A State-of-the-Art G-Band Noise Source and Cryogenic Calibration Method for Sub-THz Noise Figure Measurement (140–220 GHz)

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***Abstract*—This paper presents a G-band (140–220 GHz) noise source and calibration method for sub-THz noise figure characterization. The source achieves high ENR, spectral flatness, and stability. A liquid nitrogen (LN_2)-based cryogenic calibration provides accurate, traceable reference states. A comprehensive uncertainty analysis, reported for the first time on a commercial WR-05 noise source—addresses key error sources in sub-THz measurements. Results show excellent calibration accuracy and confidence over conventional methods, advancing high-frequency noise metrology.**

***Index Terms*—Millimeter-wave, G-band, Noise Source, Excess Noise Ratio (ENR), Sub-Terahertz, Calibration, LN_2, Uncertainty Analysis.**

I. Introduction

The rapid advancement of communication systems and instrumentation has driven strong demand for accurate noise figure measurements across devices, components, and systems. The Y-factor method, using a calibrated noise source with known excess noise ratio (ENR), remains the industry standard for this purpose [1].

Noise source technology has evolved from vacuum-tube and gas-discharge devices—limited by stability and bandwidth [2] to solid-state implementations. Avalanche diode-based noise sources became dominant due to improved performance [3]–[5], followed by recent SiGe BiCMOS amplifier-based designs offering stable ENR over defined bands [6].

Despite these advances, noise figure characterization in the sub-terahertz G-band (140–220 GHz) remains challenging due to limited high-performance noise sources and the lack of established calibration techniques. As applications in high-speed communications, sensing, and space systems expand into this frequency range, accurate and repeatable measurement becomes increasingly critical.

NIST has developed liquid-nitrogen-based noise temperature standards up to 110 GHz [7] and [8] with extensions to W-band reported by Kang et al. [9]. However, these methods have not been widely extended into the G-band, where calibration standards remain underdeveloped.

This work presents a high-performance G-band (140–220 GHz) noise source, based on solid-state technology, with typical 18 dB ENR and ±2.5 dB flatness. The device incorporates a waveguide Faraday isolator to improve impedance matching and reduce DUT-related uncertainty. It is compatible with commercial systems such as the Keysight N897X series when used with a downconverter.

Sub-THz noise measurement introduces significant challenges, including increased waveguide loss, sensitivity to mismatch, and thermal gradients between cryogenic and ambient reference planes. These effects, along with high insertion and conversion losses, require high-ENR sources to maintain sufficient measurement dynamic range.

This work extends LN_2-based waveguide noise calibration techniques from W-band into WR-05 (G-band), supported by a rigorous uncertainty analysis. The methodology is further extendable to frequencies up to 330 GHz.

II. G-Band Noise Source Design and Performance

The photo of developed G-band noise source is shown in Figure 1. The noise source is designed and manufactured to provide stable and broadband excess noise across 140–220 GHz. Key performance parameters include output ENR, and its flatness cross the frequency band are shown in Figure 2.

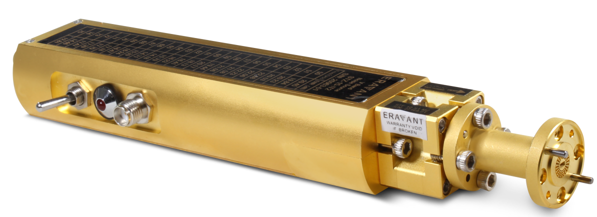

Fig. 1. The photograph of the developed noise source.

The schematic of the noise source is shown in Figure 3. The design incorporates a clean and stable DC-to-DC converter

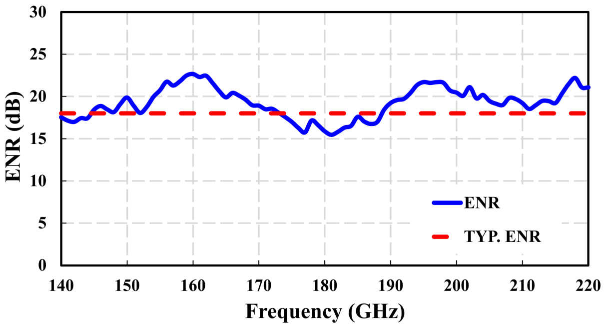

Fig. 2. The typical ENR versus frequency.

to provide the regulated bias voltage required for the high-frequency solid-state devices, ensuring stable ENR generation. Impedance matching networks and a high-performance microstrip-to-waveguide transition are integrated to achieve efficient signal coupling and broadband operation.

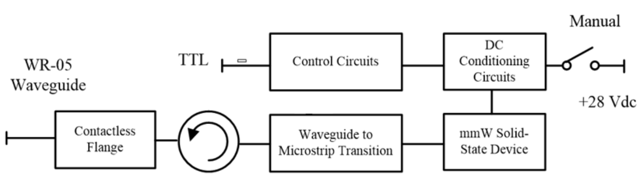

Fig. 3. The schematics of the noise source developed and manufactured.

A full-band Faraday isolator is integrated at the output to improve impedance matching and reduce measurement uncertainty from DUT mismatch. A patented contactless flange is further incorporated to minimize errors due to improper DUT connections [10].

The noise source supports both continuous-wave (CW) and pulsed amplitude modulation (AM) operation up to 1 kHz, with a TTL trigger input for automated testing and a manual on/off switch.

III. CRYOGENIC CALIBRATION METHOD USING LN_2

Noise source calibration is typically performed by comparison with known standards to characterize the device under test. The standard may be a calibrated noise source (cross-calibration method) or a known temperature standard, such as a liquid-nitrogen (LN_2) load, which provides a noise temperature reference [1]. Regardless of the specific approach, all methods aim to determine the ENR, defined as the ratio of the source's excess noise temperature to the standard reference temperature. Mathematically, ENR is expressed as:

$$ENR = \frac{T_{ns}^{h} - T_{ns}^{c}}{T_0} \tag{1}$$

In equation (1), T_{ns}^{h} and T_{ns}^{c} denote the hot (ON) and cold (OFF) states, respectively, and T_0 is the ambient temperature depending on the environmental condition, typically 290 K in RF/microwave practice.

The measurement receiver, either a bolometric power meter or a noise figure analyzer, records the total output noise power in each state. The resulting powers, P^h and P^c , define the Y-factor as their ratio, expressed as:

$$Y_{ns} = \frac{P^h}{P^c} = \frac{P_{ns}^{h} + P_{rec}}{P_{ns}^{c} + P_{rec}} = \frac{T_{ns}^{h} - T_{rec}}{T_{ns}^{c} - T_{rec}} \tag{2}$$

where P_{rec} denotes the noise temperature of the receiving system. Within the same setup, a cryogenic noise source can serve as the reference standard to calibrate the ENR of the device under test. Assuming the receiver's added noise temperature remains constant across measurements, the ENR of the noise source is given by:

$$ENR = \left[1 - \frac{T_{LN2}}{T_0} - (Y_{ref} - 1)\left(\frac{T_{LN2} - T_{ns}^{c}}{T_0}\right)\right] \left(\frac{Y_{ns} - 1}{Y_{ref} - 1}\right) \tag{3}$$

In the equation (3), Y_{ref} and Y_{ns} are the Y-factor of the cryogenic standard and noise source to be calibrated respectively. T_{LN2} is the thermal temperature of the liquid nitrogen standard. By assuming the receiving system are identical between the two measurements.

IV. CALIBRATION SYSTEM SETUP

The liquid nitrogen calibration setup is shown in Figure 4. The LN_2 side of a four-port WR-05 switch connects to a standard horn antenna, serving as the cryogenic reference. Both the horn antenna and the switch are state-of-the-art passive components manufactured by Eravant. The opposite port feeds a custom-designed full-band WR-05 downconverter from Eravant, integrating an isolator, RF low-noise amplifier (LNA), mixer, and IF amplifier with dedicated spurious-suppression. The remaining ports connect to the ambient reference and the noise source under test (DUT).

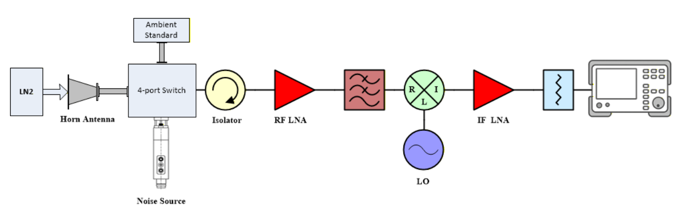

Fig. 4. Noise source calibration system setup.

V. PERFORMANCE AND UNCERTAINTY ANALYSIS

The uncertainty analysis follows the framework established for waveguide thermal noise standards by Daywitt at WR-10 [7], together with the broader treatment of NIST noise-temperature uncertainties, and extended to W-band by Kang et al. [9]. The LN_2 calibration uncertainty is decomposed into explicit contributions from the cryogenic and ambient standard temperatures, the Y-factor, the mismatch factor, the path efficiency, and other terms. The present work adapts this framework to the WR-05 band.

The LN_2 cold reference is a horn-coupled load, where a horn antenna views a microwave absorber immersed in liquid nitrogen within a cryogenic cavity. Its noise temperature is determined by the absorber properties, quantum correction, and atmospheric pressure.

Excess noise is introduced between the LN_2 standard and the downconverter by the horn and interconnecting waveguide, primarily due to dissipative loss. This effect increases with frequency as surface roughness becomes comparable to skin depth, along with additional loss from the room-temperature waveguide section. Uncertainty from switch paths (cold load vs. DUT) is evaluated via S-parameter measurements, from which path efficiency $\eta = |S_{21}|^2 / \left(1 - |S_{11}|^2\right)$ and mismatch factors are derived. The ambient path efficiency is negligible.

For full-band WR-05 downconverters, achieving 60 dB isolation is challenging even with cascaded isolators; however, isolation contributes negligibly to overall ENR uncertainty. The use of Eravant's integrated WR-05 LNA downconverter improves conversion stability and path repeatability, reducing drift-related Type A uncertainty.

At sub-THz frequencies, uncertainty contributions become increasingly significant and must be rigorously quantified. The proposed framework provides a systematic approach for total uncertainty evaluation in G-band noise figure measurements. Calibration results (Figure 5) show a typical ENR of 18 dB with a worst-case combined standard uncertainty of 0.31 dB.

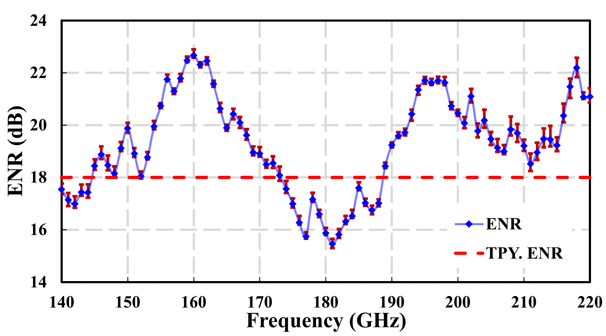

Fig. 5. ENR of the calibrated G-band noise source with uncertainty bars.

The result of the noise figure measurement of a known G-Band LNA using this noise source is shown in Figure 6.

VI. Results and Discussion

Experimental validation confirms that the proposed noise source and calibration method enable improved measurement accuracy across the 140–220 GHz range. The LN_2-based calibration provides a more stable and physically grounded reference, while the enhanced noise source performance reduces systematic errors.

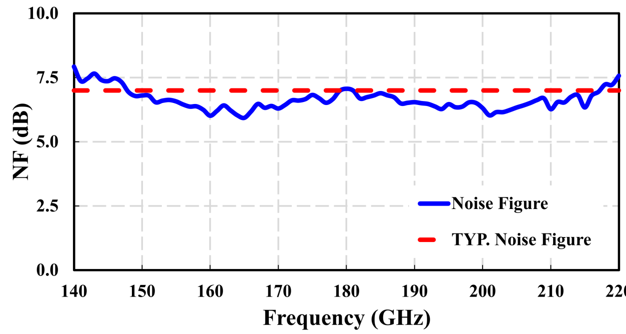

Fig. 6. Measured NF of a LNA using the calibrated G-band noise source.

VII. Conclusion

This work presents a state-of-the-art G-band noise source and a novel LN_2-based calibration methodology for sub-THz noise figure measurements. Together with a comprehensive uncertainty analysis, the approach advances the accuracy and reliability of noise characterization in the 140–220 GHz range, supporting next-generation applications in high-frequency systems.

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