Planar Offset Short Applicable to the Calibration of a Free-Space Material Measurement System in W-Band

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Abstract

The electrical properties of materials and their dependence on frequency and temperature are indispensable in designing electromagnetic devices and systems in various areas of engineering and science for both basic and applied researches. A free-space transmission/reflection method measuring the free-space scattering parameters of a material under test (MUT) located at the middle of transmit/receive antennas in a free space is suitable for non-destructively testing the MUT without prior machining or physical contact in high-frequency range. This paper describes a planar offset short applicable to the calibration of a quasi-optic based free-space material measurement system in the millimeter-wave frequency range. The measurement results of the dimensional and electrical properties for the three fabricated planar offset shorts with the phase difference of 120° between the reflection coefficients of the planar shorts in the W-band (75–110 GHz) are presented.

Key Words: Free Space, Impedance Standard, Material Measurement, Measurement System Calibration, Reflection Standard.

I. INTRODUCTION

The electrical properties (e.g., permittivity, permeability, and conductivity) of materials and their dependence on frequency and temperature are indispensable in designing electromagnetic (EM) devices and systems in various areas of engineering and science for both basic and applied researches [1, 2].

The resonator method [3–6] and the transmission/reflection (TR) method [7–9] utilizing the transmission line, such as coaxial line, waveguide, and free space, are widely used for material property measurements [10].

For resonator methods, after loading a material under test (MUT) in a resonator, the shift in the resonant frequency and the change in the quality factor of the resonator due to the MUT can provide an accurate material property at some reso-

nant frequencies only.

A guided-wave TR method measuring the scattering parameters of an MUT located inside the guided-wave structure, such as coaxial line [7, 11] and waveguide [8, 9], is used in low-frequency ranges, where precise machining of MUTs for insertion into the guided-wave structure is possible. On the other hand, a free-space TR method [12–15] measuring the scattering parameters of an MUT located in the middle of transmit/receive (Tx/Rx) antennas in a free space is suitable for non-destructively testing the MUT without prior machining or physical contact in high-frequency ranges. The coaxial line TR method provides a broadband material property, while the waveguide and free-space TR methods provides a frequency-banded property.

In general, the TR method consists of three steps [10]:

Manuscript received July 6, 2020 ; Revised September 15, 2020 ; Accepted October 12, 2020. (ID No. 20200706-098J)

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- Step 1. Calibrate the scattering parameter measurement system, including a vector network analyzer (VNA) to set the phase reference planes on both sides of an MUT;
- Step 2. Measure the scattering parameters of the MUT using the calibrated scattering parameter measurement system; and
- Step 3. Calculate the material properties of the MUT from the measured scattering parameters using EM theory.

In real measurements, there is a discrepancy between the measured data of a device under test (DUT) and its real data due to the existence of measurement errors in the measured data. In the metrological sense, the measurement error consists of a systematic error, a random error, and a drift error. The systematic error due to imperfections in an instrument to be used in the measurements is dominant among the measurement error components, is assumed to be time-invariant, and can be mathematically characterized during the calibration of the measuring instrument.

A VNA has several systematic error components due to its imperfections and is widely described by a 12-term two-port error model that consists of directivity, source and load matches, reflection and transmission trackings, and leakage in both forward and reverse directions [16]. During the calibration to characterize the systematic error of a VNA, one-/two-port standards of the independent impedance property [17] are required as follows: (1) short, open, load, and air line for a coax line case; (2) short, offset short, load, and straight section for a waveguide case; and (3) EM absorber, planar metal plate, and air section as a delay line for a free-space case.

Several calibration methods, such as Thru-Reflect-Match (TRM), Thru-Reflect-Line (TRL), and Gated-Reflect-Line (GRL) methods, are used for free-space material measurements. The TRM method [18] requires a well-matched broadband EM absorber, whereas the TRL method [12, 13] requires a precise positioning system for adjusting the separation between an MUT and Tx/Rx antennas, while both methods require a planar metal plate used as a reflection standard and movements of RF cables. On the other hand, the GRL method [19] requires a time-gating measurement during the calibration, a planar metal plate that is as thick as the MUT, and a de-embedding process for compensating for the effect due to differences in the thickness of the MUT and the planar metal plate. The GRL method is used when the separation distance between an MUT and Tx/Rx antennas is fixed.

This paper describes a planar offset short applicable to the calibration of a quasi-optic based free-space material measurement system in millimeter-wave frequency ranges. Recently, a preliminary work [20] proposed a planar offset short as a free-space reflection standard of a simple structure. In this paper, the work is extended by adding an operating principle of the planar

offset short and an in-depth analysis of its dimensional and electrical property measurement results. Section II describes the operating principle and the fabrication of the planar offset shorts. Section III describes the measurement results of the dimensional and electrical properties for the three fabricated planar offset shorts that give the phase difference of 120° between the reflection coefficients of the planar offset shorts at the center frequency (i.e., $f_c = \sqrt{75 \times 110} = 90.830$ GHz) of the W-band (75–110 GHz). Section IV summarizes this paper.

II. PLANAR OFFSET SHORT

1. Operating Principle of a Planar Offset Short

Assume a lossy transmission line terminated by a one-port device of Z_L impedance away from a phase reference plane. The reflection coefficient of the offset device may be expressed as

$$\Gamma(l) = \Gamma(0)e^{-2\gamma l} = \left(\frac{Z_L - Z_0}{Z_L + Z_0}\right)e^{-2(\alpha + j\beta)l}, \quad (1)$$

where $\Gamma(0)$ denotes the reflection coefficient at the termination plane, l denotes the offset (i.e., the separation between the phase reference plane and the termination plane), and Z_0 , γ ($= \alpha + j\beta$), α , and β denote the characteristic impedance, propagation constant, attenuation constant, and phase constant of the lossy transmission line, respectively [21].

In the case that a plane wave is incident upon an infinite metal offset plane away from a phase reference plane by an offset (l), as shown in Fig. 1(a), the reflection coefficient of the metal offset plane may be expressed as

$$\Gamma(l) = -e^{-2j\beta l} \quad (2)$$

under the assumption of $Z_L = 0$, $Z_0 = 120\pi$, and $\alpha = 0$ in Eq. (1). Eq. (2) shows that the infinite metal offset plane functions as a free-space reflection standard of the broadband linear reflection properties: (i) the magnitude of the reflection coefficient is unity regardless of the offset and signal frequency, (ii) its phase is linearly proportional to the offset and frequency, and (iii) the larger the offset, the steeper the slope of the phase with respect to the frequency.

In real free-space material measurements, a plane wave incident on an MUT should be localized because the size of the MUT is of finite extent, as shown in Fig 1(b). Quasi-optic based free-space material measurements assume that a Gaussian beam generated by a spot-focused horn-lens antenna [12, 13] or a corrugated horn antenna [22] is incident upon an MUT as a localized plane wave. In this case, a finite-extent planar metal plate of a zero offset may function as a planar flush short. If the central area of the planar flush short illuminated by the Gaussian beam is planed away (i.e., if the termination plane illumi-

Fig. 1. (a) Infinite metal offset plane illuminated by a plane wave. (b) Planar flush short and (c) planar offset short illuminated by a localized plane wave in free space.

nated by the Gaussian beam is away from the phase reference plane by an offset as shown in Fig. 1(c)), the planed-away planar short may function as a free-space offset reflection standard of the broadband linear reflection properties of Eq. (2) in quasi-optic based free-space material measurements. It is known that the diameter (D) of the planed-away area of the planar offset short should be three times larger than the waist (d) of the Gaussian beam incident upon the short for the negligible effect due to edge diffraction by the short [23].

2. Fabrication of Planar Offset Short

The planar offset short is fabricated as follows:

- Step 1. Fabricate a planar flush short of a square shape of $125 \times 125 \text{ mm}^2$ size and 8 mm thickness made of aluminum without offset, as shown in Fig. 2(a).
- Step 2. Plane away the central area (dark-yellow as shown in Fig. 2(b)) except for the four squares (blue as shown in Fig. 2(b)) of a $10 \times 10 \text{ mm}^2$ size located at each corner on one side of the planar flush short by the required offset l ($= l_1 - l_2$).

In this study, three planar offset shorts were fabricated to give the phase difference of 120° between the reflection coefficients

of the planar offset shorts in W-band; a planar flush short of 0° ($l = 0 \text{ mm}$) and two planar offset shorts with the phase difference of 120° ($l = 0.550 \text{ mm}$) and 240° ($l = 1.100 \text{ mm}$) from the phase of the reflection coefficient of the planar flush short at the center frequency ($f_c = 90.830 \text{ GHz}$) of W-band.

III. MEASUREMENT RESULTS

1. Dimensional Property Result

The offset of the fabricated planar shorts is measured using a digital indicator of 0.0001 mm resolution as follows:

- Step 1. The digital indicator is calibrated using a gauge block of the length corresponding to the nominal thickness of the planar offset short to be measured.
- Step 2. The thicknesses ($l_{1,meas}$) of the phase reference plane with respect to the offset reference plane of the planar shorts are measured twice on each area (blue as shown in Fig. 2(b)) of the four squares on the phase reference plane, and their average ($l_{1,meas}^{Avg}$) and standard deviation ($l_{1,meas}^{StDev}$) are calculated. $l_{1,meas}^{StDev}$ shows the degree of the flatness of the phase reference plane with respect to the offset reference plane for each planar short.

Fig. 2. Fabrication of a planar offset short. (a) Fabrication step 1 and (b) fabrication step 2.

Step 3. The thicknesses ($l_{2,meas}$) of the termination plane with respect to the offset reference plane of the planar shorts are measured twice at nine evenly distributed locations (dark-yellow as shown in Fig. 2(b)) on the termination plane, and their average ($l_{2,meas}^{Avg}$) and standard deviation ($l_{2,meas}^{StDev}$) are calculated. $l_{2,meas}^{StDev}$ shows the degree of the flatness of the termination plane with respect to the offset reference plane for each planar short.

Step 4. The offset (l_{meas}) of the planar flush and the offset shorts are determined by subtracting $l_{2,meas}^{Avg}$ from $l_{1,meas}^{Avg}$.

Table 1 shows that the fabricated planar offset shorts are of a machining accuracy of around 0.003 mm (i.e., the phase change of 0.793° at 90.830 GHz) because the $l_{1,meas}^{StDev}$ and $l_{2,meas}^{StDev}$ are in a range between 0.0006 mm and 0.0024 mm and the l_{meas} of the planar flush short is around -0.0014 mm. Table 1 also shows that the planar offset shorts are well-fabricated because the difference ($l_{meas} - l_{nominal}$) between the nominal and measured offsets of the planar offset shorts is smaller than the machining accuracy of the planar shorts.

The parallelism of the phase reference plane and the termination plane determines the tilting angle of the propagation direction of the Gaussian beam reflected by a planar offset short. The tilting angle may be obtained from the root-sum-square (RSS) of $l_{1,meas}^{StDev}$ and $l_{2,meas}^{StDev}$, and its maximum angle is given by

$$\tan^{-1} \left(\frac{\sqrt{(l_{1,meas}^{StDev})^2 + (l_{2,meas}^{StDev})^2}}{\text{Width of planar short}} \right) = 0.0013^\circ \quad (3)$$

for the planar flush short.

2. Electrical Property Result

The reflection property of the fabricated planar offset shorts is measured using a W-band quasi-optic based free-space material measurement system [22], as shown in Fig. 3, which consists of:

Fig. 3. Quasi-optic based free-space material measurement system in W-band.

- (i) A millimeter-wave scattering parameter measurement system: It consists of a 67 GHz VNA used as a main frame in the measurement system and two 67–110 GHz frequency extenders, #1 and #2, for measuring the scattering parameters of an MUT.
- (ii) A quasi-optic based free-space instrument: It consists of two linearly moveable benches, #1 and #2, and an MUT holder fixed between the two benches. Each bench has a Gaussian-beam forming corrugated horn antenna and an ellipsoidal re-focusing mirror on the bench and is capable of independently changing the separation between each bench and the MUT holder for supporting TRL calibration. All parts except for the antennas are made of aluminum. The MUT holder is of a square shape of 125×125 mm² size and has a circular aperture of 110 mm diameter at the center on the square. The circular aperture is four times larger than the 25 mm waist of the incident Gaussian beam at the MUT holder, and thus the effect due to edge diffraction by the circular aperture of the MUT holder can be ignored [22]. The two antennas of 26 dB gain compensate for the large insertion loss along the long signal path (in this case 1,750 mm) between the feeding ports of the two antennas, so the measured insertion loss is smaller than 2 dB in W-band.

Table 1. Offset of the fabricated planar offset shorts (unit: mm)

		Phase difference of offset		
		0°	120°	240°
Nominal offset	$l_{nominal}$	0.000	0.550	1.100
Measured thickness	$l_{1,meas}$ (8 measurements)	$l_{1,meas}^{Avg}$	8.0534	8.0622
		$l_{1,meas}^{StDev}$	0.0024	0.0010
	$l_{2,meas}$ (18 measurements)	$l_{2,meas}^{Avg}$	8.0547	7.5139
		$l_{2,meas}^{StDev}$	0.0013	0.0006
Measured offset	$l_{meas} (= l_{1,meas}^{Avg} - l_{2,meas}^{Avg})$	-0.0014	0.5482	1.0987
Offset difference	$l_{meas} - l_{nominal}$	-0.0014	-0.0018	-0.0013

The free-space material measurement system with fixed bench #1 is calibrated using the TRL method carried out with the measurements of (i) “Thru” by directly connecting reference planes, #1 and #2, (ii) “Reflect” using a metal plate (in this case of 4.675 mm thickness) inserted between the two reference planes separated by the plate thickness, and (iii) “Line” of a quarter-wavelength delay (in this case of 0.82 mm length) in air by separating the two benches by the delay length with a 100 Hz IF bandwidth and 801 stepped frequency sweep points in W-band. Reference plane #1 (i.e., test port #1) of the measurement system fixed during the calibration is used to measure the reflection property of the planar offset shorts.

Information on the reflection property of a reflection standard is a prerequisite for calibrating a VNA. Conventionally, a VNA uses a polynomial of the frequency fitted to the real measured reflection property of the reflection standard to save memory and to avoid data interpolation of the VNA. Because a planar offset short is of the linear reflection properties of Eq. (2), it is appropriate that the linear reflection property is fitted to a first-order polynomial of the frequency in GHz given by

$$y = a \times f_{\text{GHz}} + b, \quad (4)$$

where y means the magnitude and phase of the reflection coefficient of the planar shorts, a and b mean the slope and intercept of the first-order polynomial determined by using the least squares method, respectively, and f_{GHz} means the frequency in GHz.

Figs. 4–6 show the measured reflection coefficient of the fabricated planar offset shorts, its linear-fitted data, and their differences, respectively. The measured results show that ripples due to strong multiple reflections between the antenna and the planar metal short, and the scatterings from the surrounding metal structures, such as the MUT holder and mirrors, are superposed on the theoretical reflection properties of Eq. (2), where the magnitude is approximately unity regardless of the offset and signal frequency, while the phase is linearly proportional to the offset and frequency. Moreover, the larger the offset, the steeper the slope of the phase with respect to the frequency. The maximum difference between the measured data and its linear-fitted data is around 0.29 for the magnitude and 24.13° for the phase.

Multiple reflections inherent in free-space material measurements may be removed by taking a time gating and/or a smoothing (i.e., moving average) of the measured data as a post signal processing. Figs. 7–9 show the time-gated measured reflection coefficient of the planar offset shorts, its linear-fitted time-gated data, and their difference, respectively. After taking

Fig. 4. Measured reflection coefficient of a planar flush short of 0.000 mm offset: (a) magnitude and (b) phase.

Fig. 5. Measured reflection coefficient of a planar offset short of 0.550 mm offset: (a) magnitude and (b) phase.

Fig. 6. Measured reflection coefficient of a planar offset short of 1.100 mm offset: (a) magnitude and (b) phase.

Fig. 7. Time-gated measured reflection coefficient of a planar flush short of 0.000 mm offset: (a) magnitude and (b) phase.

Fig. 8. Time-gated measured reflection coefficient of a planar offset short of 0.550 mm offset: (a) magnitude and (b) phase.

the time gating, ripples due to the multiple reflections are removed, and the discrepancy between the time-gated measured data and its linear-fitted time-gated data is significantly reduced to around 0.01 for the magnitude and 0.38° for the phase compared to Figs. 4–6.

Linear fit coefficients of the calculated reflection coefficient of the planar offset shorts of nominal and measured offsets, respectively, are shown in the columns of “Nominal offset” and “Meas-

ured offset” in Table 2. Table 2 also shows the linear fit coefficients of the linear-fitted data in Figs. 4–6 and the linear-fitted time-gated data in Figs. 7–9 of the measured reflection coefficient of the planar offset shorts in the columns of “Linear-fitted” and “Linear-fitted time-gated,” respectively. Table 2 shows that the linear fit coefficients of “Nominal offset,” “Measured offset,” “Linear-fitted,” and “Linear-fitted time-gated” are well agreed with each other.

Fig. 9. Time-gated measured reflection coefficient of a planar offset short of 1.100 mm offset: (a) magnitude and (b) phase.

The reflection properties of the planar offset shorts can be calculated from the first-order polynomial of the frequency of Eq. (4) with the linear fit coefficients in Table 2 in W-band. The differences between the reflection properties of “Linear-fitted” and “Nominal offset” and between those of “Linear-fitted time-gated” and “Nominal offset” are given in the columns of “Line-

ar-fitted – Nominal offset” and “Linear-fitted time-gated – Nominal offset” in Table 3, respectively. Table 3 shows that “Linear-fitted – Nominal offset” is well agreed with “Linear-fitted time-gated – Nominal offset” (i.e., max. standard deviation is 0.004 for the magnitude and 0.656° for the phase).

The precision of the linear fit coefficients of Eq. (4) can be

Table 2. Linear fit coefficients of the reflection coefficient of the planar offset shorts

Measurand	Phase difference	$y = a \times f_{GHz} + b$							
		Nominal offset ^{a)}		Measured offset ^{b)}		Linear-fitted ^{c)}		Linear-fitted time-gated ^{d)}	
		<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
Magnitude (linear)	0°	0	1	0	1	1.500E-4	0.980	1.827E-4	0.976
	120°	0	1	0	1	1.848E-4	0.980	1.060E-4	0.986
	240°	0	1	0	1	0.279E-4	0.994	-0.094E-4	0.996
Phase (°)	0°	0	-180.000	0.003	-180.000	-0.056	-179.545	-0.050	-179.946
	120°	-1.321	-180.000	-1.317	-180.000	-1.260	-179.590	-1.332	-172.865
	240°	-2.642	-180.000	-2.640	-180.000	-2.578	-179.511	-2.580	-179.892

^{a)}“Nominal offset” is obtained from the calculated reflection coefficient of a planar offset short of a nominal offset.

^{b)}“Measured offset” is obtained from the calculated reflection coefficient of a planar offset short of a measured offset.

^{c)}“Linear-fitted” is obtained from the linear-fitted measured reflection coefficient of a fabricated planar offset short.

^{d)}“Linear-fitted time-gated” is obtained from the linear-fitted time-gated measured reflection coefficient of a fabricated planar offset short.

Table 3. Difference between first-order polynomials of the reflection coefficient of the planar offset shorts

Measurand	Phase difference	Linear-fitted ^{a)} – Nominal offset ^{b)}				Linear-fitted time-gated ^{c)} – Nominal offset			
		Difference between Linear-fitted & Nominal offset				Difference between Linear-fitted time-gated & Nominal offset			
		Min	Max	Average	SD	Min	Max	Average	SD
Magnitude (linear)	0°	-0.009	-0.004	-0.007	0.002	-0.010	-0.004	-0.007	0.002
	120°	-0.006	0.001	-0.003	0.002	-0.006	-0.003	-0.004	0.001
	240°	-0.004	-0.003	-0.004	0.004	-0.005	-0.005	-0.005	0.000
Phase (°)	0°	-5.650	-3.707	-4.679	0.562	-5.490	-3.726	-4.608	0.510
	120°	5.000	7.143	6.072	0.620	5.980	6.347	6.164	0.106
	240°	5.349	7.617	6.483	0.656	4.803	6.994	5.898	0.634

^{a)}“Linear-fitted” is obtained from the linear-fitted measured reflection coefficient of a fabricated planar offset short.

^{b)}“Nominal offset” is obtained from the calculated reflection coefficient of a planar offset short of a nominal offset.

^{c)}“Linear-fitted time-gated” is obtained from the linear-fitted time-gated measured reflection coefficient of a fabricated planar offset short.

Table 4. Standard error of linear fit coefficients of the reflection coefficient of the planar offset shorts

Measurand	Phase difference	Standard error			
		Linear-fitted ^{a)}		Linear-fitted time-gated ^{b)}	
		α	β	α	β
Magnitude (linear)	0°	1.167E-4	0.011	3.730E-6	3.471E-4
	120°	1.979E-4	0.018	9.108E-6	8.475E-4
	240°	1.771E-4	0.017	3.150E-6	2.930E-4
Phase (°)	0°	0.008	0.711	3.547E-4	0.033
	120°	0.012	1.074	2.424E-4	0.023
	240°	0.011	1.045	1.697E-4	0.016

^{a)} "Linear-fitted" is obtained from the linear-fitted measured reflection coefficient of a fabricated planar offset short.

^{b)} "Linear-fitted time-gated" is obtained from the linear-fitted time-gated measured reflection coefficient of a fabricated planar offset short.

described by their standard errors, α and β , which are defined by the standard deviation of the estimated linear fit coefficients, a and b , and can be used to construct confidence intervals for a and b . Table 4 shows that the standard error of "Linear-fitted time-gated" is much smaller than that of "Linear-fitted." This means that the measured reflection coefficient of the planar shorts with the time gating is better fitted to a linear function of the frequency of Eq. (4) than that without the time gating.

The measurement results show that (i) the time-gated measured reflection coefficient of the planar offset shorts is of the reflection properties of an infinite metal offset plane illuminated by a plane wave of Eq. (2), (ii) the reflection coefficient with time gating is better fitted to a linear function of the frequency of Eq. (4) than that without time gating, and (iii) the planar short is applicable to a broadband reflection standard in quasi-optic based free-space material measurements.

IV. CONCLUSION

This paper describes a planar offset short applicable to the calibration of a quasi-optic based free-space material measurement system in the millimeter-wave frequency range.

The dimensional and electrical properties of three fabricated planar offset shorts giving the phase difference of 120° between the reflection coefficients of the planar shorts at the center frequency of W-band are shown. The planar offset short is fabricated by planing away the central area of a planar flush short to be illuminated by an incident Gaussian beam.

The measurement results show that the time-gated measured reflection coefficient of the fabricated planar offset shorts is of the reflection properties of an infinite metal offset plane illuminated by a plane wave, whose magnitude is approximately unity regardless of the offset and signal frequency, while its phase is linearly proportional to the offset and frequency. The larger the offset, the steeper the slope of the phase with respect to the frequency. This means that the planar short is applicable to a

broadband reflection standard in quasi-optic based free-space material measurements.

This work was supported by the Technology Innovation Program (No. 20010587, Development and Dissemination on National Reference Standards) funded by the Ministry of Trade, Industry & Energy, Republic of Korea; and the Korea Research Institute of Standards and Science (No. KRISS-2020-20011051) as the project "Development of safety measurement technology for major infrastructures."

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