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500-600 GHz Submillimeter-Wave 3.3 bit RF MEMS Phase Shifter Integrated in Micromachined Waveguide

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Abstract — This paper presents a 500-600 GHz submillimeter-wave MEMS-reconfigurable phase shifter. It is the first ever RF MEMS component reported to be operating above 220 GHz. The phase shifter is based on a micromachined rectangular waveguide which is loaded by 9 E-plane stubs, which can be individually blocked by using MEMS-reconfigurable surfaces. The phase-shifter is composed of three metallized silicon chips which are assembled in H-plane cuts of the waveguide. The measurement results of the first prototypes of the MEMS reconfigurable phase shifter show a linear phase shift of 20° in 10 steps (3.3 bit) and have a return loss better than 15 dB from 500-600 GHz. The insertion loss is better than 3 dB up to 540 GHz, and better than 5 dB up to 600 GHz for all phase states, of which the major part is contributed by the assembly of the microchips between waveguide flanges which has a reproducibility error between 2 and 6 dB measured for reference chips.

Index Terms — Micromachined waveguide, phase shifter, RF MEMS, rectangular waveguide, submillimeter-wave, terahertz.

I. INTRODUCTION

Submillimeter-wave or terahertz frequency band have emerging applications in imaging systems, radar, spectral analysis, radio astronomy, and high bandwidth wireless data communications [1]. Phase shifters are, for instance, widely employed for beam steering applications in phased-array antennas used in communications and radar applications. Electrically-controlled phase shifters can replace mechanical scanning stages and thus dramatically increase both the measurement speed and system integration. Phase shifters using GaAs, MESFET, and p-i-n diode switches have high insertion loss, poor linearity performance, and large power consumption, in particular at sub-THz frequencies [2]. Ferrite based phase shifters perform well, but have large size and high cost. Phase shifters using liquid crystals [3] have too slow response time in seconds. Micro-electromechanical systems (MEMS) phase shifter can achieve low loss, high linearity, low power consumption and large bandwidth and have been shown to perform well up to 110 GHz frequency [2]. Micromachined waveguides have shown promising performance even up to 2.7 THz [4]. (Moving) MEMS-based devices have so far been reported only up to a maximum frequency of 220 GHz [5], and these attempts were limited to transmission-line based systems.

The 500-600 GHz MEMS device reported in this paper is, to the best knowledge of the authors, the first ever MEMS reconfigurable sub-millimeter wave component. It is the first

Fig. 1. Submillimeter-wave MEMS phase shifter design using 9 E-plane stubs loading a micromachined rectangular waveguide reconfigured by using independently-operated MEMS-reconfigurable surfaces.

MEMS microwave component operating above 220 GHz, the first MEMS phase shifter operating above 110 GHz, and the first MEMS waveguide component over 110 GHz.

II. DESIGN

As shown in Fig. 1, the design is based on an E-plane stub-loaded rectangular waveguide phase shifter concept [6], where each stub is blocked or unblocked by MEMS-switched surfaces [7]. The rectangular waveguide used has non-standard dimensions (0.4156 mm × 0.2078 mm) to have the phase shifter functioning in the lower WR-1.5 band. The waveguide is loaded with 9 stubs each having a nominal phase shift of 10° resulting in a total phase shift of 90° in 10° steps, i.e., ten different phase states (3.3 bit). MEMS-switched E-plane surfaces are inserted perpendicularly to the wave propagation into the waveguide stubs. Each MEMS surface

Fig. 2. Microscope photograph of the fabricated MEMS chip.

consists of distributed metallized elements, which can be reconfigured by on-chip MEMS actuators so that they can either block or unblock the TE_{10} mode wave propagation into the waveguide stubs. This is achieved by a number of vertical columns that are split into smaller sections grouped into a set of fixed and a set of movable cantilevers. The fixed set is anchored and the movable set is mechanically connected via horizontal suspension bars to electrostatic comb-drive MEMS actuators. The MEMS actuators provide synchronous lateral movement of the vertical cantilevers. When the MEMS surface is open (non-blocking), the vertical cantilevers of the fixed and moving elements are not in contact and thus allow the electromagnetic wave to propagate freely through the switched surface. When the MEMS surface is closed, the movable vertical cantilevers are laterally moved into contact with the non-movable vertical cantilevers, to form closed vertical columns which block the wave propagation through the surface. The comb-drives are symmetrically placed to the left and the right of the waveguide stubs with five comb-drive actuators on each side, as shown in the photograph of the fabricated MEMS chip (Fig. 2). The total movement is $10\text{ }\mu\text{m}$ or $\pm 5\text{ }\mu\text{m}$ around the rest position. The actuators are designed to make contact when a 30 V signal is applied.

III. MOUNTING/ASSEMBLY AND FABRICATION

The phase shifter consists of a micromachined waveguide chip, a MEMS switched stub chip with the MEMS-switched surfaces, and a cap chip terminating the stubs which are mounted as shown in Fig. 3. The micromachined waveguide and the MEMS-switched surface chips both have micromachined alignment structures which are used to align the chips to machined metal blocks as well as to each other. Fig. 4 shows the mounting and assembly procedure. The MEMS chip is aligned and placed on a machined metal block with the cap chip underneath (Fig. 4a). This is followed by aligning and placing the micromachined waveguide chip on top of the MEMS chip (Fig. 4b). The top metal block (Fig. 4c) is aligned to the micromachined waveguide chip and placed on top. Alignment pins are used to align the metal blocks to

Fig. 3. Micromachined waveguide chip, MEMS switched stub chip and cap chip arrangement of the phase shifter.

Fig. 4. Mounting/assembly and alignment of the three phase shifter chips to the machined metal blocks and waveguide flanges.

each other as well as to the waveguide flanges. The whole assembly is finally screwed together. Fig. 4d shows the photograph of the assembled phase shifter and Fig. 4e shows the RF measurement setup of the phase shifter where the phase shifter is also connected to the waveguide flanges.

The micromachined waveguide chip and the cap chip are fabricated using a silicon substrate by deep reactive ion etching (DRIE) to make the waveguide channel. The chips are then metallized by sputtering $1\text{ }\mu\text{m}$ thick layer of gold on them. The MEMS-switched stub chip is fabricated in a two-mask SOI RF MEMS micromachining process. DRIE of the handle wafer is done to make the waveguide stubs. This is followed by DRIE of the device layer to make the MEMS switched surfaces. The MEMS moving structures are free etched by wet etching of the buried oxide layer using hydrofluoric acid and critical point dryer is used to avoid stiction. A 700 nm thick gold layer is sputtered on the handle wafer and a 200 nm thick gold layer is sputtered on the device

Fig. 5. Measured S-parameters and normalized phase shift of the fabricated 500-600 GHz phase shifter.

layer. The total chip size of the micromachined waveguide chip and the MEMS switched stub chip, including contact pads, handling areas and bias-line, is 6.8 mm × 10 mm.

IV. MEASUREMENTS

DC biasing is provided by multi-contact DC probes, with a total of 12 contacts and an operation voltage of 32 V. Fig. 5 shows the measured insertion and return loss of the phase shifter for all ten phase states, measured with an Agilent PNA-X system with VDI WR-1.5 submillimeter-wave heads. The phase shifter behaves exceptionally broadband over the whole design frequency range of 500-600 GHz with the return loss better than 15 dB and the insertion loss of less than 5 dB. The phase shift in Fig. 5 is normalized to the state with all stubs blocked and shows a linear phase shift of 20° in 10 discrete steps (3.3bit) instead of the 90° expected from simulations. The cause for this discrepancy is currently being investigated and most likely due to the non-optimized sidewall roughness in the stubs, which degrades the efficiency of the stubs for creating a phase shift. Fig. 6 shows the simulated insertion loss for all states. The measured insertion loss is higher due to the H-plane split waveguide [8] and the assembly of the microchips between the waveguide flanges which has a reproducibility error between 2 and 6 dB as shown in Fig. 7,

Fig. 6. Simulated insertion loss and phase shift of the 500-600 GHz phase shifter.

Fig. 7. Measured S-parameters of 10 chips with different fixed phase states.

where the insertion and the return loss of 10 different phase shifter chips with fixed phase states is shown.

V. CONCLUSION

This paper demonstrates the first ever reconfigurable MEMS phase shifter in the 500-600 GHz frequency range. A linear phase shift of 20° has been measured (in ten steps) with a return loss of better than 15 dB and insertion loss of better than 5 dB in the designed band. The performance of this component can be further enhanced by making smoother sidewalls and improving tolerances on packaging.

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