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RESEARCH ARTICLE

Design of a Waveguide Calibration Kit Consisting of Offset Shorts for Low Measurement Uncertainty

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ABSTRACT We recently established an impedance standard for the D-band, one of the 6G candidate frequencies. However, primary standards are difficult to use for routine calibration because they require multiple impedance standards and a lot of time to calibrate the vector network analyzer (VNA). Therefore, a transfer standard is needed to efficiently apply the calibration value and to propagate the uncertainty of the primary standard to a device under test (DUT). In this paper, we describe a design method for a transfer standard with small uncertainty even when an arbitrary DUT is measured. This is achieved by propagating the uncertainty of the primary standard to the transfer standard and then propagating it again to the uncertainty of the DUT. We developed a calibration kit that has low uncertainty over a wide frequency band, from 110 GHz to 170 GHz, and consists of waveguide offset shorts for ease of production. We also propose a method to minimize DUT uncertainty and a method to minimize "phase distance" to find the optimal length of the offset short. When using three offset shorts, an uncertainty similar to that of the short-open-load-thru (SOLT) calibration kit was obtained, and when using four offset shorts, an uncertainty comparable to the primary standard was obtained. Lastly, this paper examines the repeatability of measurements and reproducibility during the production process.

INDEX TERMS 6G, calibration, impedance, measurement uncertainty, network analyzers, optimization, measurement standards, traceability.

I. INTRODUCTION

The amount of 6G research has recently increased, with many reported studies. 6G targets include a latency of 0.1 ms and a transmission rate of 1 Tbps. To achieve this, a bandwidth of several GHz is required, and as a result, sub-THz bands are being widely considered to satisfy the above requirements [1], [2].

Impedance standards above 100 GHz have been established in a small number of national measurement institutes, but international equivalence has not yet been established [3], [4], [5]. We recently established waveguide impedance standards for the V-/W-/D-/G-bands (50 GHz to 220 GHz) [6]. To have measurement traceability from the SI unit, the size of the waveguide aperture and shims were precisely measured, and the scattering coefficients of the primary standards were calculated based on the measured dimensions. From those scattering coefficients, the error terms of the vector network analyzer (VNA) were estimated, and the uncertainty was analyzed. Thus, the primary standards enables us to precisely measure the impedance of a device under test (DUT). Still, there is a problem using the primary standards for general

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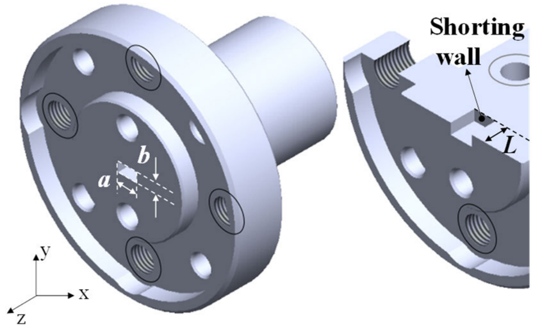

FIGURE 1. Structure of the offset short waveguide.

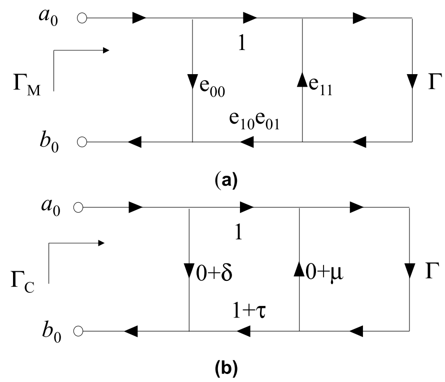

FIGURE 2. (a) VNA error model, (b) residual model.

calibration because it takes a long time and requires multiple standards (i.e., reflections, multiple shims, thru, and reciprocal adapters). Therefore, a transfer standard that can be used for routine calibration and measurement is highly required.

The short-open-load (SOLT) calibration kit, which is simple and has wideband characteristics, is widely used as the traveling standard. In addition, a study has reported that using a load and open instead line standard is more stable in above 500 GHz [7]. However, the waveguides differ from the coaxial lines, so creating a standard with the open structure is complex. Therefore, the open standard is usually made by cascading the shim (thickness of 1/4 λ at the center frequency) and the short standard. As a result, if it deviates from the center frequency, it leaves the "open" state and gradually approaches the "short" state, which has the disadvantage of increasing the uncertainty.

There have been several previous studies on the design of waveguide offset shorts [8], [9]. In this paper, we propose a new design method for a calibration kit consisting of multiple offset shorts to reduce the uncertainty of the DUT over the entire operating frequency band on the waveguide. This calibration kit is easier to make than SOLT because it does not include a broadband low-reflection reference like the load. When using the proposed method, the uncertainty of the DUT using three offset shorts was similar to that of the SOLT calibration kit. In addition, the uncertainty of the DUT using four offset shorts was comparable to the one of the primary standard.

In Section II in this paper, we show the modeling of the offset waveguide, and revisit the design method to minimize the DUT's uncertainty when calibrated using the designed waveguide calibration kit in Section III. Section IV introduces the phase distance minimization method, a new offset short calibration kit design method based on the optimization results. Section V explains offset shorts' manufacturing reproducibility and measurement repeatability, and concludes in Section VI.

II. MODELING AN OFFSET WAVEGUIDE

Fig. 1 shows the waveguide with the aperture of a by b and the offset length of L. When the conductivity of the waveguide is σ, the surface resistance R_m is as follows [10].

$$R_m = \sqrt{\frac{\omega\mu_0}{2\sigma}} \tag{1}$$

μ_0 and ε_0 are the permeability and permittivity of free space, respectively, and ω represents the angular frequency. Thus, the attenuation constant α_{10} and phase constant β_{10} of the TE_{10} mode of a waveguide are as follows.

$$\alpha_{10} = \frac{R_m}{ab\beta_{10}k_0Z_0}\left(2bk_{c,10}^2 + ak_0^2\right) \tag{2}$$

$$\beta_{10} = \sqrt{k_0^2 - k_{c,10}^2} \tag{3}$$

The wave number in free space k_0 and the cutoff wave number $k_{c,10}$ of the TE_{10} mode is as follows.

$$k_0 = \omega\sqrt{\mu_0\varepsilon_0} \tag{4}$$

$$k_{c,10} = \pi/a \tag{5}$$

Therefore, from the propagation constant γ, the scattering parameters of the offset line S_{line} with the length L, and the reflection coefficient Γ_{wall} of the waveguide shorting wall, the reflection coefficient of the offset waveguide Γ_{offset} can be obtained as follows.

$$\gamma = \alpha_{10} + j\beta_{10} \tag{6}$$

$$S_{line} = \begin{bmatrix} 0 & e^{-\gamma L} \\ e^{-\gamma L} & 0 \end{bmatrix} \tag{7}$$

$$\Gamma_{offset} = S_{line} \oplus \Gamma_{wall} \tag{8}$$

where $\oplus$ indicates the cascade of S-parameters. In this paper, we assumed $\sigma = 9 \times 10^6$ (S/m), $\Gamma_{wall} = -1$.

III. DESIGN OF OFFSET SHORT CALIBRATION KIT BASED ON UNCERTAINTY

A. UNCERTAINTY ESTIMATION FOR DUT

We proposed a method to design an offset short based on uncertainty analysis in [11]. In this section, we will briefly review it again and then analyze the optimization results.

We used the residual model for uncertainty analysis. Fig. 2 shows the VNA error term model and residual model, respectively. The VNA error model is widely used to calibrate the VNA's measurement. However, it has a disadvantage, since

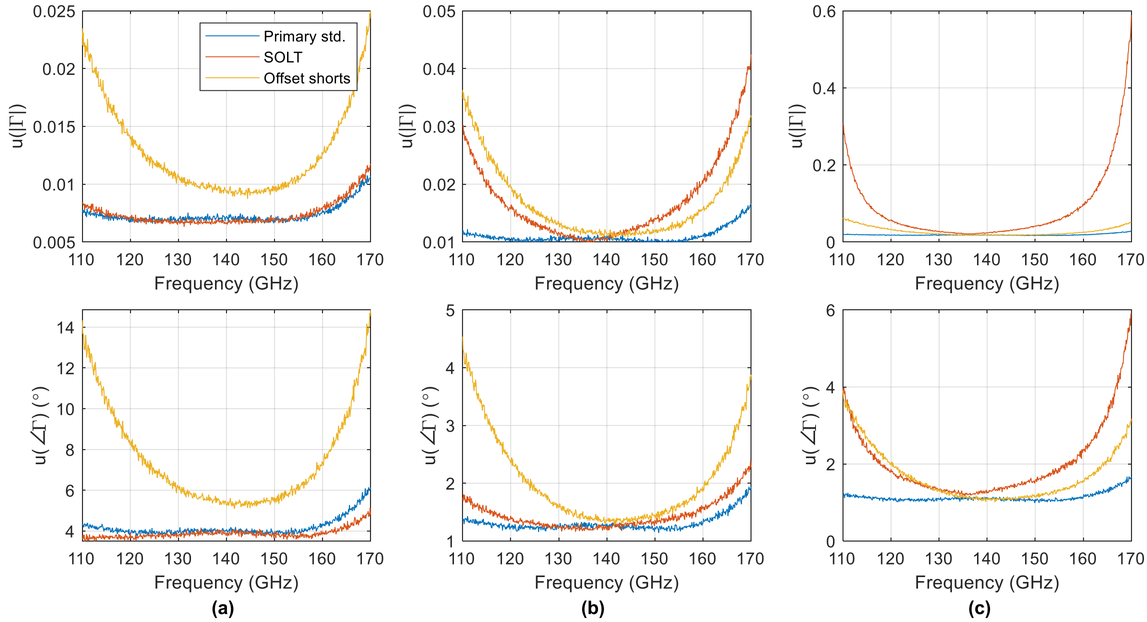

FIGURE 3. Comparison of the uncertainty for the optimized results where the reflection coefficient of DUT (a) |Γ| = 0.1, (b) |Γ| = 0.5, (c) |Γ| = 1.0. The blue, red, and yellow lines represent the uncertainty of DUT calibration using the primary standard, SOLT calibration kit, and designed offset short calibration kit, respectively.

the uncertainty analysis is complex due to the values of the error terms, and this requires uncertainty propagation from the calibration kit to the error model. On the other hand, the residual model assumes a calibrated VNA, simplifying uncertainty calculations but making it difficult to calculate the exact residual error.

Recently, a method to calculate the residual error with the same uncertainty results as the VNA error model was proposed [12], [13]. The VNA error terms (directivity e_{00}, source match e_{11}, and reflection tracking $e_{10}e_{01}$) can be obtained as follows;

$$\begin{bmatrix} e_{00} \\ e_{11} \\ \Delta e \end{bmatrix} = \begin{bmatrix} 1 & \Gamma^1_{\text{def}}\Gamma^1_{\text{M}} & -\Gamma^1_{\text{def}} \\ \vdots & \vdots & \vdots \\ 1 & \Gamma^N_{\text{def}}\Gamma^N_{\text{M}} & -\Gamma^N_{\text{def}} \end{bmatrix}^{-1} \begin{bmatrix} \Gamma^1_{\text{M}} \\ \vdots \\ \Gamma^N_{\text{M}} \end{bmatrix}, \tag{9}$$

where $e_{10}e_{01} = e_{00}e_{11} - \Delta e$. The subscript 'def' and 'M' refer to the definition and measurement values of the used standards, respectively. Thus, at least three standards are required to determine the VNA error terms. When the definitions of each standard are put in the position of the definition values (indicated by the subscript 'def'), and the multi-variable random numbers generated according to the uncertainty distribution (or covariance) of the standard are put on the position of the measured value (indicated by the subscript 'M'), e_{00}, e_{11}, and $e_{10}e_{01}$ have the mean values 0, 0, and 1. Now, their deviations can be assigned to residual errors δ, μ, and τ, respectively.

Next, we propagated the uncertainty of the primary standard to the residual error using the above approach. Then, the uncertainty of each offset short calibration kit is calculated based on Fig. 2(b) as follows.

$$\Gamma_{\text{offset,C}} = \frac{\Gamma_{\text{offset}} - \delta}{\Gamma_{\text{offset}}\mu - (\delta\mu - \tau)} \tag{10}$$

Due to the residual errors δ, μ, and τ, the Γ_{offset} of the offset short calibration kit is perturbed by $\Gamma_{\text{offset,C}}$, and this value can be assigned as the uncertainty of the offset short calibration kit. Afterwards, the uncertainty of the offset short calibration kit can be propagated again to the residual error using (9). Then, the uncertainty of the DUT with an arbitrary reflection coefficient can be calculated again using (10).

B. ANALYSIS OF THE OPTIMIZED RESULT

We optimized the offset short calibration kit's length to minimize the DUT's uncertainty using three offset short waveguides. The optimized result is shown in Fig. 3. We compared the uncertainties of our primary standard with the SOLT and designed the offset short calibration kits. The SOLT calibration kit assumed a perfectly matched load, a flush short, and an open consisting of a perfect short and 1/4 λ shim at the center frequency (f = 140 GHz). The uncertainty value changes depending on the phase of the DUT. Thus, we show in Fig. 3 the smallest uncertainty at each frequency that can be obtained by changing the phase of the DUT.

Naturally, the uncertainty of the primary standard is the smallest, regardless of the reflection coefficient of the DUT. When the reflection coefficient of the DUT is small (Γ_{DUT} = 0.1), it confirms that the uncertainty of the SOLT calibration kit is smaller than that of the offset short waveguide. This means that SOLT's calibration kit includes a load, so it can have a small uncertainty when the reflection coefficient of the DUT is small. When the reflection coefficient of the DUT

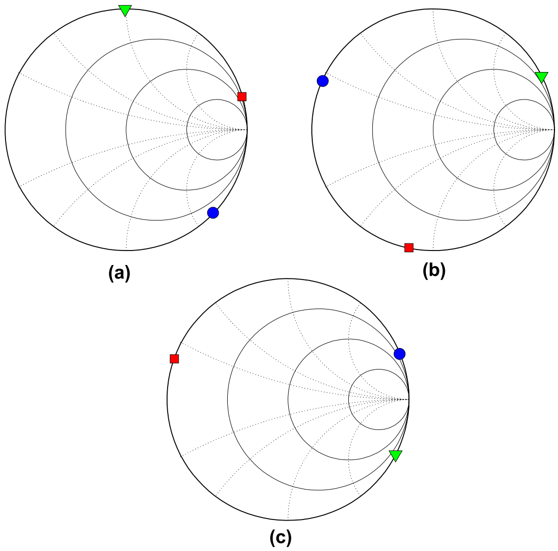

FIGURE 4. Reflection coefficient of the offset short calibration kits; (a) 110 GHz, (b) 140 GHz, (c) 170 GHz.

is large ($\Gamma_{DUT} = 1.0$), the uncertainty of the SOLT calibration kit increases significantly compared to the uncertainty of the offset short waveguide. In particular, the uncertainty increases significantly around 110 GHz and 170 GHz. This is because the phase of the 1/4 λ shim deviates from 90° in the corresponding frequency band, leaving it electrically out of the '‘open’' state.

Fig. 4 shows the reflection coefficients of the three optimized offset short waveguides on the Smith chart. When the position of each calibration kit is in the form of an equilateral triangle, the uncertainty is the lowest regardless of the reflection coefficient of the DUT. However, the uncertainty tends to gradually increase at 110 GHz and 170 GHz, where the position of each calibration kit deviates from the equilateral triangle. Therefore, to consistently have low uncertainty in all frequency bands it is best to maintain an equilateral triangle as much as possible for the DUT.

IV. DESIGN OF OFFSET SHORT CALIBRATION KIT BASED ON "PHASE DISTANCE"

In Section III, we found that keeping the offset short waveguides as equilateral as possible on the Smith chart can reduce uncertainty. In this section, 'phase distance' is newly introduced as a way of reducing the time required for optimization.

Fig. 5 represents the 'phase distance' concept. Phase distance is the distance between each offset short waveguide on the Smith chart. Here, d_1, d_2, and d_3 are each phase distances. The design time can be greatly reduced when designing an offset short waveguide using phase distance. For example, uncertainty-based optimization takes about a day when optimizing on the AMD Razen 5595WX CPU, whereas optimizing phase distance completes the optimization within a few minutes.

First, the standard deviation of d_i at each frequency was calculated, and then the largest value was assigned to the cost function as follows.

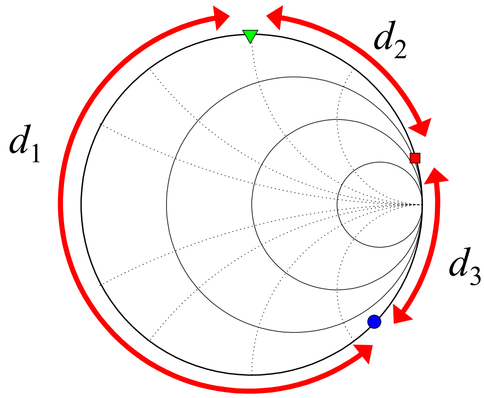

FIGURE 5. "Phase distance" between offset short waveguides.

$$Cost = \max\left(std\left(d_{\mathrm{i}}\left(f\right)\right)\right), \quad i = 1, 2, 3 \tag{11}$$

Accordingly, the optimization result will be designed to make the phase distance deviation the smallest in all frequency bands. Most importantly, if the deviation in phase distance is used as a cost function, it can be seen that the uncertainty decreases over a wide frequency band, as shown in Fig. 6. When compared to Fig. 3, it can be seen that the uncertainty in Fig. 6 increased at around 170 GHz. This is because the uncertainty of the primary standard is not the same in all frequency ranges, and the uncertainty increases toward 170 GHz. Thus, an appropriate weight function is required for the optimization cost function. So we introduce the weight function $w(f)$ that linearly increased from 1 (at 110 GHz) to 1.5 (at 170 GHz) as follows.

$$Cost = \max\left(std\left(w(f)d_{\mathrm{i}}\left(f\right)\right)\right), \quad i = 1, 2, \cdots, n \tag{12}$$

The optimization results are indicated by the purple line in Fig. 6, and it can be seen that including the weight function $w(f)$ can significantly reduce the uncertainty at 170 GHz.

Finally, a calibration kit was designed using multiple offset shorts waveguides. We found that the weight function $w(f)$ should vary depending on the number of offset shorts used. When designing four offset shorts, the weight function is linearly increased from 1 (at 110 GHz) to 3 (at 170 GHz) for four offset shorts and 1 (at 110 GHz) to 6 (at 170 GHz) for five offset shorts, respectively. It reveals that as the number of offset shorts used increases, the standard deviation in (12) decreases at 170 GHz, so the weight function value should be increased considering the uncertainty. Note that this increased rate varies depending on the uncertainty of the primary standard.

Fig. 7 shows the minimum uncertainty of the DUT when three, four, and five offset shorts are used, respectively. Interestingly, when using four offset shorts, the uncertainty is comparable to that of the primary standard across all bands. In particular, even when the reflection coefficient of the DUT is small, an uncertainty level can be obtained that is comparable to that when a "Load" standard is included. In addition, when the reflection coefficient is significant,

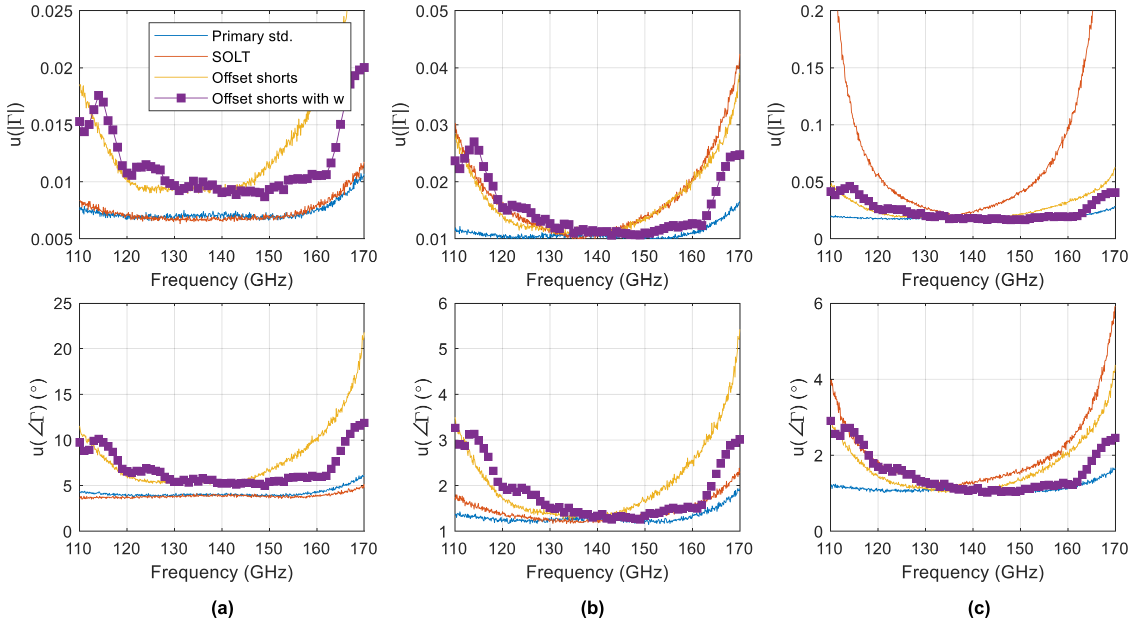

FIGURE 6. Optimized results using cost function in (11) and (12) where the reflection coefficient of DUT (a) $|\Gamma| = 0.1$, (b) $|\Gamma| = 0.5$, (c) $|\Gamma| = 1.0$. The blue, red, yellow and purple (with square marks) lines represent the uncertainty of DUT calibration using the primary standard, SOLT calibration kit, three offset short calibration kit w/ and w/o weighting, respectively.

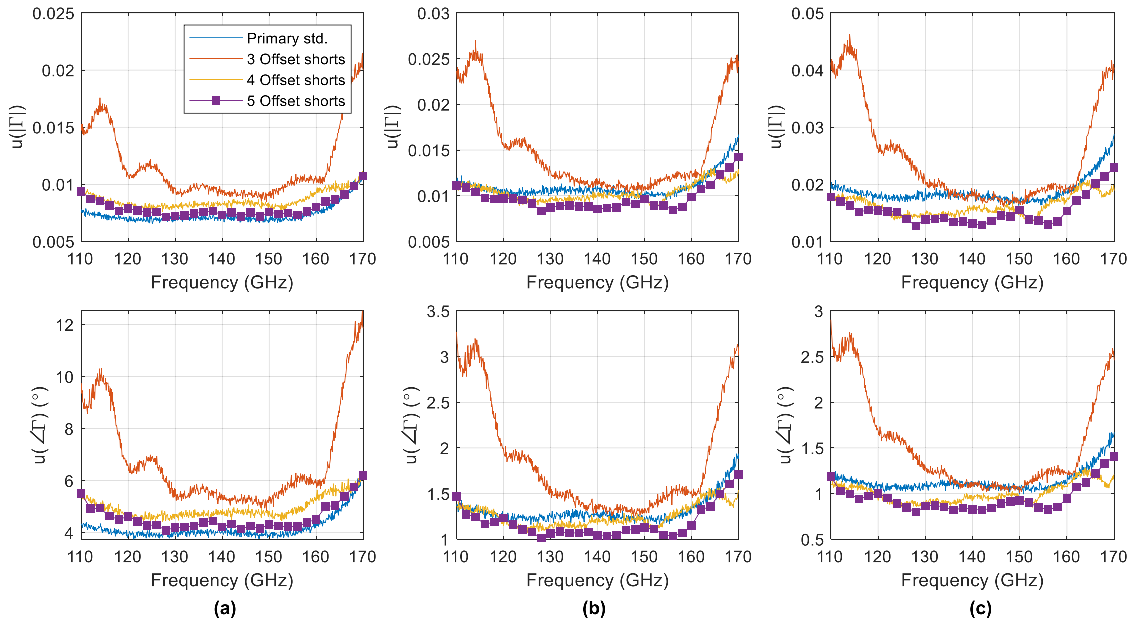

FIGURE 7. Optimized results using cost function in (12) with multiple offset shorts where the reflection coefficient of DUT (a) $|\Gamma| = 0.1$, (b) $|\Gamma| = 0.5$, (c) $|\Gamma| = 1.0$. The blue, red, yellow and purple (with square marks) lines represent the uncertainty of DUT calibration using the primary standard, three, four, and five offset short calibration kits, respectively.

unlike Fig. 6, it can be seen that the phase uncertainty is also greatly improved. However, when using five offset shorts, the uncertainty is not significantly improved compared to the case of four offset shorts. This is because even if only four offset shorts are used, a triangle shape is formed on the Smith chart in all bands. In other words, in the case of the D-band, a sufficiently low uncertainty can be achieved with only four offset shorts. However, there may need to be more offset shorts to maintain a triangle shape when we design them on other frequency bands.

V. REPEATABILITY OF THE TEST PRODUCT

Lastly, the waveguide calibration kit was manufactured according to the previously calculated offset length, and the performance was measured. The repeatability in measuring and the reproducibility in producing the fabricated waveguide were also examined. Fig. 8 shows the produced offset short waveguide calibration kit. The waveguide was made of two split blocks. The waveguide was made of copper, and the surface was plated with gold.

FIGURE 8. Example of fabricated waveguide offset short calibration kit.

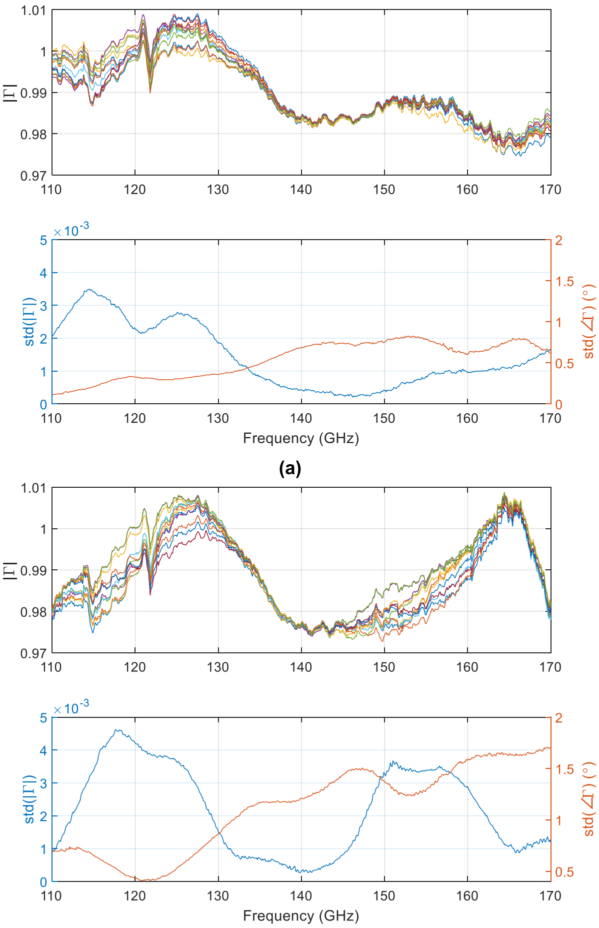

FIGURE 9. Repeatability measurement of the manufactured calibration kit (a) when repeatability is good, (b) when repeatability is bad.

Fig. 9 shows the reflection coefficient measurement of the manufactured offset short waveguide calibration kit. The reflection coefficient value changes depending on the frequency because the inside of the waveguide was not processed into an accurately square shape. However, the waveguide reflection coefficient was manufactured to be close to 1, and in particular, the phase show results that match the designed phase value within the uncertainty.

Next, two sets were produced to examine the reproducibility of the waveguide manufacturing process, and measurements were performed three times in both up and down directions to check measurement repeatability. Fig. 9(a) and Fig. 9(b) show results with good and bad production reproducibility and measurement repeatability, respectively. In both results, the magnitude repeatability is about 0.004, indicating a tiny variation. Regarding phase, they all showed good characteristics, with a standard deviation of about 0.8° to 1.6°. These results confirm that the manufactured waveguide calibration kit can be excellent when used as a transfer impedance standard.

VI. CONCLUSION

In this paper, we proposed a method to design a waveguide offset short as a transfer standard that can be used for the routine calibration of established waveguide impedance standards. The proposed method enables the design of an offset short waveguide calibration kit so that a DUT with arbitrary input impedance has the smallest measurement uncertainty. When using three waveguide offset shorts, it had a small uncertainty comparable to that of the SOLT calibration kit. Additionally, when using four waveguide offset shorts, the uncertainty was much smaller than that of the SOLT calibration kit and exhibited an uncertainty close to the primary standard. Lastly, the manufacturing repeatability and measurement repeatability were evaluated, and it was confirmed that the manufactured waveguide offset short calibration kit could be effectively used as a transfer standard.

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