or heated with boiling water to produce primary noise references. However, "stem corrections" are typically applied to account for noise contributed by transmission lines and anything else in the signal path between the thermal source and the noise receiver.[6] Despite such complications, thermal reference standards are widely used to calibrate noise sources and receivers.

Hot and cold thermal noise standards are available, either individually or integrated into more functional noise calibration systems.[7] Cold reference sources typically include a coaxial or waveguide termination placed inside an insulated Dewar flask. The flask is filled with liquid nitrogen maintained at its boiling point. A regulated heater controls the temperature profile of a coaxial or waveguide transmission line that connects the cold termination to a room temperature user interface. An example of this type of precision noise calibration system is shown in ***Figure 2***.

Thermal noise standards are often characterized by an effective noise temperature that is slightly above or below the temperature of the termination. The noise contribution from an element in the signal path may be estimated as shown in Equation 1:

$$T_E * (1 - G) \qquad (1)$$

Where:

T_E is the temperature of the element

G is the gain factor of the element

To illustrate, a transmission line with a gain factor of 0.99 (0.04 dB attenuation) held at a temperature of 200 K would add 2 degrees to the effective noise temperature of the source. A more rigorous analysis would model the signal path as a cascade of circuit elements with different temperatures.[8]

Cold thermal sources are also constructed from absorbing materials that are cooled with precision temperature controllers.[9] The thermal noise radiated by such structures is typically coupled to a receiver through an antenna with both units operating in a condensation-free environment. ***Figure 3*** shows a thermal noise source with a conical mmWave absorber. The temperature of the absorber is controlled with a circulating fluid.

ELECTRONIC NOISE SOURCES

Some of the earliest electronic noise sources were constructed with gas discharge tubes mounted inside waveguides.[10] Gas discharge tubes are still used today, but they are much less common. More recently, laser-induced plasmas in noble gases have produced extremely fast THz signal pulses.[11] Optical mixing in photodiodes also produces THz signals. A functional rendition of this idea is shown in ***Figure 4***, where THz pulses are produced when optical power at different wavelengths excites a plasma in a chamber filled with a noble gas. Another type of

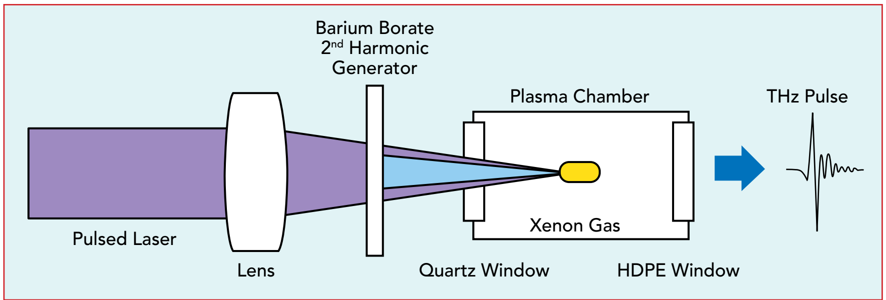

Fig. 4 **Functional diagram for THz pulses created by optical excitation.**

THz noise generator applies multiple optical signals at different wavelengths to a high speed photodiode.[12,13] The photodiode mixes the spontaneous emission noise produced by a super-luminescent LED. While such technologies appear to be in early development stages, they offer hope that THz noise sources suitable for laboratory use are on the horizon.

By the late 1970s, solid-state devices started replacing gas discharge tubes.[14,15] The sources exploit the shot noise generated in avalanche diodes and other semiconductor devices. Recent developments with avalanche diodes in silicon carbide show promise for improved high frequency performance as signal sources.[16] Field-effect transistors of various types can also be used to generate controlled levels of broadband noise.[17] At mmWave and sub-THz frequencies, suitable transistors may include GaAs FETs, InP HEMTs and GaN HEMTs. When suitably biased, such devices can produce significant levels of broadband noise.

Noise sources used for noise figure measurements must be turned on and off repeatedly. The source mismatch should be small and more importantly, unchanged between the on and off states. Different noise temperatures are observed depending on whether the source is on (hot) or off (cold). Noise sources are generally characterized by their ENR, as well as a reference termination; either a nominal impedance or a standard waveguide size.

The ENR defines the hot noise level relative to the cold noise level when the source is held at a reference temperature of 290 K.[18] The ENR is generally a frequency-dependent quantity. For noise figure measurements and many other applications, the ENR should be as flat as possible and the source mismatch should be as small as possible.

The ENR is an important consideration when choosing a noise source. As a rule of thumb, a noise source is suitable for measurements of noise figures that are up to the ENR value plus about 10 dB.[19] For higher device under test (DUT) noise figures, the difference between measured power levels for the hot and cold noise signals becomes too small to yield accurate results. However, a lower ENR should be used when possible because it tends to avoid overdriving the DUT and the receiver. Available noise sources tend to have ENR values around either 6 or 15 dB.

NOISE SOURCE CALIBRATION

Electronic noise sources are calibrated using a variety of instruments including spectrum analyzers, noise figure meters, signal analyzers and network analyzers. Any suitable instrument must have a sensitive receiver that can measure noise levels over an adequate bandwidth with sufficient linearity and dynamic range. For automated measurements, the instrument should also be capable of controlling a two-level noise source while simultaneously measuring the received power for each noise level.

Many older-model noise figure analyzers, such as the Agilent N8970 series, are essentially spectrum analyzers with additional built-in functions for measuring noise power levels and performing noise figure measurements. Newer signal analyzers, which combine the traditional functions of a spectrum analyzer with a wide range of other measurement capabilities, are rapidly becoming the tools of choice for performing noise measurements. Some of these newer signal analyzers are shown in ***Table 2***.

The Y-factor method is a well-established measurement technique for calibrating noise receivers and noise sources. It uses a pair of noise sources or a single source that provides two different noise levels. When the Y-factor is expressed linearly, it is equal to the hot noise power divided by the cold noise power, as measured by the receiver.

When a receiver is calibrated, its noise figure is obtained by performing a Y-factor measurement with a calibrated noise source connected to its input. The measurement is usually repeated each time the receiver is used and certainly whenever the measurement bandwidth changes or when the attenuation or gain settings are changed. The amplitude response of the receiver is separately calibrated using a reference signal generator, a reference power detector and/or a set of reference attenuators. Amplitude calibrations are typically performed infrequently according to a maintenance schedule or when the operating environment changes significantly.

After the noise receiver is calibrated, it can be used to perform additional Y-factor measurements and determine the ENR of an uncalibrated noise source. The calibration accuracy of the reference standard is partially transferred to the noise receiver and then partially transferred to the uncalibrated noise source. Analyzing the cumulative effects of measurement uncertainty is one of the more difficult tasks associated with noise source calibration.

Advantages of the Y-factor calibration method include its relative simplicity and its acceptable accuracy, in most cases. Power ratio measurements can be obtained quickly, minimizing the effects of temperature drift in the receiver response. However, basic Y-factor measurements typically do not compensate for mismatch effects and various other sources of measurement uncertainty.

Many studies have focused on analyzing and improving the accuracy of noise source calibrations.[20-22] Suggested enhancements can improve calibration results by applying considerably more effort in both measurements and calculations. By compensating for the measured effects of mismatches, the receiver noise parameters and temperature drift, one study achieved a two-sigma calibration accuracy of 0.046 dB for a noise source with an ENR of 5 dB.

The cold source measurement technique was developed as an alternative to the Y-factor method.[23] Measurements are performed using a single reference noise level provided by a matched termination at room temperature. The cold source method re-

TABLE 2

SIGNAL ANALYZERS FOR Y-FACTOR NOISE MEASUREMENT

Manufacturer	Model	Frequency
Anritsu	MS2850A	9 kHz to 44.5 GHz
Keysight	N9041B	2 Hz to 110 GHz
Rohde & Schwarz	FSW	9 kHz to 85 GHz

TABLE 3
EXAMPLES OF VNAS FOR COLD SOURCE NOISE MEASUREMENTS

Manufacturer	Model	Frequency
Anritsu	MS4647B	10 MHz to 70 GHz
Keysight	N5244B	10 MHz to 44 GHz
Rohde & Schwarz	ZNA67	10 MHz to 67 GHz

Fig. 5 **Frequency extenders for noise figure analyzers.**

lies on knowing the scattering parameters of the DUT.[24,25] The accuracy of cold source measurements is generally superior to that of Y-factor measurements when the latter includes mismatch compensation.[26] Additionally, the minimum noise figure and the noise parameters of a DUT can be obtained by performing multiple cold source noise figure measurements with different mismatches connected to the DUT input.

Cold source noise figure measurements require absolute noise power measurements, necessitating more accurate receiver calibrations. The measurement bandwidth must be known as well. Whereas the Y-factor method produces both the gain and noise figure of the DUT in one set of measurements, cold source noise figure measurements require independent gain measurements.

Because cold source noise figure measurements involve far more measurements and data manipulation than traditional Y-factor methods, they are usually performed using a fully integrated and automated test system. Some newer vector network analyzer (VNA) models include the ability to perform cold source noise figure measurements. Examples of these VNAs are shown in ***Table 3***. At frequencies beyond the operating range of VNAs, Y-factor measurements remain the most common method of performing receiver calibrations, noise source calibrations and noise figure measurements.

EXTENDED FREQUENCY COVERAGE

Most receivers that measure RF noise do so by converting input signals to an intermediate frequency (IF) where they are filtered, amplified and fed to a square-law detector or an analog-to-digital converter. To measure noise at frequencies beyond the limit of a given signal analyzer, an external down-converter can be used. Many general-purpose down-converters are suitable for this task.

If the down-converter uses a fixed local oscillator (LO) frequency, the noise receiver/analyzer is operated essentially the same as when measuring lower frequency signals. To preserve measurement accuracy, the noise figure of the down-converter should be comparable to that of the noise receiver. The down-converter should also provide adequate image rejection and good suppression of spurious signals.

Many down-converters built specifically for extending the frequency range of a noise analyzer are designed to accept a swept-frequency LO signal supplied by the analyzer. A frequency multiplier within the down-converter produces a higher-frequency LO signal. The result is a fixed IF for the down-converted signal fed back to the analyzer. This measurement strategy reduces the number of frequency conversions between the noise source and the IF amplitude detector, resulting in less measurement uncertainty.

Down-converters designed to extend the frequency range of noise figure analyzers are typically offered with a matching calibrated noise source. Available models provide full-band coverage up to 270 GHz. Full waveguide band coverage is generally provided with available models covering frequencies up to 170 GHz. An example of this setup is shown in ***Figure 5***.

CONCLUSION

Fundamental aspects of noise generation and measurement remain firmly grounded while noise sources and instrumentation advance toward THz capabilities. At frequencies up to about 110 GHz, noise sources and the instrumentation required to measure noise are available from multiple manufacturers. At higher frequencies, industry support is somewhat harder to find. Fortunately, newer sources produce noise signals beyond 200 GHz and newer technologies may soon provide high-quality noise sources at THz frequencies. Meanwhile, high performance down-converters are available to extend the frequency coverage of existing noise measurement tools. ■

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