LOW COST DIRECT MACHINING OF TERAHERTZ WAVEGUIDE STRUCTURES

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ABSTRACT

We present a low cost technique of direct machining of precision waveguide structures on metal blocks. The micro machine setup employs compact, precision numerically controlled (NC) stages to automate the machining process. Endmills are held in high speed pneumatic spindles, while other features are made by scraping ("broaching") in repeated small passes. We can set up two endmills and three broaches at the same time. The fabrication process is monitored under a microscope, while the ambient temperature conditions are controlled. The NC code is generated from a combination of AutoCAD drawings, commercially available CAD/CAM software and simulation software we developed for this process. Both halves of a reasonably complex tripler block can be fabricated in under 3 hours, including setup time. An estimate of the machining accuracy is about 7 μm, the accuracy being principally limited by the difficulties in visually inspecting the microscopic machined features and correcting the small tool offsets. We also discuss methods to extend this technique to the fabrication of THz waveguides.

1 Introduction

Traditional metal blocks manufactured using conventional machining techniques are used in most successful receiver systems in the submillimeter wavelength range. The components of such receiver systems include oscillators, multipliers and mixers, which mostly incorporate waveguides and their associated transitions. The waveguide is a well characterized, low-loss transmission medium, which affords easy and excellent coupling of the freespace modes to electronic circuit elements. As the desired wavelength of operation becomes smaller, so do the dimensions of waveguide and quasi-optical elements that comprise a receiver system. On the one hand, the small sizes are advantageous in the fabrication of high-resolution focal-plane imaging receiver systems. Such arrays have applications like radio astronomy, commercial and industrial applications like the extension of millimeter technology to collision avoidance

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radars, aircraft guidance and landing, contraband detection and personal communication systems, all of which benefit from having a large number of elements in a compact, practical sized system. However, as the sizes of components scale down, the cost of fabrication goes up. Indeed, the fractional cost of machined metal blocks containing waveguide electromagnetic elements in the overall budget of receiver systems, especially those that involve arrays, becomes prohibitively high with increasing frequency.

In the past decade or so, non-traditional techniques that can be collectively called "micromachining" are demonstrating practical means for producing a variety of submillimeter and terahertz frontend components [1]. Micromachining as a class is derived from manufacturing tools based on batch thin and thick film fabrication techniques of the electronic industry [2]. Many novel micromachining methods such as silicon wet etching [3], laser micromachining [4, 5], mold replication by the method of mastering, molding and casting [6] have demonstrated examples of components with performance equalling that produced by conventional machining. These new techniques, although offering great potential for the future, have many drawbacks, most of which are primarily due to the relative youth of such technologies.

At least for the submillimeter and low terahertz frequencies, conventional machining of metal, which has a long history of manufacturing engineering, can be used to fabricate receiver components. The method often used is the so-called "split-block" technique, where the circuit structures are machined on two (or more) metal blocks and then mated together to form complete components. The split-block technique offers the advantage that the machining is in principle straightforward. In addition, circuit components such as RF chokes, diodes and coupling structures can be easily placed on the split blocks prior to assembly of the complete piece. In the past, the main problems of conventional machining as applied to the fabrication of submillimeter and terahertz receiver systems have been (1) the high cost of machine tools and equipment, (2) the high level of expertise required of the machinist and (3) the fabrication time requirements. In this paper, we present a low cost technique of direct machining of waveguide structures on metal blocks that addresses all three of the aforementioned problems.

2 Micro NC Machine Setup

2.1 Positional Stages and Tooling

A schematic view of the machining setup is shown in Figure 1. The block to be machined is held in a metal plate that is attached to linear, compact, precision XYZ positioners [7]. The positioning stages employ precision ground leadscrews which have 5 μm of accuracy over the full 2 inches of travel. The resolution of movement of the stages is 0.1 μm, while the grating period and readout of the linear optical encoders sets the effective resolution to 1 μm. The drive systems for these positioners employ DC servo motors with rotary encoders for closed loop positioning feedback. The stages are made out of special-alloy aluminum tooling plate for good stiffness and long-term stability.

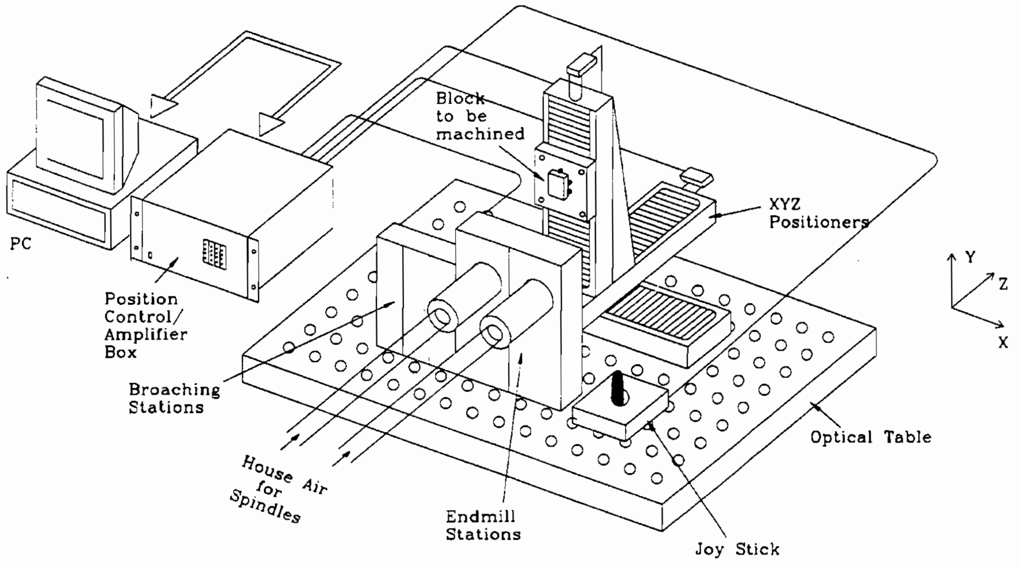

Figure 1: Schematic view of the micro NC machine.

Motion control of the positioning stages is accomplished with the PC-bus based Unidex 500 series controller [7]. The U500 interface card in the PC is connected to the DR500 amplifier/drive chassis. The amplifier and control box has cabling to control the XYZ drives. A digitizing joystick is also part of the system. The joystick allows the user to control the stages for coarse adjustments, tool registration and workpiece inspection. During actual machining, the joystick is disabled. The Windows based toolkit software has the option of loading user-supplied NC code and the option of single-stepping or free-running modes of operation.

Depending on the actual features to be cut, the removal of metal is accomplished with three different machining strategies and five different tools: milling with two endmills, broaching with an endmill insert, and scraping with two saws. Figure 2 shows a photograph showing the top view of the five tool holders.

The endmills are held in high speed, precision air bearing spindles that run at

Figure 2: Top view showing arrangement of tools.

70,000 rpm [8]. Air bearing spindles have low vibration and exhibit smaller temperature rise compared to electric motor driven spindles. For a given tool and workpiece material, there is an optimal cutting speed (CS) of machining, which is available from a machinery handbook [9]. For a given CS, measured in feet per minute (fpm), the spindle speed required, N, is given by $N = 3.82\frac{CS}{D}$ rpm, where D is the diameter of the cutting tool in inches. For small diameter endmills, required spindle speeds can be quite high. If higher spindle speeds are not available, the feed rate needs to be proportionately slower, resulting in increased time for machining. For high speed steel (HSS) endmills on brass, nominal CS is 100 fpm [9]. The required spindle speed for a 5 mil endmill is 76400 rpm. With regards to precision machining, the high spindle rpm that is a necessity for fabrication with small tools has some ancillary benefits as well: (1) High spindle speeds also has the effect of reducing the chip size by requiring a smaller feed rate per tooth, f_T (since $f_T \propto \frac{1}{N}$). Smaller chip loads result in improved surface finish. Good surface finishes are crucial for cutting down on waveguide losses. (2) High spindle rpm can reduce or eliminate secondary operations (such as deburring, or using finish passes) by improving surface finish of the workpiece in the primary machining operations. (3) The reduced cutting forces due to high spindle rpm gives better control while machining thin walls or brittle materials. (4) Reduced cutting forces reduces the heat transfer into the workpiece. A greater percentage of the heat generated by cutting is carried away with the chip in high speed machining. Reduced workpiece distortion leads to more accurate parts. (5) The high level of precision in the motion of the positioning stages is achieved in the absence of significant loads on the stages. High spindle speeds with small radial feeds are helpful in reducing the load, and hence in maintaining accuracy of the finished work. (5) High spindle speed is less likely to excite vibrations in the workpiece.

Dry, purified house air is used to power the turbines of the air bearing spindles to a constant speed of 70,000 rpm. The house air which usually has a pressure range between 85 to 105 psi is sent to a refrigerated air dryer [10]. Coalescing compressed air filters [11] are used at the inlet and outlet of the dryer. After passing through additional filters to remove any remaining particulates, the air enters a regulator which sets the output pressure to 80 PSI. A pressure switch/alarm detects any drop in pressure from the house air supply. Air for the spindle bearings is sent through a check valve. A backup nitrogen tank container is used to provide air for the spindle bearings should the house air fail during machining operations. The nitrogen tank can provide 25 minutes of bearing air in the absence of house air, so that spindles can be spun down safely. The spindle turbines are run directly from the regulated house air supply. As shown in Figures 1 and 2, two spindles are available for machining. The house air pressure is adequate for powering both spindles at the same time. However, the usual machining operation proceeds by using one of the spindles at one time.

The smallest endmill available commercially is of the order of 4 mils in diameter. Another problem machining with endmills is that they are not effective in cutting pockets where the depth is large compared to the diameter of the tool used. The typical cutting length of commercial endmills is only about 2 diameters (lengths of upto 3 diameters are sometimes available on special order). Thus endmills cannot be used for small and/or deep waveguide sections. For features smaller than 5 mils, thin saws are used in the micro NC machine. Small amounts of material are removed in repeated passes by "scraping" (broaching) type of operations where the workpiece is moved against a single saw tooth of a stationary blade. By exposing more of the tooth from the clamp, deeper cuts can be achieved. For example, a 5 mil saw was used to cut a waveguide section 18 mils deep. The saws, however are only capable of cutting straight sections of waveguide. Two saws of thickness 5 mils and 2 mils are used in the machine. The two saw blades are oriented so that their cutting motion is 180° from each other, that is, one saw cuts in the positive Y direction, while the other cuts in the negative Y direction.

Another tool that is used in the micro NC machine is a special order carbide milling insert with a sharp 90° corner [12]. This tool is used to cut diagonal feedhorns [13]. The insert was clamped in a stationary mount, and the horns cut by moving the workpiece in linear ramping motions only in the X-Z plane.

During actual fabrication, there are no tool changes involved. The workpiece is carried by the precision positioning stages to each tool. The relative coordinates of the tool positions to the workpiece are initially carefully measured by using target marks made at the same location by all tools on a corner of the workpiece. An electrical edge-finder is also used to determine tool offsets from the edges of the workpiece. In conventional milling machines many tool changes are required to fabricate parts, which can result in considerable errors in the fabricated parts.

For the sake of clarity, two other components that make up the precision machine system are not shown in Figure 1: a lubrication arrangement and a microscope viewing station. Lubrication for the machining operation is provided using a biostable, water soluble machine oil [14] that is delivered onto the work using a fixed clamp. The lubricant carries out the chips to a collecting pan and is recycled for use within a closed cycled system consisting of a gear pump, a water aspirator, a filter and a reservoir. Antifoaming additives are added to the lubricant mix to prevent foaming of the water soluble oil mixture. A specialized adjustable microscope mount allows the user to watch the actual machining operation with appropriate magnification. The microscope is mounted parallel to the Y-axis to allow for continuous monitoring of the machining operation.

2.2 Temperature Control

One of the crucial issues in precision machining is maintaining a constant temperature of the positional stages and the tool holders. At the tolerance levels required for fabricating high frequency waveguide structures, temperature changes of a few degrees can result in considerable errors. In this respect, the high speed air bearing spindles offer another advantage compared to conventional electric motor driven spindles which exhibit temperature increases of several tens of degrees during operation. The temperature rise in the air bearing spindles is only a couple of degrees centigrade after half an hour of operation, after which it remains stable. In order to understand the temperature stability of the room while operating the machine, temperature was monitored at eight different locations in and around the micro NC machine and careful records were kept.

After repeated experiments machining with and without temperature control, it was found that a closed loop temperature control system significantly improved machining accuracy and repeatability. A heater on the metal blocks that house the spindles (seen on top of the spindles in Figure 2) forms part of the control loop. Before commencing actual machining the machine is usually run for ten to twenty minutes to reach temperature equilibrium. Several fans and blowers are run around the machine to provide adequate circulation of air. At present, although the temperatures of the positional stages and workpiece are monitored, they are not controlled. The closed loop system maintains the temperature of the spindles to within half a degree of the temperature set point, 26° C, which is a few degrees above ambient.

2.3 Software Issues

The numerical control (NC) code to operate the stages is in "G-code" format, which is an industry standard. The initial design from 3-d Autocad drawings is imported into a commercial CAD/CAM package called Surfcam[15]. Surfcam is capable of generating NC code for 2-axis and 3-axis milling and for turning (lathe operations). Rectangular pockets and grooves are defined as 2-axis paths, while surface machining (where the feature bottoms could have ramps) are defined as 3-axis toolpaths. After chaining features to define the toolpaths, the NC code is generated within the software. Surfcam also has a graphical simulator to view the tool motions involved in the machining operation. A postprocessor that is specific to our chosen geometry and coordinate system was written. Running the postprocessor produces the required NC code. At present the NC code for the broaching operations is written manually. In order to test and troubleshoot the final NC program, a software program was written to convert NC code to a 3-d Autocad script file, which is subsequently run and viewed within Autocad to perform final verification. The combination of reasonably inexpensive commercially available software and overall ease of use of complimentary in-house software helps further reduce the normally high cost of precision machining.

3 Fabrication of Receiver Components

The micro NC machine described above has been used to fabricate several state-of-the-art receiver components. We have successfully fabricated several blocks of a 810 GHz tripler. The electromagnetic design for the tripler is outlined in [16]. Figure 3a shows a photograph of the split block of the fabricated tripler. Five different tools were used in the fabrication: two endmills of diameter 8 mils and 4 mils respectively, two saws of thickness 5 mils and 2 mils respectively, and the horn broach described above. Figure 3b shows a magnified view of the features in one half of the tripler block. The smallest feature of the tripler block is a 2 mil wide, 6 mil deep waveguide section. This section, that is part of the output waveguide, was cut using the 2 mil saw. The fabrication proceeded with the preliminary roughing operations with the endmills, followed by broaching with the horn broach and the saws. Subsequently, final deburring passes were required to remove chips generated by the broaching operations. After a few trial runs with dummy blocks, several fully functional units were fabricated. Careful inspection of the resultant metal blocks revealed a maximum error of $\sim 7\ \mu$m. Including setup time, both halves of the tripler block were fabricated in under three hours. The performance of the tripler fabricated with the micro NC machine was found to be comparable to a previous tripler fabricated with conventional machining. One of the finished tripler blocks now forms part of the LO system for a 810 GHz SIS receiver system being used currently at the South Pole AST/RO facility.

With this low cost precision machining technique, it is now possible to consider the construction of large format arrays of high performance heterodyne waveguide receivers. The first test SIS mixer block of a seven element 345 GHz focal plane

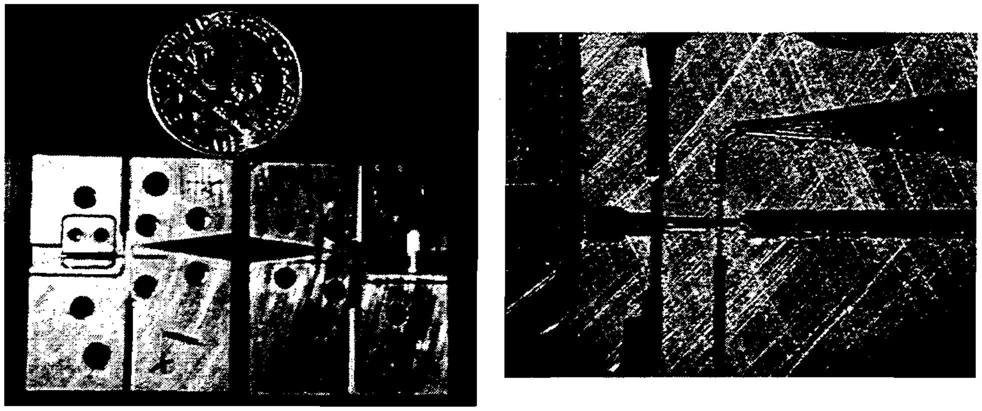

Figure 3: (a) Photograph of split blocks of a 810 GHz tripler fabricated using the micro NC machine. (b) Magnified view of one half of the tripler block showing details of the waveguide features. For details of the electrical design see [16].

array [17] for the HHT was fabricated with the micro NC machine. Figure 4(a) shows the fabricated split blocks and Figure 4(b) shows the magnified details of one half of the split block. The mixer employs a diagonal feed horn to half-height rectangular waveguide transition. A suspended stripline substrate channel orthogonal to the waveguide houses the SIS junction. The 345 mixer block was machined with the horn broach described above and a 6 mil endmill. The maximum error in the machined mixer blocks is $\sim 8\ \mu$m.

The micro NC machine has also been used as a precision lathe to turn coaxial pins to be used in multiplier circuits. The pin is held in the high speed spindle and one tooth of a saw blade held in the XYZ positioners was used as the turning tool. Preliminary results of this procedure indicates that the remaining problems to overcome in making precision, micro diode pins are mostly related to software issues.

4 Fabrication Considerations for Terahertz Components

The resolution and accuracy of the positional stages in the present system can be upgraded with commercially available stages. However, one of the principal limitations to extending this technology to terahertz waveguides is the requirement for small tools. For example, the dimensions of a half-height 2.5 THz waveguide are $\sim 96 \times 24\mu$m. To fabricate such a waveguide, one would need a cutter smaller than 1 mil in diameter. Grinding down saws to small thicknesses should be feasible by using the high-speed spindles as a microgrinder. Only straight sections of waveguide can be fabricated with these tools. The rigidity of a tool is inversely proportional to the third power of its thickness. In order to prevent breakage of thin saws, the toolholder will

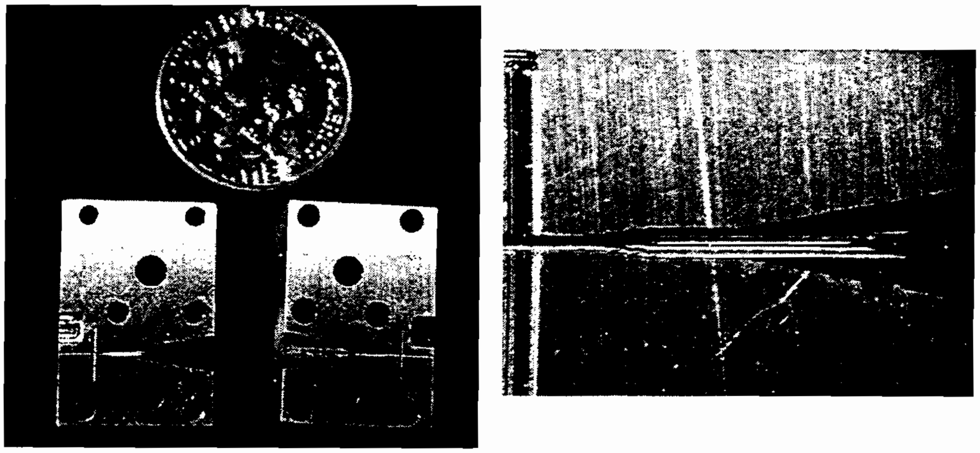

Figure 4: (a) Photograph of split blocks of a 345 GHz SIS mixer block fabricated using the micro NC machine. (b) Magnified view of one half of the mixer block showing details of the transition from diagonal feedhorn to half-height waveguide. For details of the electrical design see [17].

need to clamp the tool closer to the cutting edge, which in turn causes the maximum cutting depths to become shallower. One alternative is to make custom endmills, which when used in the high speed spindle does not suffer the rigidity problems of stationary tools.

Another challenge in the fabrication of terahertz structures is maintaining the temperature of the workpiece and toolholders. Enclosing the entire machine in a closed chamber and using a closed loop system with less than 0.1 K of absolute change in temperature will result in higher dimensional accuracy of the parts produced.

The features that are produced with the micro NC machine are extremely tiny and stretch the limit of metrology tools associated with conventional microscopes. One of the limitations of the current system is the difficulty of measurement of test target features to identify tool coordinates with respect to the workpiece. Good relative tool registration between tools and the work is crucial in the production of useful terahertz components. A metrology system with a high resolution digital camera attached to high magnification scopes and coupled with an image processing software package will be required to improve the accuracy of measurement and thus correction of relative tool positions.

5 Summary

1. A low cost technique for the fabrication of terahertz waveguide components by direct machining on metal has been presented. The machine setup uses high

speed air bearing spindles, precision positioning stages and NC programming to cut down costs, fabrication time and expertise levels required for the fabrication of high frequency components.

2. This novel micro NC machine has been used to fabricate a 810 GHz tripler and elements of a 345 GHz focal plane array.
3. With relatively minor improvements, this technology has potential to be extended to produce reliable terahertz receiver components up to 2.5 THz.

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