Wideband 220 – 330 GHz Turnstile OMT Enabled by Silicon Micromachining

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Abstract—This paper is the first publication on the first turnstile-junction orthogonal mode transducer (OMT) above 110 GHz, which is enabled by silicon micromachining. In contrast to other OMT concepts, turnstile OMTs are wideband and allow for co-planar ports, but require accurate and complex fabrication and have therefore, to the best of our knowledge, not been implemented above 110 GHz in any technology. As shown in this paper, the fabrication and assembly accuracy of silicon micromachining enables the realization of such complex OMT designs at 220 – 330 GHz with excellent performance. The measured insertion loss is better than 0.7 dB for the whole waveguide band, with mean values of 0.34 dB and 0.48 dB for the vertical and horizontal polarizations, respectively. The measured return loss for both polarizations, even with an open-ended common port, is better than 14 dB for the whole waveguide band, and an average level of 18 dB. An estimation of the worst-case cross-polarization level, derived from measurements, results in at least 20 dB for the whole waveguide band, with an average of 25 dB for the upper half of the band.

I. INTRODUCTION

There is an increasing interest in millimeter wave (mmW) receivers for remote sensing in earth and space observation missions. These receivers require orthogonal mode transducers (OMT) to discriminate between the two orthogonal polarizations present in the receiving antenna. The ALMA telescope is a good example of a system using dual polarization receivers up to 950 GHz [1], where OMTs were used up to Band 8 (385 – 500 GHz), and quasi-optical polarization grids were used at higher frequencies due to the difficulty to accurately fabricate waveguide components at high frequencies by CNC-milling. However, waveguide OMTs are preferred over wire grids due to mass and volume reduction, elimination of beam squinting, and an improved response to thermal cycling [2].

Wideband OMTs rely on twofold symmetrical geometries that require complex recombination networks for the different polarizations. CNC-milled Bøifot OMTs have been presented in the mmW range [3], [4], but other more complex OMT designs, such as the turnstile, have not been reported above W-band to the authors knowledge [5]. Turnstile OMTs are used in multi-pixel dual-polarization receivers due to their coplanar rectangular-port arrangement that allows compact integration.

Silicon micromachining, using deep reactive ion etching (DRIE), has demonstrated to be a very promising alternative to classical CNC-milling for mm-wave and THz components. It allows not only the accurate fabrication of micron sized features, but also enables the very compact integration of

MEMS reconfigurability [6] or active components [7] in the waveguide front-end.

A major challenge for silicon micromachining, when fabricating complex structures such as OMTs, is the implementation of multistep geometries which increases the assembly and fabrication complexities.

To our knowledge, the only previous silicon-micromachined OMT is a side-arm OMT design, which also achieved excellent performance, but was narrow-band (15% BW), and had a high fabrication complexity requiring 6 hard masks and sequential etch steps from one wafer surface [8].

In this paper we present the first wideband silicon-micromachined OMT, which also is, to the best of our knowledge, the first turnstile OMT implementation in any technology above 110 GHz. Design efforts were focused on simplifying the fabrication process by reducing the number of etching steps to a maximum of two from any wafer surface, and to have a coplanar port configuration which is desired from an application perspective.

II. DESIGN AND FABRICATION

A. Fabrication Technique

The OMT was micromachined in silicon-on-insulator (SOI) substrate using the DRIE Bosch process. For this particular design, up to two silicon oxide (SiO_2) hard-masks were used to transfer the different layer geometries to the Si substrate from any wafer-side. Once the waveguide trenches were etched, the substrate was coated with a 2 μ m gold layer, more than 10 times the skin depth (δ), prior to chip alignment and thermocompression bonding. The final geometry of the OMT, and the turnstile junction are shown in Fig.1. Scanning electron microscope (SEM) images in Fig.2 show the fabricated bottom and top chips of the stack-up after metallization.

B. Design

The design of the OMT follows the classic approach described in [9]. The turnstile junction, bends, and power combiners were first individually designed with a design target of better than 25 dB return loss. Some considerations had to be done to take full advantage of the fabrication technique, while accommodating its constraints.

The turnstile junction, shown in Fig.1(b), is implemented in the lowermost chip of the 3-chip stack. The scatterer-post acts as a tuning stub, providing low reflections over a large

Fig. 1: 3D drawing of (a) overall OMT design, and (b) turnstile junction.

bandwidth, and its height is limited to the chip thickness, i.e. 275 μm. This is compensated by inductive irises in the input waveguides, achieving a return loss better than 25 dB in the entire band with a simple two-step square post.

The height of the step in the post is set to 95 μm, and it is kept constant for the design of the power divider and the bends to simplify the fabrication process. Different types of bends are used to re-route the output ports from the turnstile junction (in the bottom chip) to the E-plane power combiners in the top chip.

A full wave simulation of the whole OMT was then performed to validate the complete design. The simulated OMT performance shows better than 18 dB return loss for both polarizations in the entire band and an insertion loss lower than 0.3 dB. The simulated return loss is shown for each individual component and both polarizations of the OMT in Fig. 3.

Two chip layouts were designed to facilitate different measurements: a 10 mm x 10 mm chip (shown in Fig. 4) which allows for connecting to the rectangular ports P2 and P3, and a full flange chip allowing connection to the square port P1. The first solution enables simple measurements of the return loss by leaving the square port P1 open. The insertion loss is estimated by applying a back-short on the common port P1 and measuring S_{22} and S_{33} . The return loss of an open ended square waveguide is worse than 20 dB, therefore the measured reflections in the OMT will be higher, but this method gives

(a)

(b)

Fig. 2: SEM pictures of metallized chips before assembly (a) Turnstile junction; (b) Square port and power divider.

Fig. 3: Simulated return loss of individual components and both polarizations of OMT.

a very good estimation of the RF performance. The second chip layout enables a more accurate characterization of all S-parameters, but requires additional test devices to route the signals from ports P2 and P3 due to the large flange size in comparison with the device footprint, and was therefore

not yet completed when preparing this abstract. The OMT is intended to be used in highly integrated multi-pixel systems, i.e. both layouts only comprise a test implementation, since flange connections are not necessary for on-chip integrated systems. Elliptical alignment holes, as described in [10], are used to ensure repeatable and accurate alignment between the silicon micromachined chip and the CNC-milled standard test ports.

Fig. 4: Exploded view of the chip layout composed of 3 micromachined chips.

III. RF CHARACTERIZATION

A Rohde & Schwarz ZVA-24 vector network analyzer (VNA) with ZC330 frequency extenders was used for the RF characterization of the component. The 10 mm x 10 mm chips were tested to verify the performance of the OMT. The measurement setup, with the chip aligned to the test port using the inner alignment pins of the flange, is shown in Fig.5.

The reflection measurements for both polarizations are shown in Fig.6, along with the simulated data. Note that the simulation data shown in Fig.6 has been re-simulated to consider the effect of the open ended waveguide. The measured return loss is better than 14 dB for both polarizations over the whole waveguide band, with an average value of 18 dB.

These results agree well with the re-simulated data given the simplified measurement setup. It should be noted that with proper termination of the common port, the return losses will be substantially better than the data reported in this paper.

The insertion loss was also estimated by connecting a short to the square port and measuring the resulting S_{22} and S_{33} , this measured data represents two times the insertion loss assuming ideal cross polarization levels. The measured insertion loss is below 0.7 dB for the whole waveguide band for both polarizations, with mean values of 0.34 dB and 0.48 dB for the vertical and horizontal polarizations, respectively, as shown in Fig.7.

Fig. 5: Measurement setup, with open-ended square waveguide port.

Fig. 6: Comparison of measured and simulated return loss for both polarizations of the OMT, with open-ended square port.

Fig. 7: Measured insertion loss for both polarizations, and estimation of worst-case cross-polarization.

The cross-polarization (X-Pol) could not yet be measured directly, but its worst-case level, also shown in Fig.7, was estimated from the measured data by mapping the simulated insertion loss to the measured one. This is a worst-case

estimation and the real cross-polarization level is expected to be better than the derived values, which already are better than 20 dB for the whole band, and even better than 25 dB in the upper half of the waveguide band.

IV. CONCLUSIONS

This paper presents the first turnstile OMT implementation above 110 GHz, enabled by silicon micromachining. The design uses a three-chip stack with a maximum of two etch-depths to implement the complex geometry required for turnstile OMTs. The design presented in this paper shows good performance over the entire WM864 band, (220 – 330 GHz). The reduced footprint of the component, the coplanar output port arrangement, and the ability for low-cost batch fabrication, makes silicon micromachining of turnstile OMTs a promising technology enabling integration of multi-pixel systems.

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