Laser Microchemical Etching of Waveguides and Quasi-Optical Components

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ABSTRACT
Laser induced micro chemical etching of silicon can be used to quickly and cheaply machine high-quality three-dimensional structures that would otherwise be nearly impossible to fabricate, in particular THz waveguide structures and quasi-optical components. At the University of Arizona, the construction and characterization of the first laser micro-machining system designed for waveguide components fabrication has been completed. Our system can be used to fabricate focal plane heterodyne mixer arrays, coherent beam combiners, AR grooved silicon lenses, phase gratings, single mode filters and more. Laser micro machining enables the fabrication of three-dimensional structures down to a few microns accuracy and up to 6 inches across in a short time. This presentation discusses the design and performance of our micro-machining system, and illustrates the type, range and performance of quasi-optical components this exciting new technology will make accessible.

Keywords: Laser, micro-machining, heterodyne mixer array, wave-guide, AR, spatial filtering, beam combiner, THz, FIR

1. INTRODUCTION
Laser micro chemical etching works by focusing several watts of laser power on a silicon wafer in a low-pressure chlorine ambient (200 Torr). The deposited energy vaporizes a cylindrical region 6 \( \mu \text{m} \) wide and 1 \( \mu \text{m} \) deep. Vaporized silicon atoms react immediately with chlorine molecules to form silicon tetrachloride, which is gaseous at the pressure used and prevents re-deposition on the substrate (see Figure 1). Melted silicon not captured by chlorine re-deposits epitaxially as soon as the beam is moved to a different position.

Laser micro machining possesses a significant edge over conventional techniques. It does not require the use of masks, and it is not confined to any given crystal plane. A non-contact process, laser micro machining eliminates tool wear and vibration. Processing silicon in chlorine ambient eliminates hard to remove particulate residues. The chemical activation on which this process is based minimizes the etching energy requirement and therefore reduces the potential for cracking [1]. In most cases the etch depth is only limited by the motion range (5mm) of our vertical stages. The laser micro machining process is entirely computer controlled and permits proven complex designs to be scaled to micron sizes. The system also allows fast prototyping: the magic tee structure presented in this paper (section 5.1) took less than 5 minutes to fabricate. Larger complex structures such as the corrugated feedhorn presented below may take up to 1 hour of actual machining time. Generally, the complexity of the structure has little impact on process time; in practice, only the size and volume of the region to be etched have a significant effect.

2. PRINCIPLES OF LASER MICRO CHEMICAL ETCHING
A multiline Argon-Ion laser is used to heat a microscopic portion of the silicon substrate in a chlorine ambient. At the onset of melting, volatile silicon chlorides are formed. The highly non-linear activation energy of the process confines etching to a molten zone only a few microns across. Crystalline materials like silicon have the benefit that un-etched portions of the molten zone grow back epitaxially, allowing controlled shavings to be removed plane by plane. Structures can thus be built by limiting the etch depth at each scan plane, to typically 1 \( \mu \text{m} \) (see Figure 1).
Figure 1-a (left), 1-b (right): 1-a. The focused spot of a laser is scanned across a silicon wafer. Silicon atoms are vaporized, and immediately react with the ambient chlorine molecules preventing re-deposition. Using relatively high numerical aperture (NA) optics confines the etching to a region only a few micrometers wide. The trade-off of high NA is a tapering of the beam that cause significant shadowing in some applications like high aspect ratio vertical walls [1]. 1-b. The Gaussian beam behavior of the laser provides a ~100 µm deep region [2] where vertical walls can be machined without significant shadowing or loss in resolution.

3. SYSTEM DESIGN

The system we have built at Steward Observatory (Figures. 2 through 5) is equipped with a Coherent Inc. 30W, water-cooled, Argon Ion, laser used at 488 and 514 nm. While only 4W is actually required on the sample, system losses (~50%), and the need to stop the laser beam to a small aperture to obtain a TEM$_{00}$ Gaussian beam increase the laser power requirements. The beam waist diameter when focused on the silicon is ~6µm [2]. The F/# of the system is 5, causing a beam geometrical taper angle of 6° and a practical aspect ratio of 10:1. However, in the 100 µm focal region of the laser, vertical walls with an extremely high aspect ratio can be achieved (See the waveguide elbow on figure 10). The currently available scanning range is limited by the unvignetted field of view of our scanning lens (~ 5 x 5 mm). The reaction chamber is mounted on high accuracy (0.1 µm) motion stages, which enable the stitching of structures up to 150 mm in diameter to be machined.

In our design, the laser beam is expanded to 16mm, and then telecentrically steered by a commercial two axis galvo-mirror scanner onto an achromatic scanning lens. The focused beam is then introduced through a fused silica window into a stainless steel reaction chamber containing the silicon substrate (see figure 2). The wafer surface temperature is biased to 120°C using a parabolic IR illumination source shining through a sapphire window on the backside of the reaction chamber (see figure 2). Thermal bias minimizes the amount of energy that needs to be locally deposited by the laser to vaporize silicon, and hence reduces the likelihood of cracking. Background etching does not become significant till 400°C. The process is monitored through the focusing optics using a CCD with a plate scale of 7 µm per pixel. The scanning system is driven directly from computer-generated patterns, which can be constructed using Autodesk's AutoCAD. The ensemble is mounted on computer controlled Kensington X-Y-Z precision motion stages (see figure 3) allowing the stitching of large structures.
Figure 3: The laser micro machining optical hood. The Argon-Ion laser is visible in the back. On the right side of the image, the beam can be seen reflecting off relay mirrors, passing through the electronic shutter and beam expander. The beam-splitter, wave-plates and CCD camera labeled on the image are not visible from this angle. The open reaction chamber loaded with a silicon wafer can be seen. The entire assembly is mounted on precision motion stages.

Figure 4: Left: Ensemble view of the Steward Observatory laser micro-machining system. Right: Optics shelf, a half wave plate is used to minimize losses at the beam splitter. The beam then goes through a quarter wave plate to provide the galvo mirrors with circular polarized light.
4. EXPERIMENTAL PROTOCOL

Before operation the cell is evacuated, then filled with 99.9 % pure chlorine gas to 100 Torr. After 2 hours of machining, the remaining chlorine gas and silicon chlorides are vented through a sodium thiosulfate scrubbing bubbler before release in the atmosphere. Figure 4 shows the system in our laboratory. The chlorine and nitrogen gas cylinders are stored in the gas cabinet on the right. The central hood houses the laser, reaction chamber, and optics. The vacuum pump and chlorine scrubbers are contained in the small gas cabinet on the left.

The operating parameters used to produce the structure presented in this paper were: substrate temperature of ~120°C, chlorine pressure 200 Torr, laser power on the silicon 4W and a scanning speed of 3 cm/s. Using these parameters 1µm deep layers were etched at a rate of 0.27mm³/hr, consistent with previous MIT Lincoln Laboratories findings [1]. From measurements obtained in our previous collaboration with Lincoln Laboratories, the expected surface finish out of the laser micro machining system is ~0.1µm r.m.s. This value can be improved to better than 25nm r.m.s. through the use of isotropic etches. With those numbers, the expected losses at 2THz are only 20% more than that of an ideally polished waveguide surface.

5. DEVICES

Laser micro machining permits the direct scaling of successful waveguide and quasi-optical components to THz frequencies. The process works best for structures that can be machined directly onto a 2-dimensional surface. For example, `split-block' waveguide components and anti-reflection (AR) grooves are well adapted for fabrication with this process. Here we discuss four specific examples of laser machined components, waveguide magic-Tee’s, feedhorns, and lenses and AR coatings. These components are needed at THz frequencies to enable the construction of efficient receiver systems for space and airborne astronomy as well as space-based communication systems.

5.1. MAGIC TEE

The magic tee is a four-port network in which an incident signal on any one port divides between two output ports with the remaining port being isolated. The magic tee has been used primarily at microwave frequencies in a number of applications, including coherent power combining and balanced mixers. Figure 5 is a schematic of a basic waveguide magic tee. If the E-arm (Port 3) is match terminated, then signals incident at Ports 1 and 2 will be isolated from each other and combine in phase at Port 4 (Rizzi 1988). This configuration of a magic tee could be used to coherently combine the local oscillator power from 2 or more independent sources or as the heart of a coherent beam combiner for space interferometry missions. A prism-like structure can be laser micro machined in silicon to produce the needed matched termination.

Figure 5: Schematic of magic tee structure (Rizzi, 1988).

As a proof-of-concept, we have used the laser micro-machining system to fabricate a waveguide magic tee at ~1.2 THz. An SEM photograph of the structure is shown in Figure 7. The aspect ratio of the walls is quite high and the surface finish
appears almost optical in quality. It should be noted that the structure shown in Figure 7 was our first attempt to make a magic tee and only took ~4 minutes to fabricate.

Figure 6: SEM snapshot of the central part of a 1.2 THz magic T structure.

5.2. FEEDHORNs

In the diffraction limit, Gaussian beam optics is often used in the design of telescopes and receiver systems. Waveguide feedhorns provide an extremely efficient means of launching Gaussian beams. Indeed, corrugated and dual-mode feedhorns are capable of coupling ~98% of their power into the fundamental Gaussian mode, making them the most efficient means of transferring power into and out of many quasi-optical systems. In comparison, dielectric lens planar antennas have a Gaussian beam coupling efficiency of at best ~89% (Goldsmith 1998).

Laser micro-machining can be used to fabricate corrugated and dual-mode feedhorns well into the THz range. Test results of a 2 THz laser machined feedhorn are published in an earlier THz conference proceeding (Walker et al. 1997). An SEM photograph of an 850 GHz feedhorn made at Lincoln Labs using a similar system is shown in Figure 8. The throat of the feedhorn terminates in a section of circular waveguide followed by a circular-to-rectangular transition, which is stepped to quarter height waveguide. With laser micro machining this entire structure can be fabricated in one run. There is no need for tool changes or photolithographic masks. With this technology, the fabrication of efficient, large, format feedhorn arrays becomes tractable.
Figure 7: Laser micro machined corrugated circular feedhorn with stepped transition to rectangular waveguide fabricated at MIT Lincoln Laboratories.

Figure 8, below, is a conceptual drawing of a 10x10 array of laser machined, dual-mode feedhorns to be used in an 810 GHz prime focus camera for the LBT. The small (1.2 mm diameter) feedhorns are the only quasi-optical components needed. The geometry of a dual-mode feedhorn obviates the need of split-block construction. All 100 feedhorns can be machined in a single small (~1.5x1.5 cm) square of silicon. Metallization of the feedhorns will be performed using an e-beam evaporator.

Figure 8: Left: 3D rendering of a 10x10 array of dual mode feedhorns for a prime focus camera to be used on the Large Binocular Telescope. Right: Design of individual horn.
5.3. SILICON LENSES AND ANTI-REFLECTION “COATINGS”

Dielectric lenses are widely used in sub-millimeter-wave systems. They play a critical role in forming the beam of planar antennas, such as the double slot and dipole. In addition, quasi-optical systems utilizing dielectric lenses are often more compact than comparable systems designed using reflective optics (see figure 12). The main disadvantages of using lenses are reflective losses off their surfaces and absorption of power in the lens material itself. With the proper choice of dielectrics, such as silicon, the absorption losses can often be kept to only a few percent. However, the reflected power off the surfaces of even low index of refraction materials (e.g. Teflon) can be as high as 12%. Lenses made with higher dielectric materials have shorter focal lengths and greater mechanical strength. To overcome the increase in the fractional power reflected from the surfaces of such materials, they must be coated with one or more layers of a dielectric with an index of refraction intermediate between the lens material and free space (Goldsmith 1998). Alternatively, the surface of the lens itself can be machined to simulate the required matching layer (Morita and Cohn 1955). In practice, this is usually achieved by etching concentric, $\lambda/4$ grooves in the dielectric surface.
Figure 12: Optical Microscope image of a laser micro-machined 0.1mm diameter silicon lens. The radius of curvature of this lens is 50 µm resulting in a f=~10µm lens.

An example of a 1.5 THz AR grooved silicon window is shown in Figure 8-a. The bandwidth of the matching layer can be increased by etching grooves with a triangular cross-section several wavelengths deep. However, both the rectangular and triangular concentric grooves are polarization sensitive. This sensitivity can be avoided if an array of holes is used instead of concentric grooves to simulate the required dielectric layer. If the holes have a conical cross section and are several wavelengths deep, the surface can also be used over a wide frequency band (Lesurf 1990). A 3-D CAD representation of such a surface made in silicon for operation at 1.5 THz is shown in Figure 10-b.

Due to their small size scales, it has been impossible to use simulated dielectrics as AR coatings at THz frequencies. However, with laser micro machining it is straightforward to machine either concentric grooves or holes like those depicted in Figure 8 directly into silicon quasi-optical components, such as lenses and vacuum windows. We plan to utilize these structures in THz receiver systems we are constructing for AST/RO and SOFIA.

Figure 11: Conceptual 3D rendering of 1.5 THz AR matching layers in silicon. (top) Using concentric rectangular grooves. (bottom) Using conical holes.
6. SUMMARY

Laser micro machining provides a mean of scaling successful waveguide and quasi-optical components to THz frequencies and even to far infrared wavelengths. A laser micro machining system optimized for THz applications is now in operation at Steward Observatory. We have fabricated prototype magic tee structures, single mode filters at \( \lambda = 100 \mu \text{m} \), silicon lenses and AR coatings. We are currently working on improving the reliability and calibration of our system. We will soon start fabricating and testing coherent beam combiners and directional couplers.

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