Machining of Terahertz Split-Block Waveguides with Micrometer Precision

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***Abstract*—Evolutionary improvements in tooling and techniques are allowing increasingly complicated waveguide circuits to be fabricated with conventional end-mill machining at frequencies ranging from millimeter-wavelengths up to several terahertz. Machining precision is now approaching the limits of what can be measured with an optical microscope, with the measured dimensions of the highest-precision components typically within 2 µm of the nominal design values. We summarize the capabilities of the Space Instruments Shop at JPL and show examples of recently machined components.**

I. Introduction And Background

THE Space Instruments Shop at the California Institute of Technology's Jet Propulsion Laboratory specializes in machining high-precision components for a wide variety of NASA instruments. For example, the Space Instruments Shop has machined components for the Hubble Space Telescope, the Cassini mission to Saturn, Mars Pathfinder, the Mars Exploration Rovers, the Mars Science Landers, the Galileo mission to Jupiter, the Microwave Limb Sounder on Aura, the Microwave Instrument on the Rosetta Orbiter, the Herschel Space Observatory, CloudSat, TOPEX/Poseidon, the Shuttle Imaging Radar, Deep Space 1, Genesis, the Magellan mission to Venus, and many others too numerous to name.

Early submillimeter-wave and terahertz waveguide circuits were designed and optimized using simplest-possible configurations out of necessity to maximize machinability. This design philosophy is becoming unnecessary as the combination of accurate and powerful finite-element (FEM) electromagnetic simulators and computerized numerically-controlled (NC) machining enables increasingly complex circuits to be prototyped to very high precision in reasonable time frames.

II. Results

Developing terahertz waveguide components at JPL typically begins by simulating the complete circuit with a FEM electromagnetic simulator. Once electrical performance is deemed satisfactory, the three-dimensional model from the simulator is imported into a mechanical design program, where finishing details such as flange faces, screw holes, and bias connectors can be added. The completed three-dimensional models are then imported into Computer Aided Manufacturing (CAM) software for programming tool paths. This process enables designers to use complicated circuit geometries that could not easily be dimensioned with a conventional drawing, minimizes the probability of errors from translating the RF design to a mechanical drawing, and reduces the time required to produce the parts.

Most waveguide blocks machined at JPL are split along the E plane. The sides of the two block halves are typically flat and parallel to within 2 µm, and the waveguides cut into the two block halves typically line up within 2 to 3 µm or better. Capabilities of the JPL shop include cutting narrow channels down to 15 µm wide with tungsten-carbide end mills. In-house custom tool grinding gives the shop extra flexibility, such as cutting channels with depth-to-width ratios up to about ten for high-performance circuit components including directional couplers and quadrature hybrid couplers. Custom tooling has also been useful for the fabrication of terahertz feed horns. With the accuracy of the highest-precision components approaching 2-3 µm, the greatest uncertainty in waveguide dimensions is becoming the impact of the gold plating.

Waveguide circuits recently machined in the JPL shop include a four-chip frequency tripler for the 260-340 GHz band that features branchline hybrid couplers at the input and output for good return loss and isolation (Figure 1). Multi-chip power-combined frequency multipliers accurately match path lengths for good phase matching and efficient power combining up to 900 GHz [1], while waveguide frequency multipliers operating up to 2.7 THz include very small waveguide dimensions [2,3]. A sideband-separating SIS mixer block for the 180-300 GHz band (Figure 2) features an eight-branch hybrid coupler to split the RF signal and two two-branch directional couplers for injecting the local oscillator signal [4]. Figure 3 shows a 1.5 THz balanced HEB mixer with integrated feed horn. A 2.5 THz Schottky diode mixer with 2.5 THz Picket-Potter dual-mode horn made in the

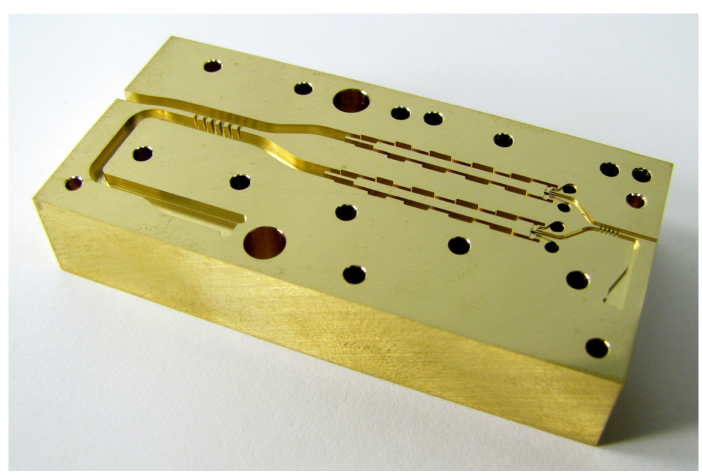

Figure 1. A quad-chip 260-360 GHz frequency tripler uses branchline couplers and internal loads to provide good return loss and isolation at the input and output.

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shop is currently in Earth orbit aboard the Aura Earth Observing System Microwave Limb Sounder (EOS MLS) [5].

The components and capabilities discussed above were machined with decade-old Bostomatic and DAC International three-axis mills. At the time of this writing, the Space Instruments Shop is installing a modern five-axis linear-drive mill that promises higher precision and faster turn-around than the tooling currently in use.

ACKNOWLEDGMENT

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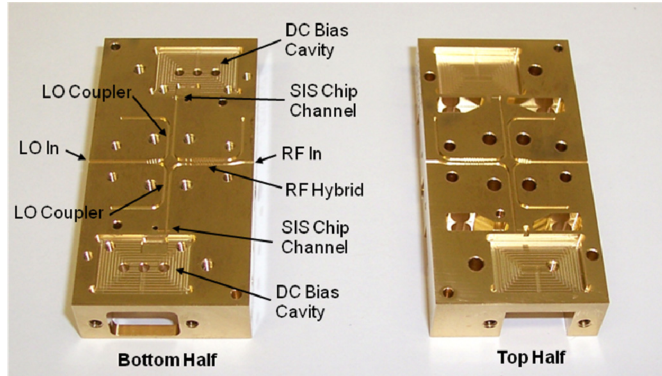

Figure 2. A 180-300 GHz sideband-separating mixer block includes an eight-branch quadrature hybrid coupler, two-branch LO directional couplers, and an in-phase LO power splitter.

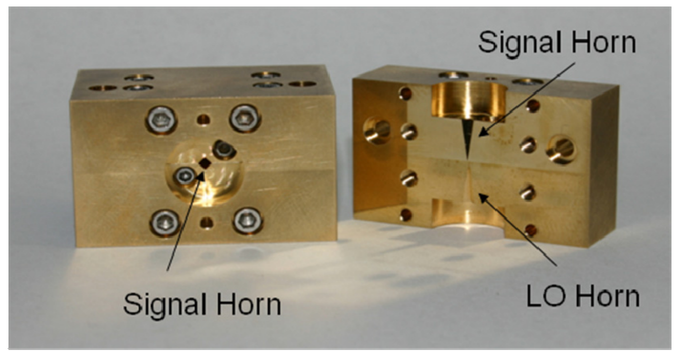

Figure 3. A 1.5 THz balanced HEB mixer with integrated feed horns. (Courtesy of Anders Skalare, JPL).