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Micromachined Silicon-core Substrate-integrated Waveguides with Coplanar-probe Transitions at 220-330 GHz

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Abstract—In this paper, we present for the first time on, to the best of our knowledge, the first silicon-core micromachined substrate-integrated waveguide (SIW) in the 220-325 GHz frequency range. In contrast to the fabrication methods used for conventional SIW known from substantially lower frequencies, micromachining allows for a full-height waveguide and near-ideal and arbitrarily shaped sidewalls. The silicon dielectric core allows for downscaling the waveguide and components by a factor of 3.4 as compared to an air-filled waveguide. At 330 GHz, the measured waveguide insertion loss is as low as 0.43 dB/mm (0.14 dB/ λ_g , normalized to the guided wavelength). Devices were manufactured using a two-mask micromachining process. Furthermore, a low-loss ultra-wideband coplanar-waveguide (CPW) transition was successfully implemented, which comprises the very first CPW-to-SIW transitions in this frequency range. The measured transition performance is better than 0.5 dB insertion loss (average of 0.43 dB in the band above 15% above the waveguide-cutoff frequency), which is lower than previously reported CPW-to-SIW transitions even at 3 times lower frequencies, and the return loss is better than 14 dB for 75% of the waveguide band.

Index Terms—substrate integrated waveguide, SIW, coplanar to waveguide transition, coplanar waveguide probes, CPW, micromachining, microfabrication.

I. INTRODUCTION

The advantages of using dielectric-filled waveguides at high frequencies are being investigated for a couple of decades [1]. Their main advantages are substantial downscaling, i.e. by $\sqrt{\epsilon}$, as compared to air-filled waveguides. The losses are higher than for air-filled waveguides, but still substantially lower as compared to planar transmission lines. In particular substrate-integrated waveguides (SIW) with integrated components and antennas have been extensively investigated [2] - [4]. The main disadvantages of conventional substrate-integrated waveguides are related to the (low-cost) fabrication techniques utilized, with the limited height resulting in far from ideal losses, and the sidewall construction by through substrate-vias which severely limits the geometrical possibilities and also limits the frequency range to about up to W-band. Furthermore, the probing interfaces require accurate dimensions which further restricts SIW to frequencies below 100 GHz for conventional fabrication methods.

Therefore, micromachining has recently been investigated for silicon dielectric filled waveguides [5] - [6], and has achieved excellent performance which rivals conventional SIW and even air-filled waveguides in the W-band [7].

The present paper reports on the first ever silicon-core micromachined substrate-integrated waveguide at 220-325 GHz, and also on the first coplanar-waveguide to SIW transitions operating in that frequency range.

Fig.1. CST Microwave Studio simulation model of the coplanar probe on the transition to the silicon-core micromachined substrate-integrated waveguide.

II. WAVEGUIDE AND TRANSITION DESIGN

An air filled rectangular waveguide of the WR-3.4 standard has a height of 432 μm and width of 864 μm , with a nominal cut-off frequency of 173 GHz. With a silicon core, the waveguide is scaled down by a factor of $\sqrt{\epsilon}=3.44$, resulting in a height of 125 μm and a width of 250 μm for the same frequency band. The waveguide dimensions chosen in this work are a height of 150 μm and width of 200 μm , resulting in a nominal cut-off frequency of 216 GHz. The 50% larger than nominal height was chosen to increase handling stability of the chips, and also positively influences the losses. To provide mechanical support to the waveguides, periodic anchor structures were added as shown in Fig. 1. In contrast to conventional fabrication techniques, micromachining allows these anchors to be very narrow with little influence on the wave propagation, and otherwise straight and vertical sidewalls. The parameters of the waveguides and transitions in this paper have been optimized by taking in to account the influence of these support elements

The design of the transitions between coplanar-waveguide probes to the micromachined, silicon-core substrate-integrated

waveguides shown Fig. 2, and is based on a W-band folded slot antenna coupling transition [5], but optimized for this particular configuration and the substantially higher frequency band. For that, a complete CPW-probe had to be modelled as shown in Fig. 1.

The waveguides and transitions were designed and optimized in CST Microwave Studio.

Fig. 2. CPW to micromachined-SIW transition: (a) SEM picture of fabricated transition; and (b) designed dimensions in μm .

III. FABRICATION

The main fabrication steps are shown in Fig. 3. The process requires only two masks. To decrease the losses in the dielectric, high resistivity ($\rho > 5000 \Omega \cdot \text{cm}$) $150 \mu\text{m}$ thickness silicon wafers were chosen.

Fig. 3. Fabrication steps: (a) deposition and lift-off the top metal to provide the transition pattern; (b) soft-mask patterning of the back side for (c) subsequent DRIEtching; (d) back side metal deposition.

The fabrication begins with the formation of the front-side metallization pattern for the transition geometry, by using a lift-off processes with a positive LOR photoresist. The metallization scheme consists of a 500 nm thick gold layer on top of a 50 nm chromium adhesion layer. The Cr layer additionally acts as an etch stop for the subsequent DRIEtching process without exposing the gold to the plasma. This is followed by the patterning of the back side. Since only $150 \mu\text{m}$ have to be etched, a soft mask ($5 \mu\text{m}$) of photoresist is sufficient. Subsequently,

the trenches defining the waveguide walls are etched by a DRIE BOSCH process. The final step comprises the sputtering of a thick $2.5 \mu\text{m}$ layer of gold on the back side, providing good waveguide sidewall coverage.

In comparison with a previously reported micromachining process flow [5] – [6] for substantially lower frequencies, the present solution provides a minimum number of masks and does not require any bonding or gluing or substrate transfer operations, and is therefore significantly less complex.

Fig. 4 shows the SEM pictures of cross section of manufactured waveguide (Fig. 4a) and the sets of waveguides with visible support structures (Fig. 4b).

(a)

(b)

Fig. 4. SEM pictures: (a) cross section with dimensions of fabricated waveguide, (b) back side of waveguide with support constructions.

IV. MEASUREMENTS AND RESULTS

Measurements were performed using a Rohde&Schwarz ZVA24 vector network analyzer with two ZC330 millimeter-wave converters for 220 to 330 GHz and Picoprobe Model 325B CPW probes. In Fig. 5, a transition before (Fig. 5a) and after probing (Fig. 5b) is shown. As for any WR-3.4 chips, accurate probe positioning is a must.

Fig.5. Microscope pictures: (a) transition before, and (b) after probing.

A. Waveguide Characterization

For characterization of the waveguides, an on-chip TRL calibration kit was designed. Fig.6 shows the measurement results of a 5 mm ($15.5\lambda_g$) long line after de-embedding of the transitions, and has an excellent agreement with the simulations also shown in the same diagram. The waveguide has a measured insertion loss of $0.14 \text{ dB}/\lambda_g$ ($0.43 \text{ dB}/\text{mm}$) at 325 GHz, which, despite being measured at 3 times higher frequency, is very similar to the values shown for the only other known micromachined silicon-core waveguide (W-band) [5]. Reference [7] reports the so far best results for an air filled rectangular waveguide which is $0.05\text{-}0.07 \text{ dB}/\lambda_g$ ($0.05\text{-}0.07 \text{ dB}/\text{mm}$).

Fig. 6. Measured and simulated S-Parameters of silicon-core substrate-integrated waveguide of 5 mm length (after de-embedding the transitions).

Fig. 6 shows that the worst-case performance ($<10 \text{ dB}$ return loss) occurs at about 288 GHz. This is caused by the support structures perforating the waveguide sidewalls, which was confirmed by simulations. The resonance frequency can be moved by the periodicity of the support structures, and can be avoided by an aperiodic support pattern.

B. Characterization of the CPW-to-Si-SIW Transition

To measure the transitions accurately, the two tier one port method of offset shorts calibration was applied [8]. The set of offsets standards was manufactured in the same process on the same chips; hence a high-quality measurement standard was guaranteed.

Fig. 7 shows the measured S-parameters of a CPW-to-micromachined-waveguide transition, with the S_{12} being better than 0.5 dB for the whole band above 250 GHz (with 250 GHz being 15% above the cut-off frequency, since the waveguide is narrower than a nominal WR3.4 silicon-core waveguide would be), and averaging to only 0.35 dB over that band. The measured S_{11} is below -14 dB for the 240-315 GHz frequency range which means that this transition is of very low-loss and very wideband. The figure also shows the simulated transitions, with excellent agreement between the simulation and the measurement data.

Fig. 7. Measured and simulated data of the de-embedded coplanar to waveguide transition alone.

V. CONCLUSION

This paper reported on the first silicon-core micromachined waveguide at 220-325 GHz, including the first CPW-to-SIW waveguide transitions in that frequency band. The obtained measurement results, namely an insertion loss of $0.14 \text{ dB}/\lambda_g$ ($0.43 \text{ dB}/\text{mm}$) at 325 GHz of the waveguide, and an insertion and return loss of the transitions of 0.34 dB and 14 dB , respectively, are excellent and very well with the simulation results.

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