Experimental Verification of Excavated Structure on Multi-Layered Substrates for Millimeter-Wave Signal Vertical Transition Using Copper Balls

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ABSTRACT This paper presents a vertical transition of millimeter-wave signal for interconnection between multi-layered substrates, which utilizes copper balls for vertical interconnection, as both for electrical connection and physical support. In particular, the copper balls were used to configure a quasi-coaxial transmission line at the vertical interconnection. The key idea was to create an excavated structure at the location of the copper balls to fix it, given that the copper balls slightly fluctuate during reflow soldering when simply placed on a flat surface. Such activity of the copper balls defines large variation in transmission characteristics at millimeter-wave band that produce low yield rate. Practically, with the proposed method of an excavated structure, the location error of the copper balls can be minimized, leading to high reproducibility in determining the copper balls location, and small variation of the transmission characteristics. To verify the method’s effectiveness, a prototype having three vertically stacked multi-layered substrates with the excavated structure was fabricated. The excavation had a depth of 90 µm and diameter of 0.45 mm. The copper balls used had a 0.3-mm diameter. Five samples were fabricated and then evaluated by X-ray images and S-parameter measurements. Based on the results, the reflection characteristics of the measurement were less than −10 dB from dc to 97 GHz in the best-case scenario, whereas the variation in the S-parameters was comparatively small up to 70 GHz. Moreover, the X-ray images showed relatively small copper balls location error. These results indicate that the proposed excavated structure is effective for millimeter-wave vertical interconnections using copper balls, in small wireless terminal applications.

INDEX TERMS Transmission line, copper ball, vertical transition, millimeter-wave measurement, millimeter-wave transmission line, surface roughness, electromagnetic field simulation, dielectric substrate, multi-layered substrate.

I. INTRODUCTION

In terms of allocated bandwidth, fifth generation (5G) cellular networks, now ready for realization [1], are a step ahead of 4G networks. The wider bandwidth in a 5G network is utilized in the millimeter-wave (MMW) band range, where high-level software and hardware technology is indispensable for the network’s realization. Conventionally, a 28-GHz-band from the MMW band is suitably used for the 5G system, but some studies have essentially proposed the applicability of the 60-GHz-band, more particularly, with 60-GHz-band radio-frequency integrated circuits (RFICs) [2]–[5], for future mobile communication systems in 6G or 7G. For example, a measurement of the 60-GHz propagation characteristics inside bus was demonstrated [6]. Furthermore, the applicability of the 60-GHz-band in antennas, filters, and other systems has been widely proposed.

Packaging technique is also important for MMW applications because the distributed element components, i.e., transmission lines and antennas, become physically small in the shorter wavelength, as compared to those in conventional microwave. Hence, it is desirable to add high-density packaging for installation of new MMW communication hardware in wireless terminals, such as smartphone, tablets,
and wearable devices. In essence, high-density packaging can be realized with the key technologies of vertical transitions for MMW signal transmission, in combination with a lateral transition line [7], [8]. Vertical transitions can be categorized into four types: (a) an inner substrate type, (b) an outer-substrate type for integrated circuit (IC) packaging, i.e., ball grid array (BGA), (c) an outer-substrate type excluding IC packaging, and (d) a non-substrate type. The inner substrate type vertical transition has been proposed in a number of studies, which include the vertical via transition inside a low-temperature co-fired ceramic (LTCC) substrate for V-band [9]–[11]; vertical via transitions inside a liquid crystal polymer (LCP) substrate [12], a Rogers substrate [13], and anodized aluminum substrates [14]; vertical transmission line in a Si substrate known as through-silicon via (TSV) [15]–[17]; microstrip–strip vertical transition [18]–[20]; microstrip–microstrip transition [21] and; conductor-backed coplanar waveguide (CPW) and parallel-strip transition [22]. On the contrary, the outer-substrate type vertical interconnection is widely used in IC chip packaging. For instance, the BGA, its most popular form, has been used all over the world for electronic equipment manufacture. In case of technical research, there is the TSV–BGA vertical transition at MMW band [23], the waveguide-to-planar transmission line transition, and the typical microstrip-to-waveguide transition [24]–[27] and CPW-to-waveguide transition [28], the latter of which is a non-substrate type. More essentially, the coaxial-waveguide transition [29] is one of the representative structures of a non-substrate type vertical transition.

From a fabrication point-of-view, additive manufacturing (AM) [30] or 3D printing technology [31] is employed in vertical transitions. In particular, AM is used for manufacture of vertical antenna feeders [32]–[35] and for packaging of IC chips [36]. Moreover, AM is applicable for MMW components as shown in its display of MMW characteristics [30], [33]–[36].

Vertical transition applications were also exemplified in a wideband balun [37], in the study of the parasitic element of interchip vertical interconnection [38], in a failure analysis of TSV in 3D IC [39], and in a proposed bond via array method using wire bonding [40].

Practical-wise, vertical transition for interconnection between substrates at MMW band is indispensable for realization of the high-density packaging. Here, several substrates are stacked vertically in the high-density package for a MMW transceiver, and the ICs and other chip components are mounted onto the substrates. Moreover, as the ICs and other components should be placed on the substrate, the length of the vertical transition should exceed the IC thickness. It affects the MMW signal transmission characteristics, and thus, hinders greatly the realization of MMW vertical transition technology.

In terms of materials, a copper pillar [41] and a copper ball [42]–[44] are ideal candidates for the vertical transition. Reference [41] analyzed the plastic deformation of a copper pillar in flip-chip package using finite element method, and demonstrated its more stable characteristic impedance (compared to the copper ball) due to its cylindrical geometry. Nevertheless, it was easier to handle the copper ball (than the copper pillar) because the direction or angle was no longer required for such. Reference [45] utilized the interconnection with copper balls as a feed line for a dipole array antenna at 60 GHz. As with a copper balls’ interconnection [44], the quasi-coaxial transmission line [46] was designed, whereas an oval shape ground via was designed for the LTCC substrate [47]. In [48], the via resonance of the quasi-coaxial line in a multi-layered substrate was analyzed up to 50 GHz, whereas a ground conductor placement type was discussed and measured in [49]. Here, the quasi-coaxial transmission line structure was easily realized when ground copper balls consisting of concentric circles were mounted. They also exhibited compatibility with the existing facilities. Thus, the conventional manufacturing machine of the BGA can be used for copper balls mounting. In contrast, copper balls are known for low packaging yield rate and large variations of MMW band transmission characteristics, the first being mainly caused by location error of the copper balls during mounting and warping of the multi-layered substrate when being heated. In the worst case, a copper ball of center conductor connects to ground (short) or is not soldered well (open). In this sense, the location error is a critical element in determining the characteristics of the MMW band, because the characteristic impedance of the quasi-coaxial transmission line using the copper balls may vary with changes in the distance between the center conductor ball and the ground balls. Actually, previous works utilizing copper balls for 3-D packaging [42], [43] reported MMW transmission characteristics [44]. Here, the transmission line was used as a feed line of a 60-GHz-band array antenna [45], and the copper balls were simply mounted onto the flat surface in a conventional structure [44]. Although a donut shape solder resist was used as a self-alignment effect in reflow process was initially expected, the fabrication results showed inevitable fluctuations in the transmission characteristics.

This study highlights a new MMW vertical interconnection method for vertically stacked multi-layered substrate interconnection, which makes use of copper balls to facilitate a quasi-coaxial transmission line as the vertical interconnection. To improve the fabrication yield rate, an excavated structure was created at the location of the copper balls, where essentially the location error and the variation in transmission characteristics can be minimized when the copper balls fall into the excavation. Thus, this method is quite unique from those applied in earlier studies [42]–[44] mainly because of the excavated structure at the copper balls position, which produces good yield rate in reflow soldering and low variation in MMW transmission characteristics.

The remainder of the paper is organized as follows. A structural design of the prototype is presented in Section II, mainly using 3-D electromagnetic field simulation. The structure is then fabricated and X-ray-evaluated in Section III.
Measurement results of the S-parameters as high as 110 GHz are provided in Section IV. In the final section, Section V, the reasons for discrepancies between the results of the simulation and the measurement are laid out and discussed. The study’s main conclusions are drawn in Section VI.

II. STRUCTURE DESIGN

The vertical interconnection between substrates utilized as a MMW signal transmission line [44] is a conventional structure that uses copper balls for the interconnection. The location of the copper balls is unstable due to the flat substrate surface, thus, they can easily fluctuate or move when reflow soldering. Such fluctuation causes variation in transmission characteristics resulting to a worse yield rate. Additionally, there is low tolerance on the substrate flatness as the multi-layered substrate often gets warped by heat during reflow soldering. The effect of this phenomenon is enlarged with a larger substrate. Consequently, the substrate warp around the circumference area of the substrate often hinders the physical and electrical interconnection using copper balls, resulting in complete failure.

To overcome these two issues, a structure was excavated at the copper balls mounting position. Fig. 1 shows a cross-sectional image of the copper ball vertical MMW transmission line where two multi-layered substrates are stacked. Here, the copper balls act as a vertical signal transmission line as well as supports the substrate physically. The MMW signal then passes through the upper layer of the lower substrate to the lower layer of the upper substrate. Using a conventional method, the copper balls were mounted on a normal flat conductor of the substrate, as shown in Fig. 1(a). In Fig. 1(b), the excavated structure was introduced in both the upper and lower substrate to ensure that the copper balls can be dropped down into the excavation. With this configuration, the location error of the copper balls can be minimized during reflow soldering as the movement of the copper balls were restricted by the excavation wall. Moreover, solder paste quantity introduced can be increased, which ensures vertical interconnection even when the distance between the substrates is increased due to warping of the substrates. As shown in Fig. 1(b), the vertical distance between the two substrates could go up to 150 µm, under assumption of a 100 µm-thick IC chip. Note that the excavation depth and copper balls diameter should be carefully designed with this restriction.

The difference between the proposed copper ball method with the excavated structure and the existing solder-ball technology of BGA packaging can be framed under the possibility of multi-substrate stacking. For instance, the conventional BGA often used for motherboard design and mobile phones manufacture, includes only one interconnection between the package and the substrate. On the contrary, the proposed copper balls interconnection is capable of many substrates stacking. This packaging style is usable and effective for future MMW transceiver high-density packaging. Thus, from the viewpoint of multi-substrate stacking capability, a vertical signal transition design using three substrates was introduced in this study, with relevant details in the succeeding section. Another feature of the copper balls interconnection is its capability for ICs or other chip components placement between substrates (Fig. 1). Here, the diameter of the copper balls was determined in consideration of the ICs thickness, as shown in Fig. 1(b). Consequently, the self-alignment effect in reflow soldering will no longer be effective for copper balls alignment with stacking of the several substrates because the weight, especially of the downward substrate, the copper balls should be fixed by the weight. The self-alignment is effective only for when one or two substrates stacking at the reflow soldering process depending on the total weight on the copper balls. More essentially, the location of copper balls can be determined by the excavation if using the proposed excavated structure, and the location will not change while reflow soldering. Hence, there is no worry as to whether or not the self-alignment will be effective, which makes the proposed excavation method ideal for multi-substrate stacking packaging.

The block diagrams of the vertical interconnection using copper balls are displayed in Fig. 2. Here, the quasi-coaxial line for the vertical interconnection was configured using copper balls, while a grounded coplanar waveguide (GCPW) was used for a transmission line on the substrate. In the conventional design [44], a transition between the quasi-coaxial line and the GCPW was used, as shown in Fig. 2(a); however, in the proposed method, a stripline was added for connection to the excavated structure. Such addition is not preferential.
to avoid unnecessary discontinuities; however, the excavated structure effectively improves the manufacturing yield rate.

The subsequent texts provide a brief introduction on how to determine the location of ground copper balls (considering they were utilized for the creation of the quasi-coaxial line). Fig. 3 displays a theoretical image of a coaxial line having characteristic impedance $Z_0$ given by [50]

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}} \frac{1}{2\pi} \ln \frac{B}{A}, \tag{1}$$

where $\varepsilon = \varepsilon_\text{o}\varepsilon_r$, $\mu = \mu_\text{o}\mu_r$. In this case, $\varepsilon_r = \mu_r = 1$ as the quasi-coaxial line using copper balls is located in the air. Thus, a reference plane can be defined to calculate the characteristic impedance as a cut plane at the center of the copper sphere, as shown in Fig. 4. The value of $A$ can be determined initially. Indeed, $2A = 300(\mu\text{m})$ because the center conductor diameter of the copper ball was fixed to $300\mu\text{m}$, as shown in Fig 1(a). Next, $B$ can be calculated under the condition, $Z_0 = 50(\text{ohm})$. Moreover, $2B = 700(\mu\text{m})$ as the resulting value was rounded for ease when input in CAD design. Finally, $Z_0 = 50.8(\text{ohm})$ when $2A = 300(\mu\text{m})$ and $2B = 700(\mu\text{m})$.

$$f_c = \frac{1}{\pi \sqrt{\varepsilon \mu (A + B)}. \tag{2}$$

Applying $2A = 300(\mu\text{m})$ and $2B = 700(\mu\text{m})$ yields 191 GHz, which is sufficient for MMW band module application, especially, for 60-GHz-band modules.

An illustration of the copper balls location using the theoretically calculated result is shown in Fig. 4. Note that the theoretical design gives just a distance between the center conductor and the outer conductor. The cylindrical surface of the outer conductor is generally a theoretical assumption; however, in this study, the copper balls were used instead of the cylindrically shaped outer conductor. To proceed, a vertical transmission line was defined as a quasi-coaxial transmission line using the copper balls. A total of six ground copper balls were used herein [44].

The proposed excavated structure was tested using a prototype designed with a 3-D electromagnetic field simulator, CST Studio Suite. Fig. 5 shows the prototype simulation model, which consists of three multi-layered substrates, namely, lower, middle, and upper substrates. The S-parameters were used for evaluation of the MMW signal transmission characteristics. Ports 1 and 2 were located in the lower and upper substrates, respectively, and were connected by a GCPW-type transmission line. Here, the MMW signal was allowed to pass through the copper balls vertical interconnection twice to show multi-substrate stacking capability.

Meanwhile, GCPW and quasi-coaxial transmission lines are normally used in the conventional copper balls interconnection structure. However, in the proposed structure,
a stripline was added mainly because the excavated structure could be realized by utilizing the inner layer conductor of the multi-layered substrate. Thus, stripline was the preferable transmission line structure as the contact layer with the copper balls was the inner layer. A cross-sectional image of the prototype is shown in Fig. 6. Apparently, a stripline was added and used in the lower substrate, along with a conventional GCPW. Moreover, three transition types were considered in the prototype: GCPW–stripline transition, stripline–quasi-coaxial transition, and quasi-coaxial–GCPW transition. Fig. 6(b) shows the enlarged stripline–quasi-coaxial and quasi-coaxial–GCPW transitions, where the multi-layered substrate could be seen with six conductor layers while the ground part was electrically connected using many vias. A summary of the parameter values can be found in Table 1.

![Cross-sectional image of the prototype](image1)

**FIGURE 6.** Cross-sectional image of the prototype: (a) entire view and (b) enlargement of the stripline–quasi-coaxial and quasi-coaxial–GCPW transitions.

**TABLE 1.** Parameter list of the proposed structure (unit: millimeter).

| a  | b  | c  | d  | e  | f  | g  | h  | i  |
|----|----|----|----|----|----|----|----|----|
| 8.40 | 8.40 | 5.40 | 5.90 | 0.15 | 0.40 | 0.30 | 0.09 | 0.45 |

Fig. 7 displays front and back views for each substrate. At the vertical interconnection, the quasi-coaxial transmission line was constructed for vertical transmission of the MMW signal. Inside the substrate, it was easy to fabricate a coaxial transmission line structure using via holes. By contrast, it was difficult fabricating the same on the outside, but the copper balls could be utilized to create a quasi-coaxial transmission line [44]. One copper ball was employed for the center conductor, and 12 for the ground to compose the quasi-coaxial transmission line. Nevertheless, several ground copper balls may be eliminated to avoid structural interference. Additionally, around the edge of the middle and upper substrates, additional copper balls, having assumed negligible

![Front and back views of each substrate](image2)

**FIGURE 7.** Front (left) and back (right) views of the each substrate: (a) upper substrate, (b) middle substrate, and (c) lower substrate.
effects on the MMW signal transmission characteristics, were placed to support themselves in a stable manner. Furthermore, the proposed excavated structure was fabricated for each copper ball mounting position.

Fig. 8 shows the simulation results for the S-parameters. $|S_{11}|$ achieved a magnitude lower than $-10$ dB and insertion loss of less than 1.3 dB, for frequencies reaching 91.0 GHz. This implies that the designed structure is applicable as a vertical transmission line between substrates for up to 91.0 GHz.

Likewise, the simulation results of the electric field distribution are displayed in Fig. 9. As depicted in Figs. 9(a) and (b), there was a strong field distribution around the signal line at 5 and 60 GHz, respectively, which could be described as smooth at the three transitions in both frequencies. Nevertheless, compared to that in the 60-GHz frequency, there was no remarkable difference observed in the

III. FABRICATION AND STRUCTURE EVALUATION BY X-RAY

Fig. 10 displays images of the prototype design patterned from the fabricated multi-layered substrate with excavated structure. The prototype was created from three pieces of substrate using 300-µm-diameter copper balls. As shown in Fig. 10(a), the excavation was formed properly as designed using laser via process.

Accordingly, the copper balls were mounted to the excavation, and then fixed electrically and mechanically by solder paste, as shown in Fig. 10(b). The finished product after entire reflow soldering is shown in Fig. 10(c). Five samples were fabricated to evaluate the effect of the excavation to the S-parameters. Likewise, five samples of conventional flat substrate without excavation was fabricated and packaged.

Fig. 11 shows X-ray images of the fabricated prototype from front face. In particular, Fig. 11(a) is a conventional
flat surface, whereas Fig. 11(b) is the prototype surface. Two images were shown for each sample, in which the black portion indicates the shadow of the copper ball and the white part with donut shape is the dielectric portion of the multi-layered substrate, having no metallic materials. Comparing both figures, the black and white areas were clear in Fig. 11(b) than in Fig. 11(a), mainly because of the relatively small vertical location error as a result of the proposed excavated structure. Additionally, the copper balls were stably located repeatedly at the designated place, thus, small location errors were found. Hence, these X-ray images confirm the effectiveness of the proposed excavated structure.

IV. MEASUREMENT OF S-PARAMETERS
Figs. 12 and 13 give the measurement results for the S-parameters with and without the excavated structure. The reflection characteristics of the measurement were lower than $-10$ dB from dc to 97 GHz in the best-case scenario. Moreover, the variation among the five samples was relatively large in the conventional (without the excavated structure) samples compared to the proposed (with the excavated structure) samples. Furthermore, the reflection characteristics shown in Fig. 13(a) worsened around the low-frequency region as compared to those in Fig. 12(a), which could be attributed to the excavation, the additional stripline, and the additional reflection at the discontinuity. Another reason for the degradation was insufficient optimization of the structure due to design time limitation. As future work, further optimization will be carried out to effectively improve the S-parameter characteristics. Furthermore, the transmission characteristics shown in Fig. 13(b) were similar with those in Fig. 12(b) for up to 70 GHz, which indicate that the proposed excavated structure and additional stripline transition have little influence on the S-parameters.

As described earlier, the proposed excavated structure effectively improves the packaging yield rate. Note that the variation of S-parameter characteristics in Fig. 12 was relatively larger than in Fig. 13. More specifically, Sample 3 in Fig. 12 exhibited different characteristics especially within 60–90 GHz. Thus, using Sample 3 in the 60-GHz-band packaging would lead to crucial results, such as a bad yield rate. However, such defect was not observed in the S-parameter characteristics in Fig. 13, which indicates the proposed excavated structure’s effectiveness in improving the yield rate. Although the fabricated prototype uses only three substrates, the proposed excavated structure can be assumed to be strongly effective with some applications, including a vertical transmission line for a large-scale array antenna with over 10 stacked substrate structures, for yield rate improvement. However, in this case, the trade-off between the improvement of the yield rate and degradation of the S-parameter characteristics should be deeply considered. Practically, the proposed structure is effective for improving the yield rate with a little sacrifice on the part of the S-parameter characteristics because of the added stripline.
V. CONSIDERATION OF ERROR BETWEEN SIMULATION AND MEASUREMENT

Fig. 14 displays a comparison of the results between the measured (blue dashed lines) and simulated (red solid lines) S-parameters. Note the relatively large discrepancies in the two results. The discrepancies can be explained in several, certain reasons; however, the focus in this study was the etching error and surface roughness of the copper foil. Relatively, the etching error of the thin line was a critical reason for the width error. In the design phase, the center conductor of the stripline has a fine line with a 50 \( \mu \)m width. The center conductor and the ground also had a 50 \( \mu \)m gap in between. Nevertheless, the fabricated substrate had a thinner line than the designed structure. In consideration of this gap, a 15-\( \mu \)m etching error was adopted for the L2 layer stripline. Therefore, the line width and the gap of the stripline were 20 and 80 \( \mu \)m, respectively. In addition, surface roughness of copper foil was a big issue in the MMW circuit substrate, because of the fact that insertion loss becomes especially larger with rougher surface. Because surface roughness was not considered in the initial design, the surface was thus assumed to be completely flat. In consideration, a 1-\( \mu \)m surface roughness was taken into account in this study.

Accordingly, these three conditions were considered in the simulation results of S-parameters, as reflected in Fig. 14. The conditions of only etching error, only surface roughness, and a combination of both are indicated in orange-dotted, green-dashed, and two-black-dotted-chain lines, respectively. Compared to the original simulation, considering the etching error affected the \( |S_{11}| \) characteristics. Apparently, \( |S_{21}| \) characteristics were especially degraded around the frequency of a large \( |S_{11}| \). Moreover, as to the effect of surface roughness in the original simulation (red solid line) and with consideration of surface roughness (green dashed line), the effect on \( |S_{11}| \) was relatively small, but with \( |S_{21}| \) being degraded, which can be explained simply using the general theory [51]–[53]. Finally, considering a combination of both etching error and surface roughness (two-black-dotted-chain...
TABLE 2. Comparisons of some published transitions.

| Frequency bandwidth (GHz) | Topology | Center conductor diameter (µm) | Number of substrate stack | Fabrication feature and complexity |
|---------------------------|----------|-------------------------------|---------------------------|-----------------------------------|
| This work 0–70 (S11 | Vertical transition between substrates 300 | 3 | Use of three substrates with excavated structure and Cu balls |
| [7] 0–50 (S11 | Vertical transition inner substrate (coaxial) 150 | 1 | Use of LTCC process |
| [9] 0–50 (S11 | Vertical transition inner substrate (GCPW-GCPW) 150 | 1 | Use of LTCC process |
| [12] 0–65 (S11 | Vertical transition inner substrate 280 | 1 | Liquid crystal polymer substrate |
| [23] 10–40 (S11 | Vertical transition between substrate and chip 100 | 2 | GaAs chip and Si carrier |
| [28] 110–170 (S11 | Waveguide-to-coplanar - | - | Mechanical milling requirement |
| [29] 13–40 (S11 | Coaxial-to-waveguide - | - | Mechanical milling requirement |
| [36] 0–67 (S11 | Vertical transition between substrate and chip 75 | 2 | Additive manufacturing |

In turn, such reliability indicates the good stability of electrical connection and low location error of the copper balls. Moreover, the method is effective for improvement of yield rate and achievement of low-fluctuation and stable MMW transmission characteristics among many samples. Furthermore, the proposed vertical interconnection technique is a feasible, low-cost technique, and promotes reliable MMW wireless communication modules for small wireless terminal applications.

For future work, this study is geared into looking at the other reasons for the discrepancy between the simulated and measured results, which may include the thickness error of each dielectric layer in the multi-layered substrate, anisotropy of dielectric material, effect of nickel–gold plating, and further etching error in each layer.

VII. ACKNOWLEDGMENT

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