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A Silicon Micromachined 220-330 GHz Turnstile Orthomode Transducer (OMT) in a Low-Loss Micromachining Fabrication Platform

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ABSTRACT

The work presented in this paper reports on the first wideband OMT in any frequency band implemented by micromachining. This turnstile-junction design provides full waveguide-band operation (220-330 GHz) and is the first implementation of a turnstile-OMT above 110 GHz, since very accurate fabrication is required for this topology. The measured insertion loss is below 0.5 dB and below 0.6 dB for the two polarizations, respectively, with an average measured return loss of 22 dB. Except for some spikes which still are below 30 dB, the cross-polarization is between 50 and 60 dB.

INTRODUCTION

Silicon micromachining is overcoming many of the manufacturing problems of CNC milling for waveguide components at millimeter-wave and sub-THz frequencies [1-4]. Silicon micromachined components have shown filters with outstanding low-loss / high-Q factors [1], low insertion loss waveguides [2], and allow for near-ideal reconfigurable components due to the integration of micro-electromechanical (MEMS) actuators [3].

Millimeter wave receivers are often required to handle two orthogonal polarizations for some applications, such as radio astronomy [5], where the operation bandwidth is large, and the use of wideband components helps to reduce the number of required receivers. Orthomode transducers (OMT) are key components in the receiver frontend; and their bandwidth, insertion loss, return loss, and cross-polarization are considered the most relevant figures of merit [6].

The turnstile OMT presented in this paper is designed for full-band operation in the WM864 band, 220 – 330 GHz, and is, to the best of our knowledge, the first broadband OMT implemented by micromachining, and only the second attempt (besides [7]) to implement a turnstile OMT at frequencies above 110 GHz.

The OMT was implemented in a micromachined-waveguide fabrication-platform available at KTH, which has only 0.04 dB/mm losses at 330 GHz and 0.01 dB/mm at 170 GHz and allows for unloaded-Q factors in excess of 750 at 330 GHz and of beyond 1500 at 170 GHz. Specific challenges for the implementation of such a high-complexity and tolerance-sensitive component are described in this paper together with a complete electromagnetic characterization.

DESIGN

The design of this turnstile OMT is described in detail in [8]. The common square port of the OMT feeds a turnstile junction with a 2-step square scatterer post. The geometry and dimensions of the junction are shown in Fig. 1. The turnstile junction separates each of the orthogonal polarizations present in the square waveguide into two rectangular waveguides with a -3 dB power level each and a π rad phase shift. The twofold symmetry of the turnstile junctions provides a theoretical infinite isolation between the two polarizations, that must be recombined into the two output ports using E-plane power combiners, as shown in Fig 1. All sub-components in the recombination network are designed with the goal of minimizing the number of fabrication steps, but still achieve higher than 25 dB return loss in the whole band.

Fig. 2. shows the cross-section of the three-chip stack that was used for the implementation of the OMT, with three etching steps each. The non-idealities of the fabrication were considered during the entire design process, modeled with a reduced gold conductivity of 2.1×10^7 S/m due to the roughness of the vertical walls of the waveguide, and a 4° sidewall angle due to the nature of the Bosch process, as shown in Fig. 2. These values were estimated from test fabrication runs of similar geometries, as described in [2]. The simulated return loss for both polarizations of the OMT are shown in Fig. 3, together with the return loss of each individual component in the recombination network. All simulations were carried out with the commercial software CST Microwave studio. The OMT has a simulated return loss better than 18 dB for the entire band, which is a trade-off with fabrication complexity.
Fig. 1. 3D drawings of the turnstile OMT design. Left: top view of the turnstile junction including all design parameters, and right: complete OMT design.

Fig. 2. Cross section views of the turnstile junction and the E-plane power combiner. The drawing shows the predicted side-wall slopes characteristic for deep-silicon etching.

Fig. 3. Simulated return loss of individual components and both polarizations of OMT.
The OMT was micromachined on a silicon-on-insulator (SOI) wafer using an advanced deep reactive ion etching (DRIE) Bosch process in an Applied Materials Centura Etch tool at KTH. The SOI wafer used for this component has a handle layer of 275 $\mu$m, a device of 30 $\mu$m, and a buried oxide of 3 $\mu$m. Silicon oxide (SiO$_2$) hard-masks were used to transfer the different geometries to the silicon substrate from both sides of the wafer, using a total of three masks for the whole process, as shown in Fig. 2. This multiple-mask process allows to implement the multi-step geometry required for the scatterer post and the rest of impedance matching structures. Fig. 4 shows scanning electron microscope (SEM) images of the turnstile junction before (left) and after (right) the second DRIE step.

After performing all etching steps, the individual chips, shown in Fig. 5, are cleaned and metallized with a 2 $\mu$m layer of gold. The metallized chips are aligned, and thermo-compression bonded at 250$^\circ$C. Fig. 6 shows SEM images of the top and the bottom chips in the stack, containing the turnstile junction, routing networks, and E-plane power combiners. A more detailed description of the entire fabrication process can be found in [8].

![Fig. 4. SEM picture of turnstile junction. Left: after first etching step in the handle layer, and right: after second etching step in the handle layer.](image_url)

![Fig. 5. Picture of the chips before metallization.](image_url)

![Fig. 6. SEM pictures of metallized chips before assembly. Left: Turnstile junction; right: square port and power divider](image_url)
MEASUREMENT RESULTS

A Rohde & Schwarz ZVA-24 VNA with ZC330 frequency extenders was used for the RF characterization of the component. Two different chip sizes with identical OMTs were implemented: a 10mm x 10mm chip which allows for connecting to the rectangular ports only, and a full-flange sized 20mm x 20mm chip also allowing the connection to the square port, both configurations are shown in Fig. 7. The first solution enables the basic measurements of the return loss by leaving the square port open, which was measured for both polarizations of three components manufactured in two separate batches. These measurements together with the simulated data considering the effects of the open-ended square port are shown in Fig. 8. These measurements show a good repeatability both within the same batch and between batches.

The second chip layout provides access to all three ports of the OMT, but requires the use of two additional, custom-made micromachined test fixture chips for routing the waveguide ports of the OMT to the standard waveguide ports of the frequency extenders of a vector network analyser (VNA). The measurement setup used for these measurements is further described in [8]. Fig. 9 shows the return loss, insertion loss, and cross-polarization measurements of the OMT. The return loss is always better than 16 dB for both polarizations, with an average value of 22 dB. The insertion loss value is better than 0.6 dB, with an average value of 0.3 dB. The cross-polarization shows a few spikes that are always kept below -30 dB, while the average level is below -50 dB. The cause of these spike is analysed and documented in [8].

Fig. 7. Silicon micromachined OMT mounted in standard waveguide flange. Left: 10 mm x 10 mm chip for open-ended measurements, and right: 20 mm x 20 mm chip for full characterization of S parameters.

Fig. 8. Measured return loss with an open-ended square port of three different OMTs fabricated in 2 different fabrication runs. Solid lines show measured data, dashed lines show simulated data.
CONCLUSIONS

This paper shows the first high performance turnstile OMT above W-band, and the first wideband silicon micromachined OMT in any frequency range. The device is implemented in a three-chip stack configuration reducing the manufacturing complexity as compared to other OMT implementations at millimeter wave frequencies. The micromachining technology at KTH, used for the fabrication, provides unique low loss and extremely good batch-to-batch repeatability. The OMT shows a mean return loss value of 22 dB, insertion loss value of 0.3 dB, and cross-polarization always better than 30 dB. The resulting device is as compact as 10 mm x 10 mm x 0.9 mm, including alignment pins for flange connection. The compactness, high performance, and repeatability of silicon micromachined OMTs makes them suitable for high performance applications.

REFERENCES