INVITED PAPER Special Section on Microwave and Millimeter-Wave Technology

Low Cost, High Performance of Coplanar Waveguide Fabricated by Screen Printing Technology

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SUMMARY This paper presents an innovative fabrication process for a planar circuits at millimeter-wave frequency. Screen printing technology provides low cost and high performance coplanar waveguides (CPW) lines in planar devices operated at millimeter-wave frequency up to 110 GHz. Printed transmission lines provide low insertion losses of 0.30 dB/mm at 110 GHz and small return loss like as impedance standard lines. In the paper, Multiline Thru-Reflect-Line (TRL) calibration was also demonstrated by using the impedance standard substrates (ISS) fabricated by screen printing. Regarding calibration capability validation, verification devices were measured and compare the results to the result obtained by the TRL calibration using commercial ISS. The comparison results obtained by calibration of screen printing ISS are almost the same as results measured based on conventional ISS technology.

key words: screen printing technology, coplanar waveguide, scattering parameters, on-wafer measurements, impedance standard substrate (ISS), verification

1. Introduction

In recent years, the millimeter-wave frequency electronic device technology is strongly demanded from the telecommunication industry. For installing device technology to mobile telecommunication equipment, applications require not only performance but also light weight with ultra-slim. In the consumer production, cost efficiency and high throughput capability are key factors to familiarize the product to the public. Currently set of conductor deposition, photolithography patterning and etching processes are commonly used in the traditional passive device fabrication and device packaging. The fabrication process is, thus, basically complex and expensive due to spending much process time, and produces waste fluid by the end of fabrication process. Recent interest in the electronic device applications is driven by not only the low cost and environmental friendly, furthermore substrate material flexibility is demanded[1]–[5] from the mobile telecommunication and healthcare sectors connecting to the internet of things (IoT).

Some laboratories have proposed printing technology as solutions for microwave and millimeter-wave circuit fabrication [1]–[5]. However, almost the research employs an inkjet printing technologies in order to getting a fine dimensional resolutions suitable for millimeter-wave circuit design, but it stands up poorly to high-volume productions due to low throughput fabrication process in general. Screen printing technologies have to be a solution of circuit fabrication process for high-volume productions. The difficulties of adopting the screen printing process to microwave and millimeter-wave circuits are control and adjust of fabrication conditions, i.e. mesh count (resolution), ink paste characteristics and baking temperature, etc..

The paper proposes new fabrication process, screen printing technology, for an Impedance Standard Substrate (ISS) for on-wafer measurements at microwave and millimeter-wave frequencies. Our screen printing technology has provided coplanar waveguides (CPW) lines with low transmission loss, 0.30 dB/mm at 110 GHz, and high precision contact repeatability at millimeter-wave frequency up to 110 GHz [6]. Then, multiline Thru-Reflect-Line (TRL) calibration was performed by using ISSs fabricated by screen printing technology. To verify calibration standard capability, verification devices, i.e. “Keysight Verification Substrate (KVS)” were measured. In the paper, eight types of verification device were measured in order to comparison between both ISSs for certifying a calibration and measurement capability using screen printing technology to measurement standards.

2. Performance of Printed CPW Line

2.1 CPW Design and Fabrication Process

CPW lines with ground plane was designed on a 0.254 mm thick alumina substrate (Fig. 1). A fabrication process providing the highest precision dimensions have to be used for ISS realization, and thus the printing technology should provide high dimensional precision, durability, reproducibility and reliability for the ISS fabrication. This means that the demonstration of ISS fabrication and measurements represents the capability of screen printing technology for pre-

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Fig. 1 Designed structure of CPW adopted in this study
cision millimeter-wave circuit fabrications. On the Almina substrate ($\varepsilon_r = 9.8$) in this paper, short circuits, open circuits, and transmission lines with length, $L$, 220 $\mu$m, 450 $\mu$m, 900 $\mu$m, 1800 $\mu$m, 3500 $\mu$m, and 5350 $\mu$m, were designed and fabricated (Table 1).

In the screen printing process, we used Screen Hand Printer. Specification of screen mask with size of 320 mm × 320 mm used in the process are CAL-640 of mesh count providing 39% of open area. Line conductor was made by silver paste ink with contains 83% silver and provides 310 Pa.s viscosity at 25°C. The CPW lines were printed on an aluminia substrate by screen hand printer and formed by baking at 600°C for one hour in nitrogen gas flow due to preventing the oxidation of silver ink as conductors and lower resistiv-

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design value</th>
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</thead>
<tbody>
<tr>
<td>Signal line width</td>
<td>50 $\mu$m</td>
</tr>
<tr>
<td>Ground line width</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Gap width between lines</td>
<td>25 $\mu$m</td>
</tr>
<tr>
<td>Conductor thickness</td>
<td>1.0 $\mu$m</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>125 $\mu$m</td>
</tr>
<tr>
<td>Dielectric constant of sub.</td>
<td>9.8</td>
</tr>
<tr>
<td>Line length</td>
<td>220 $\mu$m, 450 $\mu$m, 900 $\mu$m,</td>
</tr>
<tr>
<td></td>
<td>1800 $\mu$m, 3500 $\mu$m, 5250 $\mu$m</td>
</tr>
</tbody>
</table>

![Table 1](image)

![Fig. 2](image) Cross sectional views of CPW line formed by screen printing technology together with CPW lines on a commercial ISS. Drawing of printed CPW has 2 $\mu$m offset in Y-axis.

![Fig. 3](image) (a) Scattering parameter ($S_{21}$) measurement of 5250 $\mu$m long transmission lines and (b) photograph of ISS formed by screen printing technology
2.2 Electrical Characteristics

A Keysight Technologies (formerly Agilent Technologies) N5250A constructed by E8361A vector network analyzer and 1.0 mm frequency extension modules with mm-Wave controller were used to measure the S-parameter of CPW lines in the range from 10 MHz to 110 GHz. 1.0 mm coaxial probes, Cascade MicroTech Infinity SP-I110-A-GSG-06 with 150 μm pitch, were used (Fig. 2). In the measurement, first, multiline-TRL calibration was performed on commercial ISS (Cascade Microtech 101-190C ISS) at the probe tips. In this calibration, “Thru” line, \( L = 220 \, \mu m \), was used as “flush thru”, then, uncorrected factor of insertion loss of “thru” line remained as “offset insertion loss” in VNA measurement results after the on-wafer calibration. S-parameter (\( S_{21} \)) measurement results of printed CPW lines are shown in Figs. 4 together with commercial CPW lines. There are averaged S-parameters for 900 μm, 1800 μm, 3500 μm and 5250 μm-long CPW lines formed at baking temperature of 600°C. Insertion loss, shown in Fig. 4 (a), is almost the same...
value of CPW line on commercial ISS, 1.0 dB at 60 GHz, however, insertion loss is getting better than commercial CPW line for longer line, $L = 5250 \mu$m. Insertion loss is 0.7 dB better than commercial CPW line at 110 GHz for longer line. This means that conductor resistivity might be low and little bite thick thickness compared to commercial ISS. Printed CPW lines with other lengths have same behavior of longer CPW line. In addition, line formed by screen printing technology achieved no ripple on insertion loss trace due to small return loss as shown in Fig. 4 (b). This is from some reflection points in the CPW line. (Commercial ISS has higher dimensional precision compared to Printed ISS.) Return loss of CPW lines formed by screen printing technology provides almost the same return loss characteristics in this paper. Return loss in the line are most sensitive to signal width compared to gap width. Thus almost $50 \Omega$ characteristic impedance in CPW lines formed by screen printing technology is achieved by almost the same signal width of a commercial CPW line. Furthermore, resulted insertion loss also have a significant advantage over previous research achievements [1]–[4].

3. Performance of CPW Line as Impedance Standards for On-Wafer Measurements

3.1 Verification Devices and Measurement Set-Up

In performance verification of printed CPW lines as measurement standards in the on-wafer measurement, following eight types of planar device in the Keysight Verification Substrate (KVS) were used

i) Thru Line as low transmission loss device;
ii) Open as high reflect characteristic device;
iii) Short as high reflect characteristic device;
iv) Matched load as low reflect characteristic device;
v) 30 dB Attenuator as mid loss device;
vi) Mismatch line as various transmission loss with reflection device;
vii) 25 ohm series resistors as mid reflect device;
viii) 100 ohm series resistors as mid reflect device;

Each verification standards were measured by two different calibration conditions, i.e. printed CPW lines and commercial CPW lines. Then, verification standards were
measured under the each calibration by 6 times. Measurement set-up has been described in Sect. 2.2. In the uncertainty evaluation, dimensions of CPW on the ISSs were measured and characterize the line impedances. The difference between system impedance, i.e. 50 ohms, and CPW line’s impedance over several GHz provides to the calibration uncertainty. In addition, contact repeatability, presented by Ref. [6], was also taken into account to the calibration and measurement uncertainty. Finally, the two types of measurement results for the verification devices were compared.

3.2 Verification Results and Comparison

To verify the both verification device measurement results, we compared two different values from on-wafer measurement calibrated by two different ISS, i.e. printed and commercial CPW lines.

The degree of equivalence between the S-parameter results obtained by printed and commercial CPW lines as standards is expressed quantitatively by two terms: the difference between the both values, \( \Delta \), and, the uncertainty of this difference at a 95% level of confidence, \( U(\Delta) \). For each S-parameter measurand, these were calculated as follows [7]:

\[
\Delta S_{ij} = |\text{Printed CPW} - \text{Commercial CPW}|
\]

\[
U(\Delta) = k \sqrt{u^2_{\text{Printed}} + u^2_{\text{Commercial}}} \quad (2)
\]

Here, \( k \) and \( u \) are coverage factor and standard uncertainty.

Figures 4 and 5 show the both values, difference \( \Delta \), and equivalency \( U(\Delta) \), i.e. uncertainty of difference \( \Delta \), in the comparison of S-parameter measurement results in amplitude for some of verification devices. In the case of \( \Delta < U(\Delta) \), both measurement results are agreed with each other. However, in the opposite case, some unknown uncertainty factor or measurement error are still remained in the measurements.

In Figs. 5, regarding matched load, high reflective devices and thru line, difference, \( \Delta \), is smaller than equivalency, \( U(\Delta) \) entire measurement frequency range. This means that the measurement results are almost agree with each other within uncertainty.

In Figs. 6, regarding two port devices with high reflection characteristics, i.e. 75 ohms Beatty line and 100 ohms series resistor, the both measurement results are not agree with each other within uncertainty at some frequency regions as high reflection characteristics. This was because that dimensional un-uniformity of “Thru” and “Line” standards, on printed ISS, transferred to residual mismatch er-
ror in VNA measurements. In the measurement of two port device with high reflection characteristics, our uncertainty calculation slightly underestimated the actual error in the measurement at some frequency points, due to movement of cable between frequency extender modules to VNA.

4. Conclusions

This paper presented capability of screen printing as an innovated fabrication technology to use for millimeter-wave applications and precision measurement systems. CPW lines formed at 600°C baking achieved low insertion loss and low reflection characteristics up to 110 GHz and comparable to the CPW lines on the commercial ISS. In addition, we are demonstrated a capability of transmission lines fabricated by printed electronics to use for calibration standards. According to comparison between commercial ISS and printed ISS, almost characteristics of verification devices is agreed within uncertainty. However, for two port devices having mismatch characteristics, transmission characteristics obtained by printed CPW lines are not equivalent to those obtained by commercial CPW lines. This might be “Thru” and “Line” standard imperfection from dimensional un-uniformity and error of dimension of the lines. However, improvement of fabrication precision by using different screen printing technology, i.e. offset screen printing etc., will provide accurate ISS. Screen printing technology is leading simultaneously to precision forming, mass production and therefore cost efficiency and environmental acceptability.

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References


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