Transmission loss of screen-printed metallization at millimeter-wave frequency

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Abstract: This paper is the first report on transmission loss of screen-printed metallization of transmission lines at frequencies ranging up to 340 GHz. We observed that the printed transmission lines exhibited significantly reduced transmission losses when compared to conventional lines on the commercialized impedance standard substrate (ISS). The conductivity of Ag metallization was considered the reason for this reduced loss. Though degradation of the loss was observed in transmission lines approximately 3 years post fabrication, the printed line retains a smaller loss than conventional lines on the ISS. Further, despite the printed line having inferior production reproducibility, the screen-printed technology was considered to be an improved solution for the fabrication of millimeter-wave circuits, even in the 300 GHz band.

Keywords: screen-printing, transmission loss, planar-circuit

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Communication technology has become very essential for our society today. Especially, the Internet of Things (IoT) technology, which handles tremendous communication traffic, attracts major interest from the research community. Previously, communication technology was used to transmit a microwave frequency signal among electronic devices. However, increased communication traffic has led to the depletion of frequency resources and resulted in degraded communication quality. Therefore, certain novel communication devices were designed to utilize the millimeter-wave (mmW) frequencies because of their unoccupied frequency-band. The mmW frequency is expected to work not only for their available frequency resources, but also for high-speed and large-capacity communications. Although, some devices operating up to 110 GHz have already been commercialized, the use of mmW frequency (>110 GHz) is still in its early stages of development [1, 2]. Generally, planar circuits are utilized for integration of circuits in a device. As the operating frequency of these devices increases, finer fabrication technology is required to avoid unwanted modal signal-propagation [3]. Moreover, because the IoT requires a large number of electrical components, a low-cost fabrication process is essential. Although the lithography process has been traditionally used to fabricate a fine metallization on dielectrics, the process is expensive. In this scenario, screen-printed technology is expected to be an effective solution because it can offer a fine and low-cost fabrication process [4, 5]. Indeed, certain passive devices were fabricated by the screen-printed technology, and have demonstrated operations at mmW frequency up to 110 GHz [6, 7]. However, to our knowledge, there is no report of a printed metallization used for operations above 110 GHz. In this study, the transmission loss of the screen-printed metallization is
evaluated at frequency ranges up to 340 GHz. The impact of the other types of loss, such as dielectric loss of a substrate, are out of the scope of this study. The transmission line design and fabrication are described in section 2. Sections 3 and 4 explain the transmission line characterization and transmission loss evaluation, respectively.

2 Instrumentation and experimental details

2.1 Preparation of transmission lines

The printed transmission lines were fabricated on an alumina substrate by using a handheld printer ZT320 (Tokyo Process Service). The fabrication conditions are summarized in Table I. A silver paste CA-T31, manufactured by Daiken Chemical Group, was used as the conductor material. The average grain size and viscosity of the paste were 0.3 µm and 310 Pa·s, respectively. A hybrid binder, which is a mixture of polyester and acrylic, was used as the plastic binder and butyl carbitol acetate was used as the solvent. The as-printed transmission line was dried in an air oven for 30 min at 130 °C and annealed in the inert oven for 1 h at 600 °C. The dimension of the transmission line was determined according to the commercialized impedance standard substrate (ISS) modeled 138-357 manufactured by Cascade Microtech.

### Table I. Fabrication conditions

| Conditions               | Value          |
|--------------------------|----------------|
| Squeezing speed          | 100 mm/s       |
| Mesh count               | 730 mesh       |
| Thickness of emulsion layer | 7 µm          |

2.2 Measurement instruments

Two measurement systems were used for each measurement frequency band. Fig. 1 shows the constructed on-wafer measurement system for measurement frequencies ranging from 190 GHz to 340 GHz. The system set up for the measurement frequencies up to 110 GHz is shown in [8, 9]. Table II lists the information of the measurement systems and conditions. The measurement system was calibrated by thru-reflect-line (TRL) calibration with the commercialized ISS which is indicated in the table. The radio frequency signal detection technique was used for the probing procedure [8, 9].

3 Microscopic view

Fig. 2 shows an image of the printed line fabricated on the alumina substrate. Although the transmission line was fabricated continuously, it demonstrates a periodic change in the line width, as illustrated in Fig. 2. The pitch of the change was approximately 100 µm. A similar imperfection was reported in our previous study, where no significant degradation of electrical property was observed at the frequency ranging up to 110 GHz [6].
4 Evaluation of electrical properties

4.1 Transmission loss of the printed transmission line

The transmission coefficient of 5250 µm transmission lines on the ISS 138-357 and the printed transmission line were evaluated. Fig. 3 shows transmission coefficients of the lines at the frequency ranges of 10 MHz–110 GHz and 190–340 GHz. The printed transmission line exhibited remarkably smaller transmission loss in the 300 GHz band than that on the ISS, despite the periodic change in line width. Uncertainty was estimated by using a calculation algorithm [10]. The algorithm can estimate uncertainty with regards to dimension of standards, system drift, system noise, system linearity, and variation in probe position. The error bar in Fig. 3(a) indicates the range of uncertainty. As shown in the Fig. 3(a), the difference in transmission loss exceeds the range of uncertainty. The origin of the smaller transmission loss of the printed line was investigated by using electro-magnetic (EM) simulation. EM-simulator Femtet (Murata Software) was used for the inves-

| Table II. Measurement system and conditions |
|-----------------------------------------------|
| Frequency | 10 MHz–110 GHz | 190 GHz–340 GHz |
| IF bandwidth | 100 |
| Measured points | 201 |
| Vector Network Analyzer (VNA) | N5260A-016 | N5256AW03 |
| RF probe model | i110-GSG-150-A | i325-S-GSG-75-BT |
| ISS for calibration | 138-357 | 138-356 |

Fig. 1. Images of the VNA system at 300 GHz band. (a) Overview, and (b) Close-up image.

Fig. 2. Microscopic images of the printed transmission line. The arrows indicate the periodic change in the line width.
tigation. The materials utilized for metallization were set as Ag and Au for each model. Fig. 4 shows the simulated transmission coefficient. The Ag line exhibited smaller transmission loss than that of Au. The conductivity of Au and Ag are known to be $4.2 \times 10^7$ and $6.3 \times 10^7$ S/m, respectively. Therefore, it is the higher conductivity of silver that helps in reducing transmission losses. From our previous study [6], we understand that the surface roughness of the printed line was slightly larger than the line on the ISS. However, the surface roughness may not present a critical impact, because the improvement in the transmission coefficient was 0.2 dB at 50 GHz in Fig. 3, which was larger than the 0.1 dB observed in the simulated results.

4.2 Degradation in transmission loss
As described in the previous section, the more conductive Ag may contribute to smaller transmission losses in the printed transmission line. However, Ag generally degrades faster [11]. Consequently, degradation of the transmission loss should be investigated. The transmission coefficients of the printed line were published in [6]. The opened circles in Fig. 5 were quoted from the reference, which was published in September 2015. The solid line indicates the traces acquired in June 2016 and August 2018. Though degradation of the printed line was not detected between September 2015 and June 2016, the loss became larger in August 2018, and moved out of uncertainty range. Despite the degradation in approximately three years, the printed line still demonstrated a smaller loss than the line on the ISS.

Fig. 3. $S_{21}$ traces of the printed line and the line on the ISS. (a) 10 MHz–110 GHz, and (b) 190 GHz–340 GHz. The error bar in the (a) indicates uncertainty range at 100 GHz.
4.3 Productive reproducibility

As shown in Fig. 2, the pitch of the change in the line width was approximately 100 µm. This change would impact the characteristic impedance of the line. Therefore, the production reproducibility would be worse in shorter lines. In this study, production error in 5 of the shortest 135 µm lines were evaluated in the frequency range up to 110 GHz. This frequency was chosen to avoid the impact of coupling between probes that disturbs the investigation on production reproducibility at the 300 GHz band. Fig. 6 shows the $S_{21}$ traces of the five shortest lines. Variations in the transmission coefficient of the printed line were obviously larger than that of the line on the ISS. The periodic change in the line width of the printed line appears to cause larger variation in the transmission coefficient. However, all traces were in the uncertainty range at 100 GHz despite different fabrication methods. Fig. 7 shows production reproducibility in the 5250 µm lines. Four of the printed lines and two of the lines on ISS are illustrated in the figure. Though the printed line demonstrates worse reproducibility than the line on the ISS, it exhibited smaller loss than the line on ISS, even in the worst case.
5 Conclusion

The transmission loss of the screen-printed metallization was evaluated at frequencies ranging up to 340 GHz. The printed transmission line exhibited smaller transmission loss than the line on the ISS. The reason for this reduced transmission loss was considered to be the better conductivity of Ag. The degradation of the Ag metallization was observed in this study. However, the loss was better than the conventional line on the ISS even after the degradation. Consequently, the results strongly support screen-printing technology having a higher potential as a fabrication technique for electrical devices used in the mmW frequency. The production reproducibility is a problem that needs to be addressed for practical usage.

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