Deep Reactive Ion Etching Based Silicon Micromachined Components at Terahertz Frequencies for Space Applications

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***Abstract*—Jet Propulsion Laboratory (JPL) is using Deep Reactive Ion Etching (DRIE) based silicon micromachining capabilities to develop the critical waveguide components at submillimeter wavelengths that will lead to highly integrated multi-pixel spectrometers, imagers, and radars. In this paper we describe the design and fabrication of silicon micromachined critical waveguide components operating in the 325-500 GHz frequency band for space applications. We also address the challenges of testing these devices when interfaced with metal waveguide test fixtures.**

I. Introduction And Background

FUTURE multi-pixel, multi-functional, high performance instruments operating at frequencies from hundreds of gigahertz to several terahertz will require waveguide circuits with very small feature sizes and high precisions. Indeed, state-of-the-art missions currently in development, such as the ground-breaking HIFI instrument on Herschel [1], are based on single-pixel, single-ended double-sideband receivers. It is well known that at frequencies beyond a few hundred gigahertz, the feature sizes of all but the simplest waveguide circuits are too small and the required tolerances are too demanding to be fabricated using even the best state-of-the-art conventional machining. On the other hand, silicon micromachining shatters the barriers of conventional machining, and brings the added benefits of rapid turn-around time and excellent process control. Furthermore, silicon micromachined circuits are light weight and capable of achieving a high degree of integration on a single chip. While there have been several demonstrations of waveguide circuits fabricated with silicon micromachining [2] and other techniques [3], few if any of these circuits have been subjected to any significant electrical testing.

Submillimeter-wave integrated silicon micromachined circuits for array receivers have never been demonstrated. Deep reactive ion etching (DRIE) based silicon micromachining is the most viable option for the fabrication of these high performance components in an array instrument which require deep vertical profiles in waveguides [4]. The silicon etching process in DRIE consists of an etching cycle flowing only Sulphur hexafluoride (SF_6) and a sidewall passivation cycle flowing only octofluorocyclobutane (C_4F_8). The advantage of DRIE over wet anisotropic etching is that DRIE exhibits little crystal plane dependence, therefore, reducing the geometric restrictions [5]. As a result, DRIE enables fabrication of trenches that are independent of crystal planes, thus making it possible to develop micromachined waveguides with vertical sidewall profiles. Compared to silicon laser micromachining [6], DRIE is more efficient in etching large volumes of substrate. Moreover, the DRIE process is much simpler for mask alignment issues as compared to other micromachining techniques where the mask alignment has been proven to be extremely challenging. Moreover, one of the key problems with the current generation of silicon micromachined components has been the difficulty to design an interface to mate the components to metal waveguide test equipment for the proper characterization of the individual components. In this paper we will describe the design and fabrication of silicon micromachined critical waveguide components operating in the 325-500 GHz frequency range (WR-2.2 waveguide band). We will also discuss the design of a novel test fixture that we have developed at JPL to address the issues of testing and characterization of these components.

II. Design, Fabrication, And Testing

We designed broadband quadrature-hybrid couplers, directional couplers, in-phase power dividers, and other components, as shown in Fig. 1, for operation in the 325-500 GHz frequency range using three-dimensional electromagnetic simulators (Ansoft HFSS) and linear circuit simulators (Agilent ADS). We also designed waveguides of different lengths for on-wafer calibration capability. These components were fabricated on silicon substrates in JPL's Micro Devices Laboratory using DRIE technique. We also fabricated silicon alignment pins to align the two spilt waveguide blocks. We evaporated gold on the silicon micromachined components by mounting the wafer at an angle for uniform metal deposition. Fig. 2 shows SEM photograph of the fabricated components, showing close up of the surface properties of the wall. Fig. 2 shows uniform gold deposition and no noticeable excessive deposition at the base of the post for the hybrids.

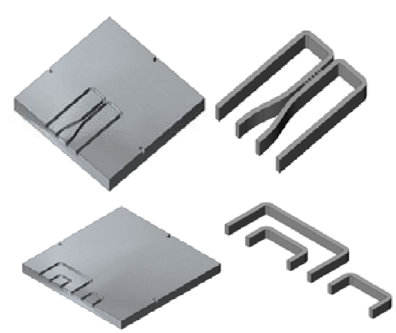

Fig. 1: Quadrature hybrids, different lengths of waveguides, and other components designed in the 325-500 GHz frequency band for silicon micromachining.

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Previous efforts to demonstrate micromachined waveguides have been severely limited by the difficulty of testing the fabricated components, especially due to issues involving mating the silicon components to calibrated test equipment. We have invented a novel test system to eliminate these difficulties and allow rapid and accurate testing of the micromachined circuits. With our system, the prototype components will be assembled in an innovative test fixture, as shown in Fig. 3, and tested with a 325-500 GHz vector network analyzer. Our test fixture brings the dual benefits of being compatible with the brittle nature of silicon (e.g., no screws or alignment pins mate to the silicon components, with spring plungers providing the necessary contact forces) as well as allowing the waveguides to be quickly aligned with the test equipment with a precision several times better than what is achievable with the best conventional microwave flanges. Furthermore, with our system, the vector network analyzer can be calibrated a single time, and then used to test a whole series of test components all in a single test fixture. Only one test fixture will be required to test all the prototype components. In future we will integrate multi-component waveguide circuits such as the waveguide portions of sideband-separating and balanced heterodyne receivers and will characterize them in the 325-500 GHz frequency band.

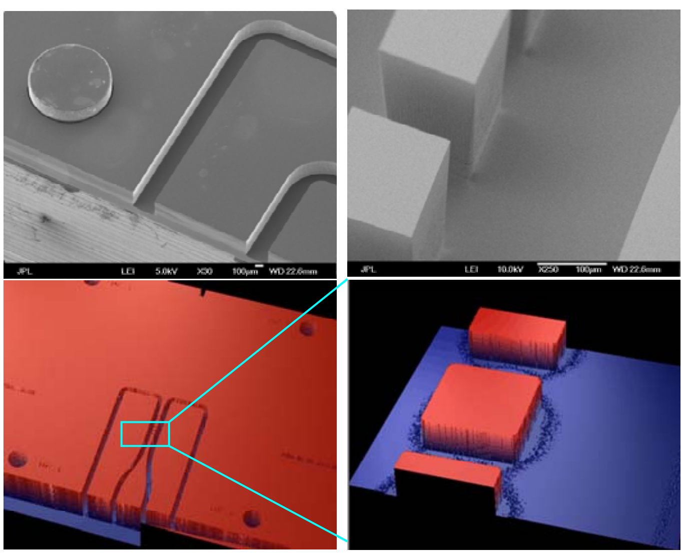

Fig. 2: SEM photographs of the waveguides and the silicon alignment pin (top left) and close-up of the posts for the hybrid (top right). Photograph of the roughness of the surfaces measured with Wyko interferometer system (bottom).

III. Summary

We have fabricated waveguide components in the 325-500 GHz band using DRIE-based silicon micromachining. We have also machined a metal test fixture to measure the fabricated components in a rapid and reliable fashion. On wafer calibration standards will be used to calibrate the network analyzer for testing these components. The gold plated micromachined components shows good vertical profile and smooth surface characteristics. Testing and characterization of the components are under progress currently in our laboratory.

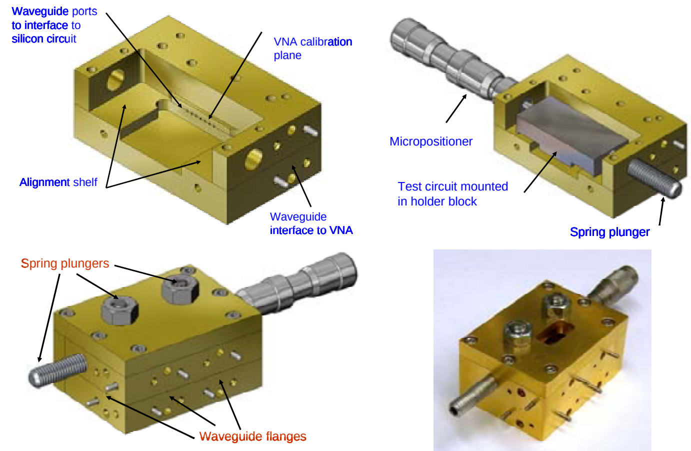

Fig. 3: Schematic of the test fixture used to measure the silicon micromachined components. A photograph of the machined test fixture is shown on the bottom right.

IV. Acknowledgements

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