Automated CNC Micromachining for Integrated THz Waveguide Circuits

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Abstract— **Computer Numerically Controlled (CNC) machining of splitblock waveguide circuits has become the primary method of constructing terahertz waveguide circuits. The majority of these circuits have been made on traditional CNC machining centers or on custom-made laboratory machining systems. At both the University of Arizona and Arizona State University, we have developed techniques for machining splitblock waveguide circuits using purpose-built ultra high precision CNC machining centers designed for micromachining. These systems combine the automation of a traditional CNC machining center, including a high capacity toolchanger, workpiece and tool metrology systems and a large work volume, with the precision of custom laboratory systems. The systems at UofA and ASU are built by Kern Micro and deliver typical measured dimensional accuracies of 2-3 microns. Waveguide surface finish has been measured with a Veeco white light interferometric microscope to be Ra~75 nm. Tools of sizes between 25 microns and 10mm are available, with toolchanger capacities of 24-32 tools.**

The automated toolchanger and metrology systems allow a metal blank to be machined into the final part in one machining cycle, including both micromachining operations and traditional machining operations. This allows for perfect registration between all block features, in addition to very short cycle times. Even the most complicated blocks have machining cycle times of no more than a few hours. Workpiece and tool metrology systems also allow for fast setup times and straightforward part re-work. In addition, other high-throughput techniques such as palletization are enabled for the simultaneous manufacture of large numbers of blocks.

Using these machines, we have successfully produced waveguide circuits at frequencies ranging from W-band to 2.7 THz, including highly integrated blocks. The Supercam project relied on these machines to produce integrated 8-pixel SIS mixer array units with integrated low noise amplifiers, bias tees and blind mate connectors. In addition, the 64-way corporate power divider used for LO multiplexing was machined using these techniques. This system consists of 17 split-block circuits containing E-plane power dividers, waveguide twists, diagonal horns and all associated flanges. The final system consists of a single WR-3 UG-387 input and an 8x8 array of 11mm aperture diagonal feedhorn outputs. This is one of the largest submillimeter waveguide circuits ever constructed. Future large focal plane arrays and other applications requiring highly integrated waveguide circuits will critically depend on this type of highly automated micromachining technology.

We present the capabilities and machining process used with these machining centers, along with several waveguide circuits that were manufactured with this process including measured results from these circuits. Future directions for improving manufacturing quality and automation for large focal plane arrays will be discussed, including the use of palletization, in-situ metrology, and automatic workpiece changers. Using these techniques, construction of the necessary waveguide blocks for even kilopixel class heterodyne array receivers should be realizable in a manageable time with high part yield and relatively low incremental cost.

Figure 1: The Kern Model 44 (left) and Kern MMP (right) micromilling systems used at Arizona State University and the University of Arizona.

MICROMILLING SYSTEMS

The state of the art Kern micromilling systems at ASU (Model 44) and the University of Arizona (MMP) allow for the automated production of terahertz waveguide and quasioptical components with micron level accuracy and nanometer scale surface roughness (See figure 1). Both machines are equipped with laser tool measurement systems and strain-gauge touchprobes which allow the measurement and control of both tool sizes (both diameter and length) and workpiece location to the micron level. These machines are capable of maintaining their rated accuracies over their entire work volume, which enables very large integrated terahertz circuits to be produced, while maintaining dimensional accuracy and splitblock alignment. Both machines are 3-axis fully CNC controlled systems and are equipped with large capacity toolchangers. This allows all machining operations (both standard and micromachining) to be completed in one clamping, eliminating the need to align micromachined features to traditionally machined components. This dramatically increases productivity while maintaining the best possible quality. Future upgrades to 5-axis machining are possible with both machines.

These machines are capable of cutting traditional waveguide block materials (brass, copper, and aluminum) as well as more exotic materials including stainless steel, hardened steel, ceramics and silicon. Their high precision and large work volumes also make them particularly well suited to the production of terahertz optical components, optical systems and precision mechanical components.

TABLE I
MICROMILLING SYSTEM SPECIFICATIONS

	Kern Model 44	**Kern MMP**
Positioning accuracy	+/- 0.5 micron	+/- 1.0 micron
Surface Finish	Ra<0.1 microns	Ra<0.2 microns
Work Volume	300x280x250mm	250x220x200mm
Max workpiece mass	50kg	30 kg
Spindle	Vector controlled 50 krpm	Vector controlled 40 krpm
Toolchanger	32 positions	24 positions
Tool measurement	Laser diameter and length	Laser diameter and length
Workpiece setting	Touchprobe	Touchprobe
Cutting lubricant	Temperature controlled cutting fluid	Oil mist lubrication system

MICROMACHINING PROCESS

The micromachining process at the UofA and ASU combines electromagnetic design, mechanical design, CAM programming, machining, metrology, assembly and RF testing in one location. This allows for rapid progress from design to finished, working components, and also allows for multiple design cycles for the refinement and optimization of complex THz circuits. The CAM system used with both processes (Openmind Hypermill) is integrated into the CAD package used for design. This system automatically updates CAM programming when the solid model is changed in the CAD package. Toolpaths are calculated to an accuracy of 0.1 microns.

MICROMACHINED TERAHERTZ COMPONENTS

The Kern MMP at the University of Arizona was originally purchased to fabricate the waveguide structures for the Supercam 64 beam array receiver [1]. The Supercam 8-pixel mixer module is shown in figure 2. The block consists of eight single ended SIS waveguide mixers, with integrated diagonal horns. LNA modules, IF and bias distribution and electromagents are all contained in this single, large (160x50x11mm) waveguide splitblock. All waveguide, feed and classical machining is done in a single clamping per side in the Kern MMP. 20 tools, and approximately 4 hours of machine run time are required to complete a single splitblock half.

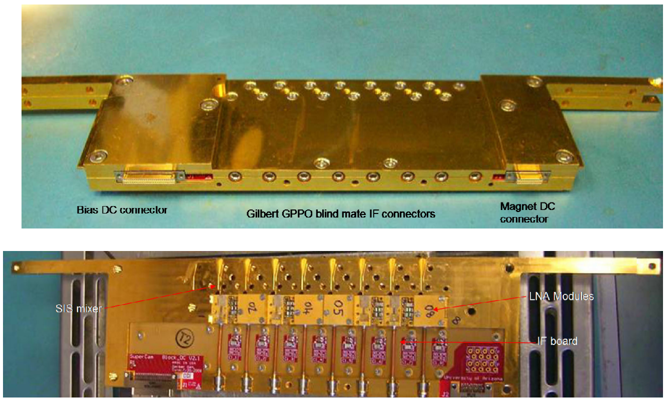

Figure 2: The Supercam 8-pixel mixer module. The single splitblock contains 8 single ended SIS mixers, 8 low noise amplifier modules, 8 electromagnets, and all DC and IF distribution circuitry.

LO power multiplexing for Supercam is also accomplished using a micromachined waveguide structure. The 64-way LO power divider shown above-left consists of 17 separate waveguide splitblocks with custom interface flanges. The first waveguide splitblock consists of 7 WR3 E-plane Y-splitters in a binary tree. This tree of splitters divides the output of a single Virginia Diodes LO chain by 8, with equal waveguide pathlength for each output port (see figure 3). The output ports end with splitblock waveguide twists. This block's 8 output ports then meet 8 additional waveguide splitblocks. These blocks have an idential tree of 7 E-plane Y-splitters, but the output ports end with diagonal feedhorns (see figure above-right). The diagonal feedhorns are then extended with another set of splitblocks to reach 11mm aperture size. The final block achieves even pixel-to-pixel splitting of LO power to within 10%, with a total loss of 2 dB compared to a lossless divider [2].

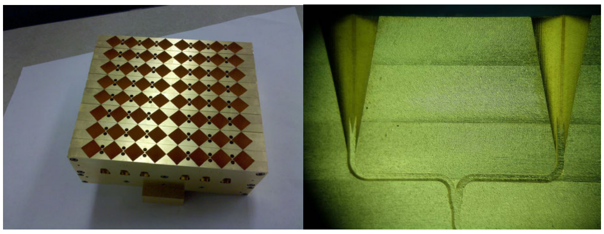

Figure 3: The completed Supercam LO power divider (left) and a close up photo of one of the E-plane Y-junctions inside the splitter (right).

In addition to Supercam, many other waveguide components have been produced. The spatial filter shown in figure 4 was designed to improve the beam quality of a 2.7 THz QCL [3]. This is currently the highest frequency waveguide structure to be designed, fabricated and tested using our micromachining process.

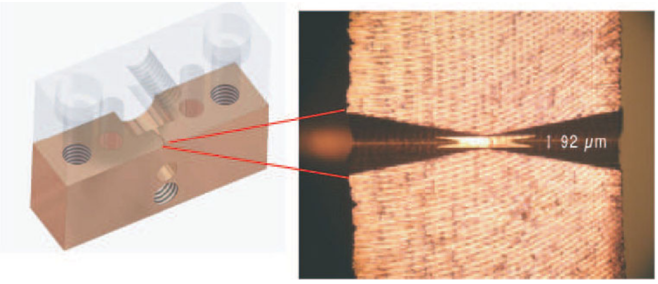

Figure 4: A solid model and photo of a 2.7 THz spatial filter made at the University of Arizona using the micromachining process described in this paper.

Highly integrated THz waveguide circuits are possible to fabricate using our micromaching process. The 660 GHz sideband separating mixer shown in figure 5 is fabricated from a splitblock containing two branch line directional LO couplers, 1 branch line hybrid coupler, two SIS mixers, an integrated diagonal LO feedhorn and associated IF circuitry and magnets [4]. The 1.45 THz mixer shown in figure 6 was fabricated using a 25 micron diameter cutter [5]. The b-dimension of the waveguide is 42 microns. Feature depths are 18 microns for the waveguide backshort and 8 microns for the device channel. The coupler slot shown below right was cut with a 100 micron tool with a 5.5:1 aspect ratio.

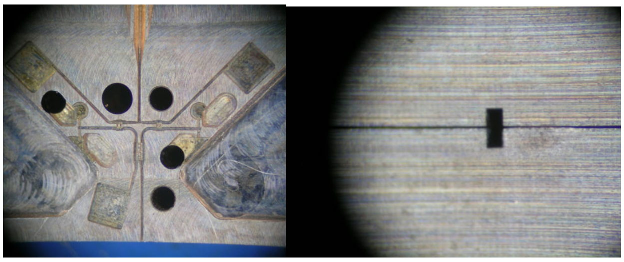

Figure 5: A 660 GHz sideband separating mixer block (left), and the splitblock alignment of the two halves of this block (right). The size of the full-height waveguide is 145x310 microns, with +/- 2 micron splitblock alignment.

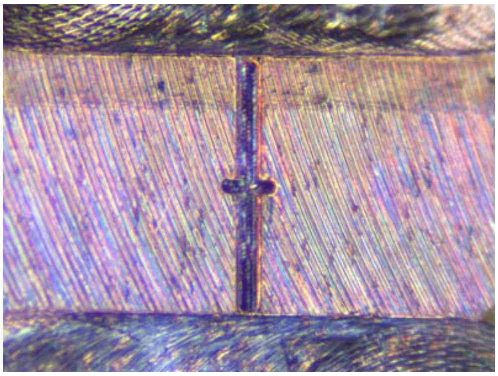

Figure 6: A 1.4 THz HEB mixer block for the Stratospheric Terahertz Observatory experiment. The dimensions of the waveguide backshort are 160x42 microns, with a 18 micron depth. Features were machined with a 25 micron diameter endmill.

METROLOGY

Metrology is a critical component to any micromachining process. High performance waveguide circuits are impossible to successfully fabricate without the ability to measure micron-level dimensions and nanometer scale surface roughnesses. Both micromilling systems are equipped with laser tool measurement systems and touchprobe systems which allow the measurement of tool length and diameter to the micron level, and the location and rotation of the workpiece to the same level of precision. Combined with the exceptional positioning accuracy of the machine axes, these systems allow on-the-part accuracies of ~2um. Structure dimensions can then be measured to micron accuracies using a 3-axis measurement microscope with photographic capability. At the University of Arizona, a Veeco white light interferometric microscope is available to measure surface roughnesses. Typical surface roughness is Ra~75 nm. An example of such a waveguide is shown in figure 7.

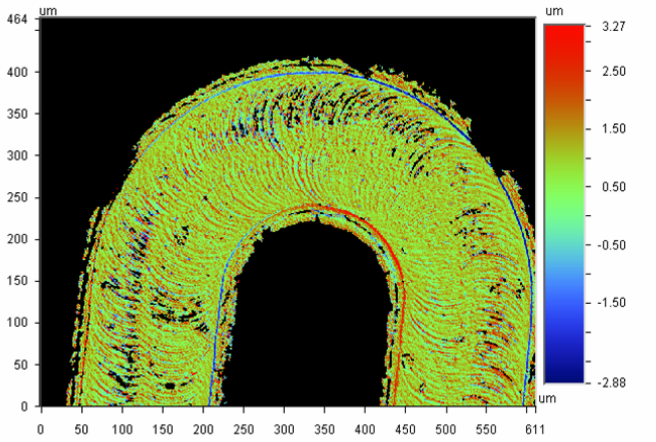

Figure 7: A white light interferometric microscope image of the floor of a 350 GHz waveguide. The measured surface roughness is Ra~75 nm.

FUTURE DIRECTIONS

Automation techniques used for decades in classical machining systems can now be applied to high precision micromachining. Rather than producing one or a few waveguide blocks at a time, automation systems can allow the production of hundreds of blocks at a time without user intervention. The Kern Evo's toolchanger can be expanded to up to 96 tools. The System 3R workpiece chuck allows straightforward palletization of workpieces, and allows the removal and reinstallation of the chuck with a precision of 2um or better. The chuck can be combined with an automatic workpiece changer to allow the automated loading and unloading of pallets. Combined with the laser tool metrology system and workpiece touchprobe, very large numbers of THz waveguide blocks could be produced economically and quickly. Future instruments with large (~1000) pixels are feasible using these production techniques, in addition to the expansion of THz technology to the private sector.

REFERENCES

[1] Groppi, C.E., Walker, C.K., Kulesa, C., Golish, D., Kloosterman, J, Puetz, P., Weinreb, S., Kuiper, T., Kooi, J., Jones, G., Bardin, J., Mani, H., Lichtenberger, A., Cecil, T., Hedden, A., Narayanan, G. SuperCam: a 64 pixel heterodyne imaging spectrometer, Millimeter and Submillimeter Detectors and

Instrumentation for Astronomy IV, Edited by Duncan, William, Holland, Wayne, Withingtonm Stafford, Zmuidzinas, Jonas, Proc. SPIE 7020, 26, 2008.

[2] Christopher Groppi, Christopher Walker, Craig Kulesa, Dathon Golish, Jenna Kloosterman, Sander Weinreb, Glenn Jones, Joseph Barden, Hamdi Mani, Tom Kuiper, Jacob Kooi, Art Lichtenberger, Thomas Cecil, Patrick Puetz, Gopal Narayanan, Abigail Hedden, Testing and Integration of Supercam, a 64-Pixel Array Receive for the 350 GHz Atmospheric Window, 21st International Symposium on Space Terahertz Technology, in press, 2010.

[3] Abigail Hedden, Patrick Pütz, C. d'Aubigny, Dathon Golish, Christopher Groppi, Christopher Walker, Benjamin Williams, Qing Hu, John Reno, Micromachined Spatial Filters for Quantum Cascade Lasers, 17th International Symposium on Space Terahertz Technology, P2-11, 2006.

[4] F.P. Mena, J. Kooi, A.M. Baryshev, C.F.J. Lodewijk, T.M. Klapwijk, R. Hesper, W. Wild, RF Performance of a 600 - 720 GHz Sideband- Separating Mixer with All-Copper Micromachined Waveguide Mixer Block, 19th International Symposium on Space Terahertz Technology, pp. 90-92, 2008.

[5] J. Kawamura, A. Skalare, J. Stern, E. Tong, C. Groppi, THz waveguide HEB mixer using Silicon-on-Insulator substrates for STO, 21st International Symposium on Space Terahertz Technology, in press, 2010.