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Error analysis and uncertainty estimation for a millimeter-wave phase-shift measurement system at 325 GHz

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ABSTRACT

Error analysis and uncertainty estimation for a millimeter-wave phase-shift measurement system at 325 GHz are presented. The measurement errors due to inductive voltage divider, receiver noise, phase drift, mismatch at test ports, gauge-block attenuator, leakage and repeatability have been identified and evaluated. The standard uncertainty of these error components have been estimated and combined to obtain the expanded uncertainty in phase-shift measurement. The differential phase-shift measurement uncertainty for a 0–60 dB WR-03 rotary vane attenuator is estimated to be 0.57–1.3° at 325 GHz.

1. Introduction

Microwave and millimeter-wave are increasingly being used in broadband communications, biomedical imaging, security imaging and non-destructive testing [1–6]. Accurate measurement of millimeter-wave transmission phase-shift is important in many applications. A 70 GHz phase-shift measuring system has been developed for plasma diagnosis [7]. This system used a single-channel homodyne receiver to derive the millimeter-wave phase-shift through a phase-comparator at 2 MHz. Millimeter-wave phase-shift measurement standard has been studied using a vector network analyser (VNA) and an air line with 1.85 mm connector for frequencies up to 65 GHz [8]. The increasing demand for fast wireless data transmission applications requires communication systems around 300 GHz [4,9,10]. A millimeter-wave network analyzer [11] or a dual-channel VNA [12,13] can be used to measure phase-shift at 50–1000 GHz. The expanded uncertainty of attenuation measurement for a 30 dB attenuator using a VNA is estimated to be 0.78 dB at 220–325 GHz [13]. Based on the attenuation measurement uncertainty, the expanded uncertainty of transmission phase-shift measurement for a 30 dB attenuator using VNA can be estimated to be 5.4° at 220–325 GHz [12]. We have developed a millimeter-wave phase-shift measurement system at 220–325 GHz to provide phase-shift measurement with high accuracy [14]. A variable phase changer or a waveguide shim measured by this system can serve as a phase-shift reference standard to provide reference for VNA or other millimeter-wave instruments. The detailed measurement error analysis had not been given in [14]. In this paper, we will provide a detailed analysis of the measurement errors in the phase-shift measurement system at 325 GHz and estimate the overall measurement uncertainty.

2. Comments on the measurement system

The differential phase-shift of a variable attenuator or phase changer and the insertion phase-shift of a

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waveguide shim or a fixed attenuator at 220–325 GHz can be measured using a dual-channel heterodyne receiver. A block diagram of the measurement system is given in Fig. 1. A millimeter-wave signal at 220–325 GHz is generated by a microwave synthesizer via a multiplier chain ($\times$18). Two subharmonic mixers are used to down-convert the signal to a main and a reference intermediate frequency (IF) signal at 2.5 GHz, which are further down-converted to 5.02 kHz. The differential or insertion phase-shift of a device under test (DUT) is measured by detecting the phase changes of the audio frequency (AF) signal using the LIA.

The attenuation of the DUT will decrease the AF signal level at the output of main radio frequency (RF) mixer. An inductive voltage divider (IVD) is used to keep the magnitude of the AF signal at a constant level when it is measured by the LIA so that the nonlinearity of LIA does not affect the phase measurement accuracy. The measured phase-shift is the difference between two measurements of the phase angle detected by the LIA, thus the phase angle detection need to be stable to ensure good measurement precision and accuracy. The receiver has been designed to reduce the effect of thermal noise and phase noise so that the random fluctuation and short-term drift in phase angle reading can be minimized.

3. Error analysis and uncertainty estimation

There are multiple sources of error in the measurement of phase-shift using our system. These include phase errors due to IVD, receiver noise, receiver phase drift, mismatch error at the test port, leakage, measurement repeatability and phase-shift measurement error of gauge-block attenuator (for DUT with attenuation more than 20 dB). Detailed analysis of these measurement errors and estimation of their standard uncertainties are given in the following subsections. The standard uncertainty of each error component will be combined to obtain the combined and expanded uncertainty of the measurement system [15].

3.1. Phase error due to IVD

The millimeter-wave signal is down-converted to a signal at 5.02 kHz, which goes through an IVD before its phase is measured by the LIA. A seven-decade IVD is used in our system. The IVD input voltage, V_{in}, and output voltage, V_{out}, is related by

$$V_{out} = V_{in}\, d(1 + \alpha + j\beta) \quad (1)$$

where d is the ratio setting of the IVD, α and β are the in-phase and quadrature deviation of IVD, respectively [16,17]. Values of α and β for the first 3 dials of the IVD are obtained from calibration of IVD. α ranges from 3.1×10^{-6} to 1.6×10^{-4}. β ranges from -5.0×10^{-5} to -2.0×10^{-5} for $0.5 \leqslant d \leqslant 0.8$ and from 4.8×10^{-5} to 6.9×10^{-4} for $0.008 \leqslant d < 0.5$. The above equation can be rewritten as

$$V_{out} = V_{in}\, d\sqrt{(1+\alpha)^2 + \beta^2}\, e^{j\theta_e} \quad (2)$$

where

$$\tan\theta_e = \frac{\beta}{1+\alpha} \approx \beta \quad (3)$$

since α is much smaller than 1. θ_e indicates the phase angle error introduced by IVD.

The IVD ratio changes involved in our measurement is from 0.008 to 0.8. We assume the phase-shift measurement error due to IVD is uniformly distributed in $[-e_i, e_i]$. Based on the β values provided by IVD calibration report, the maximum absolute error in phase-shift measurement

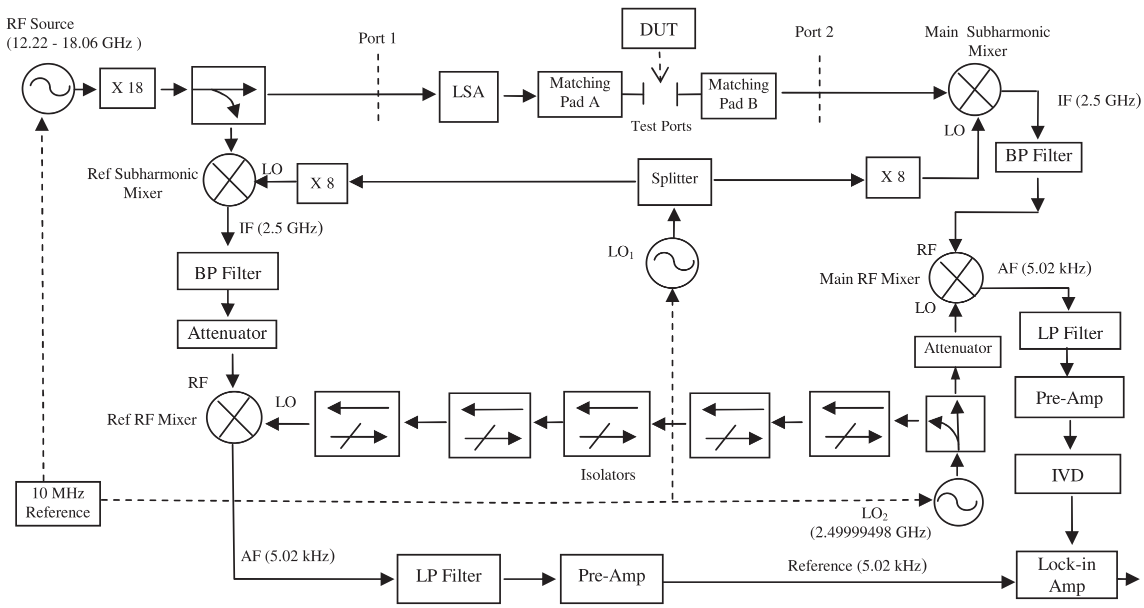

Fig. 1. Block diagram of a dual-channel millimeter-wave phase-shift measurement system from 220 GHz to 325 GHz.