Low-Loss Micromachined Inverted Overlay CPW Lines with Wide Impedance Ranges and Inherent Airbridge Connection Capability

Youngwoo Kwon, *Member, IEEE*, Hong-Teuk Kim, *Student Member, IEEE*, Jae-Hyoung Park, *Student Member, IEEE*, and Yong-Kweon Kim, *Member, IEEE*

***Abstract*—A new type of overlay coplanar waveguide (CPW) structure, "inverted overlay CPW (IOCPW)" is developed using micromachining techniques to provide easy means of airbridge connection between the ground planes, as well as to achieve low losses over wide impedance ranges. Measured IOCPW showed less than 1 dB/cm loss at 50 GHz over a wide impedance range from 25 to 80 Ω. It also offered low effective dielectric constant, and insensitivity to the substrate losses. Wide impedance ranges and simple process steps make IOCPW a promising uniplanar transmission line medium for mm-wave monolithic applications.**

***Index Terms*—Coplanar waveguide, micromachining technology, transmission line.**

I. Introduction

LOW-LOSS transmission lines are one of the most important components for extending the frequency limits of the planar circuits. Numerous attempts have been made to reduce the loss of the transmission lines at millimeter-wave frequencies. Micromachining techniques have been most effective in this regard. For example, microshield lines, where the strip lines are suspended on a thin membrane by selective removal of the substrate material underneath the strip lines, achieved an extremely low loss of 0.35 dB/cm at 40 GHz for high-impedance (100 Ω) lines [1]. However, they are limited for practical applications, by the need for sophisticated backside processing and incompatibility with the conventional MMIC processes. On the more practical side, coplanar waveguide (CPW) lines with finite ground planes have been very successful for MMIC applications at W-band and above [2]–[4]. While sharing many of the advantages of CPW lines such as uniplanar configuration and ease of fabrication, they can further extend the operation frequency beyond that of CPW by controlling the cut-off frequencies of the higher-order modes. Another modified CPW structure of interest is channelized coplanar waveguide (CCPW) lines [5]. They use notched channels underneath the CPW lines for easy ground connections through the bottom part of the substrate without resorting to airbridges or via-holes. Higher order cut-off frequencies are also drived toward higher frequencies by adding the notched channels.

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The authors are with the Center for 3-D Millimeter-Wave Integrated Systems, School of Electrical Engineering, Seoul National University, Seoul 151-742 Korea (e-mail: ykwon@snu.ac.kr).

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However, the CPW-based transmission lines generally suffer from limited usable impedance ranges. This is due to the fact that the line losses of the CPW-based lines tend to increase rapidly at low-impedance and (to a lesser degree) at high-impedance extremes as shown in [1] and [6]. In order to reduce the line losses for high-impedance CPW lines, there have been attempts to elevate the center conductors [7]–[11]. The capacitance of the lines was decreased in this way, and wider center conductors could be used to reduce the conductor loss. Elevated center conductors also helped to alleviate current crowding problems. On the other hand, to solve the more serious loss problems of the low-impedance CPW-based lines, an Overlay CPW (referred to as "OCPW" hereinafter) has recently been introduced by the authors [12]. OCPW presented low losses for low-impedance lines by partially overlapping the elevated center conductor with the ground plane. It was thus possible to achieve low losses over a broad impedance range. However, OCPW line, in its present form, is not easily applicable to monolithic applications due to the difficulty of implementing airbridge connections between the ground planes to equalize the ground potentials. In this work, an "Inverted Overlay CPW" (IOCPW) line, where the edges of the ground planes, instead of those of the center conductors (as in OCPW), are elevated and partially overlapped with the signal line, is developed to provide an easy way of airbridge connection, as well as to benefit from the advantages of OCPW lines such as low loss characteristics over a wide impedance range.

II. Structure and Fabrication

The schematic of the inverted overlay CPW (IOCPW) is shown in Fig. 1, together with the that of the overlay CPW of [12], for comparison. The edges of the ground planes are elevated using surface micromachining techniques and partially overlapped with the signal line. The proposed IOCPW is thus identical to the overlay CPW except for the arrangement of the conductors; the ground line is now over the signal line to facilitate airbridge connections, making IOCPW readily compatible with MMICs. The operation principle is consequently very similar to OCPW. The impedance of the IOCPW line is controlled by the overlap ("O" in Fig. 1) between the center conductor and the ground. The overlap (O) can be negative for high-impedance lines; negative overlap designates separation between the ground and signal lines. A wide impedance range

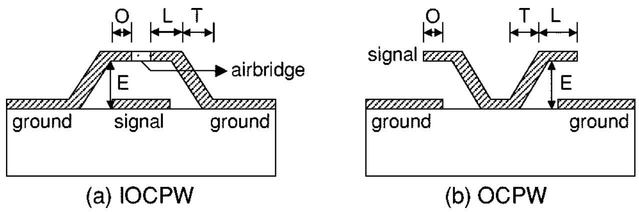

Fig. 1. Schematic diagram of (a) IOCPW and (b) OCPW lines.

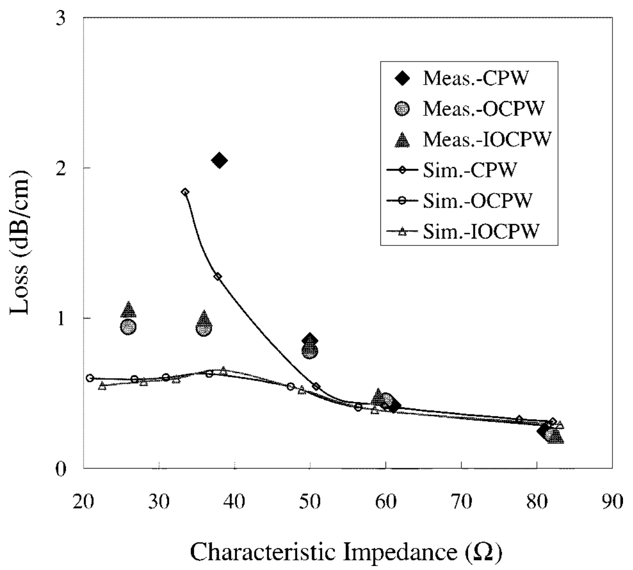

Fig. 2. Comparison of simulated (shown as lines) and measured (shown as points) loss characteristics of CPW, OCPW and IOCPW lines at 50 GHz. Curves labeled as "Meas.-" denote the measured results while those labeled as "Sim.-" denote the simulated results.

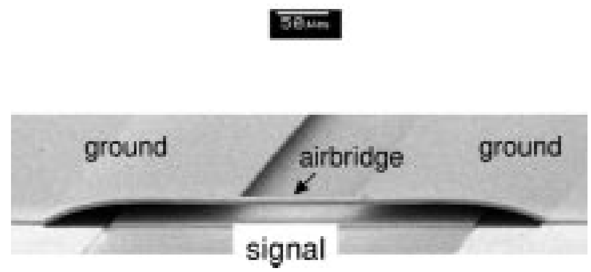

Fig. 3. Closeup SEM photograph of the fabricated IOCPW lines showing the airbridge connections between the ground planes.

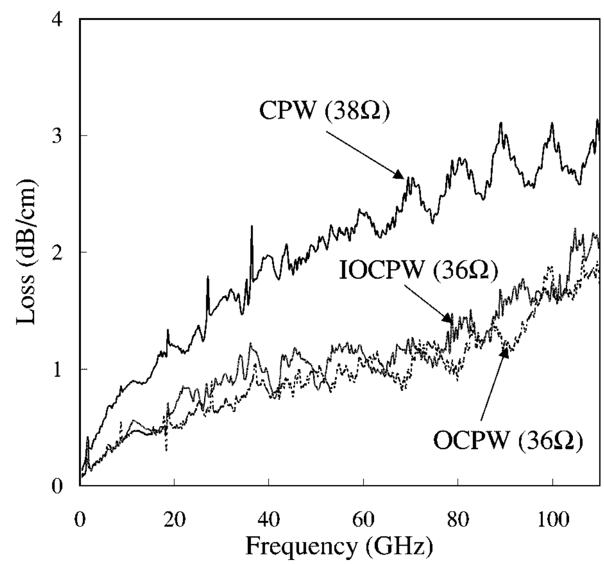

Fig. 4. Measured frequency dependence of loss characteristics of low-impedance (36–38 Ω) CPW, OCPW and IOCPW lines up to 110 GHz.

can be easily obtained by controlling this overlap. Sloped elevation of ground planes in IOCPW helps to reduce the conductor loss by redistributing the current over smooth surface area away from the edges. In addition, screening effect from the substrate losses can be obtained by confining the electric field in between the conductor plates. The effective dielectric constant is also lowered in this way, which is another useful feature for certain applications such as traveling wave amplifiers [13].

The transmission line parameters such as characteristic impedance (Z_0), loss (dB/cm), and effective dielectric constant (ϵ_{eff}) were simulated by a commercial software, IE3D. The loss of the line was calculated as a function of Z_0 by varying the overlap (O). The simulated loss characteristics of IOCPW are compared with those of CPW and OCPW at 50 GHz in Fig. 2. The substrate was 520 μm-thick quartz. The elevation of the ground plane was set to 15 μm for IOCPW and OCPW, and the ground-to-ground spacing was fixed at 200 μm for all the lines. In case of CPW, the line loss degrades rapidly as the impedance decreases below 30–40 Ω. The excessive line losses, as well as the photolithographical restrictions during fabrication, limit the use of CPW lines for impedances values lower than 30 Ω. On the contrary, a wide impedance range down to 20 Ω can be implemented without additional process difficulty in IOCPW by increasing the overlap (O). Furthermore, the insertion losses are maintained to less than 1 dB/cm (at 50 GHz) over a wide impedance range from 20 to 85 Ω. As expected, IOCPW and OCPW show very similar loss characteristics. The effective dielectric constant is also lower in IOCPW compared to CPW. For example, 36 Ω-IOCPW line showed an ϵ_{eff} of 1.4 while the CPW line with the same impedance showed an ϵ_{eff} of 2.2.

For loss comparison, three types of the aforementioned "CPW-like" lines (CPW, OCPW and IOCPW), each with a length of 1 cm, were fabricated on a 520 μm-thick quartz substrate. The ground and signal lines were realized by 3 μm-thick electroplated gold. The gold electroplating process was carried out using commercially available noncyanide electrolytic solution (NEUTRONEX 210 B) at a temperature of 60°C. The thickness of the electroplated structures was controlled by the plating time while fixing the current density at 2 mA/cm^2. The resulting electroplating rate was 0.125 μm/min, and the surface roughness of the electroplated structure was less than 0.061 μm. To form a 15 μm-thick sacrificial layer to realize elevated ground planes, thick photoresist (AZ 4620) was spin-coated and patterned by UV lithography. The patterned sacrificial layer was thermally cured at 200°C to reflow the photoresist for smooth metal overlay. After electroplating of the overlaying ground planes, the sacrificial layer was ashed in oxygen plasma. The closeup SEM photograph of the fabricated IOCPW line is shown in Fig. 3, showing the airbridge connection between the ground planes.

III. Measured Performance

CPW, OCPW and IOCPW lines with various impedances were fabricated and compared. For this purpose, the S-parameters of 1 cm-long lines were measured up to 110 GHz using a HP 8510 XF network analyzer and a CASCADE on-wafer prober. For on-wafer probing, OCPW and IOCPW lines included 80 μm-long OCPW-to-CPW and IOCPW-to-CPW transitions, respectively. The return loss of the back-to-back transition was better than 25 dB. The measured results of IOCPW and OCPW reported in this paper, thus, include the losses due to the transitions. Fig. 2 shows the measured losses (shown as points) of the three different CPW structures at 50 GHz as a function of the characteristic impedances together with the simulated data (shown as lines). At high-impedance levels ($>50\ \Omega$), IOCPW and CPW show comparable losses. However, for low-impedance lines (e.g., $Z_0 \sim 35\ \Omega$), the measured loss of IOCPW is much smaller (1 dB/cm versus 2 dB/cm) than that of the conventional CPW as expected from simulation. This clearly shows the advantage of IOCPW lines for low-impedance applications. Measured loss is within 0.4 dB of simulation, validating the analysis method. The frequency dependencies of the line losses for 1 cm-long 36–38 Ω lines are compared in Fig. 4 up to 110 GHz. The IOCPW line (36 Ω) shows losses less than 2 dB/cm up to 110 GHz while the conventional CPW line (38 Ω) shows more than 3 dB/cm loss at 110 GHz. The differences in the loss values are expected to grow as the line impedance is reduced further.

IV. Conclusions

In this work, a new type of overlay CPW structure, "inverted overlay CPW (IOCPW)" is developed to provide easy means of airbridge connection between the ground planes while maintaining the advantages of the OCPW lines, such as low insertion loss over a wide impedance range, low effective dielectric constant, and insensitivity to the substrate losses. Measured IOCPW showed low and even loss characteristics (less than 1 dB/cm at 50 GHz) over a wide impedance range from 25 to 80 Ω. Low loss and simple process steps make IOCPW lines a promising candidate for uniplanar millimeter-wave integrated circuits.

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