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# Ultrashort laser micro-machining of thick terahertz mesh filters

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**Abstract**

The laser micro-machining technology is an attractive alternative to conventional photoresist-based technologies for manufacturing terahertz (THz) cross-shaped mesh filters. However, laser micro-machining results side-wall tapering that impact both achievable geometrical and dimensional accuracy and also affects negatively the performance of THz filters. This research proposes a novel fabrication process, called laser precession machining, that addresses the laser micro-machining limitations in producing THz mesh filters. It employs an ultrafast laser and a “precess” module to vary the beam incident angle and thus to reduce the taper angle on the sidewalls of the filters’ cross-shaped through holes. A significant reduction of this negative tapering effect was achieved on micro-structures produced with this new method that led to a significant improvement of their performance. Also, the performance of fabricated THz mesh filters were in good agreement with the simulation results.

**Keywords:** Terahertz, Cross-shaped, Mesh Filter, Laser Micro-machining, Precession, Tapering Effect.

## 1. Introduction

Photolithography that employs SU-8 photoresist has been used to manufacture THz components and frequency selective surfaces. This technology typically produces components with a very high geometrical accuracy, especially in regard to the taper angle on the micro-structures’ sidewall, that affects the mesh filters’ performance. However, photolithography can only process photoresist materials with their limited mechanical, thermal and electrical properties. In addition, SU-8 has a high electrical resistivity and therefore the photoresist-based manufacturing technologies for producing THz devices have to include a metallization step. Another limitation of this technology is that they are capital intensive and therefore are mostly viable for relatively large batch sizes while the unit costs are still relatively high. In this context, laser-based micro machining offers unique advantages compared to photoresist-based manufacturing technologies, especially for producing THz frequency selective surfaces. It is a direct write and non-contact process and can be used to structure almost any material [1].

This research reports a feasibility study in the use of this technology for producing THz devices, especially THz mesh filters. The specific objective is to investigate the capabilities of a novel laser micro-machining technology, called precession laser micro-machining, for producing cross-shaped, free-stranding THz mesh filters out of metal materials directly without requiring any dielectric substrates. We also choose to demonstrate the capability of lasing processing by machining a ‘thick’ mesh filter structure [2] which presents additional fabrication challenges. In particular, a precession module was integrated into a reconfigurable workstation to control the incident angle of the laser beam. In this way, it was possible to control the beam incident angle and thus to minimize and potentially eliminate the negative tapering effect on accuracy of micro structures. The feasibility study was conducted by manufacturing THz mesh filters with different dimensions and aspect-ratios for their critical features, and thus to demonstrate the capabilities of this novel laser micro-machining process. As a reference for comparison purposes, recently reported approach for minimizing the tapering effect, called two-side laser micro-machining [3], was employed to fabricate the same THz mesh filters.

## 2. THz mesh filter design and fabrication method

### *2.1. Cross-shaped THz mesh filters*

Two designs of terahertz mesh filters was used in the research which were designed to allow frequency of 0.3 THz (300 GHz) to pass through them. The first mesh filter design (Design 1) is a single-pole filter that transmits only one peak frequency. While the second mesh filter design (Design 2) is a two-pole filter and allows two peak frequencies to pass through it. In general, the functional feature of the two filters’ designs are arrays of cross-shaped through holes with dimensions as shown in Fig. 1. The sidewalls of the cross-shaped holes are normal to the mesh filter surface. 99.9% purity copper was chosen as a substrate material.

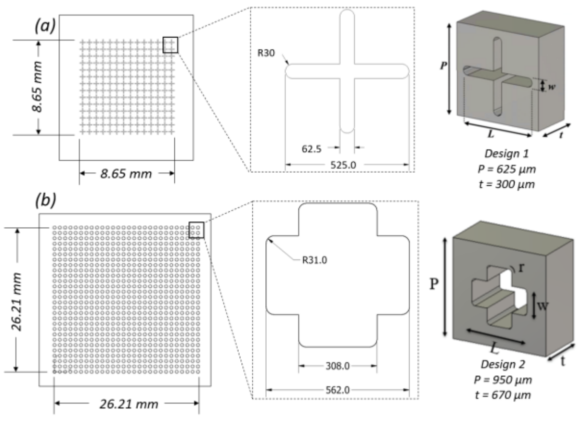


Fig. 1. The two THz mesh filter designs: (a) Design 1 and (b) Design 2. Note: the dimensions of cross-shaped holes are given in µm. P – Periodicity; L – Length; w – Width and t – thickness.

### *2.2. Laser micro-machining system*

The THz mesh filters were fabricated using a LASEA LS-4 workstation that integrates a laser source with wavelength of 1030 nm and pulse duration of 390 femtoseconds. A schematic representation of the laser micro-machining setup is provided in Fig. 2. The maximum pulse energy was 80 µJ at a repetition rate of 100 kHz. The LS-precess module allows a parallel offset and rotation of the laser beam about the beam central axis with a maximum speed of 30,000 rpm. The laser beam is then steered with X and Y deflectors before the focusing telecentric lens with focal length of 100 mm to achieve beam spot size of approximately 30 µm at the focal plane. The workpiece is placed on a stack of X and Y direct-drive linear stages. Each individual cross-shaped hole was machined by using only the X and Y beam deflectors while the mechanical stages were used to reposition the beam for machining the arrays of holes. A fume extractor was used to evacuate any debris from laser-material interaction.

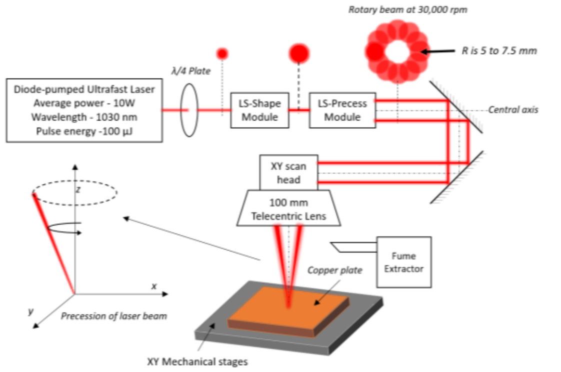


Fig. 2. A schematic representation of the laser micro-machining setup.

*2.3. Precession laser machining*

The LS-precess module allows a beam offset in the range from 5 to 7.5 mm while the beam remains parallel to the original central axis [4]. Then, the laser beam is rotated at high speed (up to 30,000 rpm) to create a donut ring with a diameter from 10 to 15 mm after the LS-precess module. The precession movement of the laser beam after the focusing lens is created by focusing the donut ring with a telecentric lens as depicted in Fig. 3. When the beam is offset and parallel to its central axis, the angle between the approaching beam and the first surface of the telecentric lens is no longer normal. Consequently, the output beam approaches the workpiece surface with a controllable attack angle (Fig.3a). The diameter of the donut ring was kept at 12 mm approximately and thus to maximize the attack angle while avoiding any potential clipping of the rotating laser beam at the scan head aperture. This resulted in a beam attack angle of 3.46 degree after the telecentric lens. The advantages of using an incident beam that is not anymore normal to the focal plane and at the same time rotates at high speed are to ablate the material at the holes' sidewall more efficiently. This is very important when high aspect ratio structures have to be produced and the evacuation of the ablated material becomes much more difficult. Using this technique, through structures with vertical sidewalls or even a negative taper angle can be produced as shown in Fig.3b.

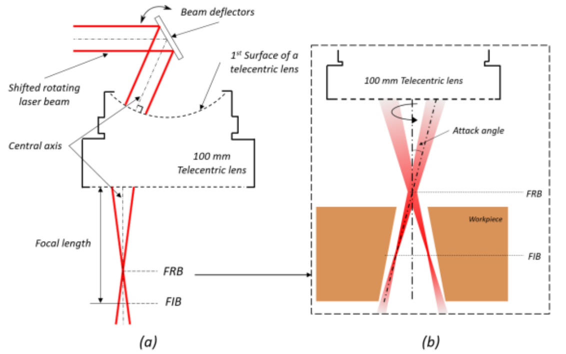


Fig. 3. A schematic representation of laser beam precession movements: (a) the precession movement of the laser beam created by focusing the rotating beam, (b) zero or negative tapering effect achievable with a precession laser beam.

*2.4. Two-side laser machining*

The two THz filter designs were also fabricated using the two-side laser processing method [3]. An ultrafast laser source was used to produce the filters while the same circular polarization, 100 mm telecentric focusing lens and same mechanical stages were utilized. The maximum pulse energy was set at 80 uJ and achieve an accumulated fluence of 8.2 J/cm$^2$. In addition, a hatching strategy with a step-over distance of 10 µm was deployed to produce the holes. The pulse repetition rate was 100 kHz.

## 3. Results and Discussion

*3.1. Dimensional Accuracy*

Four samples of the THz mesh filters were fabricated by employing the two laser micro-machining approaches described in Section 2. Sample 1 (S1) and S2 are single-pole filters, while S3 and S4 are two-pole ones. The two-side laser machining approach was employed to produce S1 and S3 while S2 and S4 were produced with the precession laser machining method. In general, the ultrafast laser processing of copper substrates results in clean structures with well-defined edges.

*3.1.1. Taper angle analysis*

Table 1. Average taper angles at the sidewalls of the two THz mesh filter designs with the machining times (T-S – Two-side; P – Precession)

| ***Filter designs*** | ***Design 1*** | | ***Design 2*** | |
|---|---|---|---|---|
| | ***S1*** | ***S2*** | ***S3*** | ***S4*** |
| ***Method*** | ***T-S*** | ***P*** | ***T-S*** | ***P*** |
| ***Taper angle [deg.]*** | *4.1* | *1.6* | *11.5* | *1.9* |
| ***Machining time [hr]*** | *6* | *6* | *24* | *26* |

The precession laser machining method led to better results with regard to the geometrical accuracy of the cross-shaped holes. Table 1 provides the measurement results, showing the reduction of the tapering effect at the sidewall in comparison to the two-side method. The average taper angle was reduced 2.6 times from 4.1 degree to 1.6 degree for the single-pole filter (Design 1). A bigger reduction of the taper angle was achieved for the two-pole filter, i.e. from 11.5 degree to 1.9 degree (6.1 times). In addition, it is important to note that this improvement was not at the expense of total machining time in spite of the fact that the precession machining process was not optimized. Especially, the machining times of S1 and S2 were the same while there was an increase of only 2 hours for S4 in comparison to S3. Fig. 4 shows the cross-shaped hole's morphology obtained with by two-side method. The narrowing of the hole at the middle is an inherent issue associated with the two-side method. This is the result of the tapering effect that is common for any structure machined with a normal incident beam. This effect can be almost fully eliminated when the structurers are machined with a precession beam which leads to a significant increase of their accuracy, both dimensional and geometrical. It is worth stating that the taper angle could even be eliminated through a further optimization of the precession machining process.

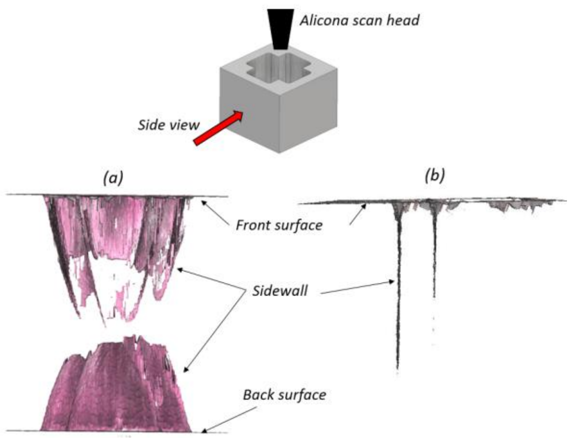


Fig. 4.A comparison of hole's morphologies obtained with the two laser machining methods: (a) the narrowing effect in the two-side method; and (b) the straight vertical cuts along the hole profile produced with the precession method that define the sidewalls.

*3.1.2. Dimension in XY plane*

It can be seen in Table 2 that length and width of the S1 holes are generally bigger than those of S2 in X and Y, and also on both sides of the single-pole filter. In general, the deviations are more pronounced on the front side in comparison with the opposite one of the single-pole filters produced with both methods. The deviations from the nominals were higher for the two-pole filter fabricated with the precession method (S4) compared to those on the S3 filter produced with the two-side one. However, the better accuracy in XY plane achieved with the two-side method did not lead to a smaller taper angle or more importantly to a better filter's performance. In general, the variation of S2 and S4 dimensions were smaller on the exit side in comparison with the values obtained on the entrance side of the filters produced with the precession method. The sources of errors in the two-side method were discussed in details in another research [3]. The deviation between measurements and the nominals of the filters fabricated with the precession method can be attributed to several reasons. First, the ellipticity of the laser beam played a role and has led to deviations of the dimensions in X and Y plane. The second reason is the larger divergence of the focused precession beam than that of the "conventional" laser beam. Therefore, the precession beam is more sensitive to variations of the focal distance, e.g. due to any flatness deviations of the substrates used to produce the filters. The third reason is non-optimized machining strategy and processing parameters that were used to produce the filters with the precession method. In particular, the negative effects of multiple cuts and passes on dimensional accuracy in the layer-based machining strategy can be minimized by optimizing the process and by introducing compensations to the X and Y dimensions. In addition, the errors associated with the used telecentric lens to focus the precession laser beam should be investigated and taken into account in optimizing the process. Finally, the repeatability of beam deflectors and the uncertainty associated with the measurements also contributed to the obtained deviations from the nominals. The periodicity deviations from the nominal values of S1 and S2 were less than those on S3 and S4. This can be explained with the smaller number of cross-shaped holes and thus the machining fields of S1 and S2 are smaller and less prepositional movements with the mechanical stages are required. At the same time, the better periodicity obtained with the precession method can be explained with the machining of the filters from one side only and thus avoiding the alignment error in the two-side method.

Table 2.Dimensional measurements of the single-pole (S1 and S2) and two-pole (S3 and S4) THz mesh filters produced with the two machining methods.

| Dimensional measurements | | Nominal dimensions [μm] | | Average Measured Value [μm] | | | | Average deviations from nominals and standard deviation of measurements [μm] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | D1 | D2 | S1 | S2 | S3 | S4 | S1 | S2 | S3 | S4 |
| Method | | | | T-S | P | T-S | P | T-S | P | T-S | P |
| Front side | Length X | 525 | 562 | 554 | 539 | 585 | 647 | 29 ± 4.4 | 14 ± 2.2 | 23 ± 3.1 | 85 ± 8.6 |
| | Length Y | 525 | 562 | 577 | 556 | 552 | 662 | 52 ± 3.3 | 31 ± 3.7 | -10 ± 4.4 | 100 ± 4.7 |
| | Width X | 62.5 | 308 | 108 | 62 | 329 | 392 | 45 ± 2.9 | -1 ± 3.0 | 21 ± 2.3 | 84 ± 9.6 |
| | Width Y | 62.5 | 308 | 111 | 77 | 298 | 409 | 49 ± 5.7 | 14 ± 6.2 | -10 ± 4.7 | 101 ± 3.6 |
| Back side | Length X | 525 | 562 | 557 | 520 | 586 | 607 | 32 ± 3.8 | -5 ± 2.2 | 24 ± 2.6 | 45 ± 6.3 |
| | Length Y | 525 | 562 | 561 | 523 | 552 | 610 | 36 ± 2.2 | -2 ± 3.3 | -10 ± 3.5 | 48 ± 6.1 |
| | Width X | 62.5 | 308 | 93 | 56 | 330 | 353 | 31 ± 3.7 | -7 ± 1.4 | 22 ± 2.0 | 45 ± 6.6 |
| | Width Y | 62.5 | 308 | 81 | 64 | 296 | 355 | 19 ± 1.8 | 1 ± 3.8 | -12 ± 4.0 | 47 ± 4.9 |
| | Periodicity X | 625 | 950 | 625 | 625 | 951 | 951 | 1.3 ± 1.7 | 0.7 ± 0.8 | 1.5 ± 1.9 | 1.5 ± 1.8 |
| | Periodicity Y | 625 | 950 | 626 | 626 | 950 | 951 | 1.2 ± 1.3 | 1.2 ± 1.0 | 1.7 ± 2.2 | 1.3 ± 1.5 |

*Note: D1 – Design 1; D2 – Design 2; T-S – Two-side and P – Precession.*

*3.2. Performance of THz mesh filters*

The ultimate assessment and comparison of THz mesh filters produced with the two-side and the precession methods can be obtained by analyzing their functional performance, i.e. the S-parameters obtained with the free space Quasi-Optic system [5]. Fig. 5 shows the measurement results of single-pole filters fabricated with the two different machining methods. It can be seen that the S1 filter fabricated with the two-side method provide a single pole (S11 parameter) but the peak of the resonance frequency was shifted to the right of the simulation ones. The minimum insertion loss of the S1 filter was 3.9 dB. The high-than-expected insertion loss can be attributed to the low dimensional accuracy achieved by the two-side method, especially, the narrowing effects in the middle of the S1 cross-shaped holes. In contrast, the performance of the S2 filter was much better, especially the single pole frequency (S11) was sharply defined. The resonance frequency was slightly shifted to the lower frequencies in comparison to the simulation results with 3 GHz offset (~1% error). The minimum insertion loss of S2 filter was 0.8 dB when the filter was measured at its original reference orientation. The bandwidth was also closer to the S2 simulation results.

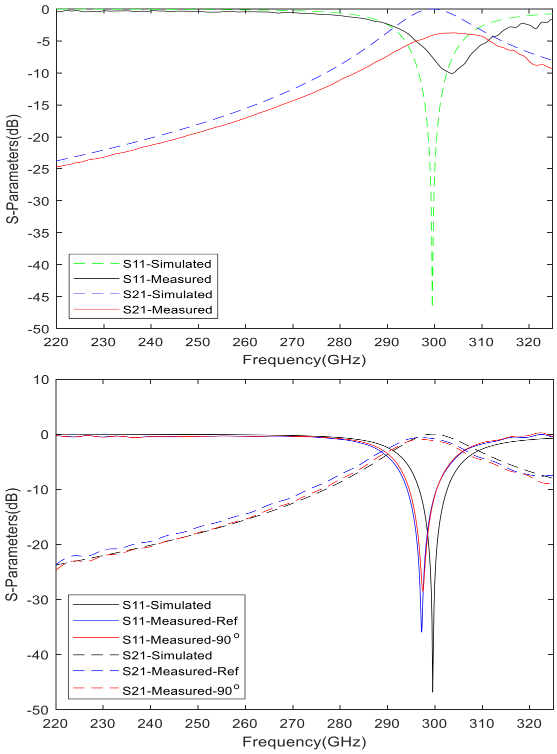


Fig. 5. The performance characteristics of single-pole filters: (top) S11 and S21 parameters of the S1 filter; (bottom) the S11 and S21 parameters of the S2 filter.

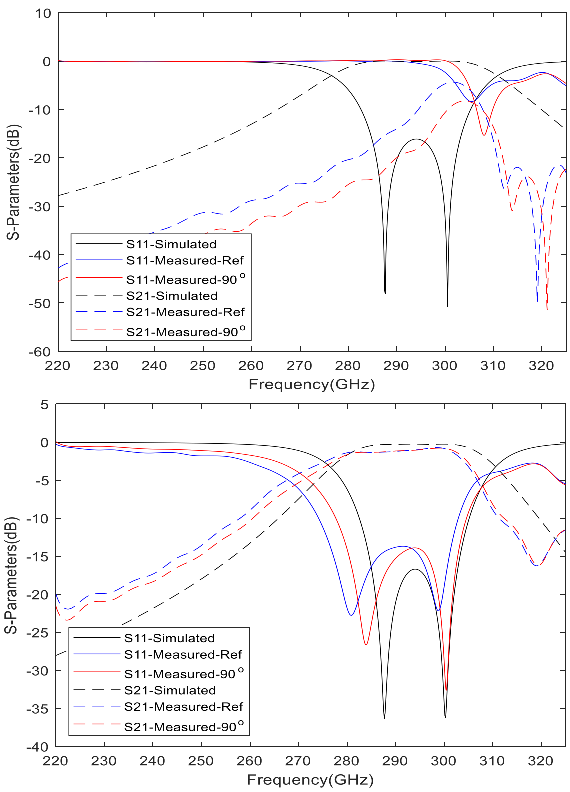


Fig. 6. The performance characteristics of two-pole filters: (top) S11 and S21 parameters of the S3 filter; (bottom) the S11 and S21 parameters of the S4 filter.

The performance of the two-pole filters is depicted in Fig. 6. Again, the performance of the filter fabricated with the two-side method (S3) was not satisfactory due to the large deviations from the nominal dimensions. The S11 measurements did not show two well defined poles and there was a significant shift of 10 GHz to the higher frequency. The minimum insertion loss was 4.6 dB and the bandwidth was much smaller than the simulation results. On the other hand, the S11 and S21 characteristics of the S4 filter were in good agreement with the simulation results. The two poles of the 2nd-order filter can be clearly seen and one of the poles coincides exactly with the simulated frequency of 300 GHz. The S21 measurements showed a minimum loss of 0.8 dB. In addition, the S4 bandwidth was very close to the simulation results but was slightly shifted to the lower frequencies.

It can be clearly seen that the S2 and S4 filters provided similar results with their two different orientation that indicates a consistent performance. The shifting of frequency (S11) can be attributed to the difference between designed and actual thickness of the filter [6].

## 4. Conclusion

Two different designs of cross-shaped THz mesh filters with thickness of 300 µm and 670 µm were successfully fabricated by laser precession machining of copper substrates. By employing this method, it was possible to reduce the taper angle by 3 times and 6 times in producing the through cross-shaped holes of single-pole and two-pole filters, respectively, compared to the reference two-side method. The performance of the produced THz mesh filters were had demonstrated clearly the process potential in spite of employing a sub-optimal machining strategy. The S-parameters of the single-pole filter were very closed to the simulation results, with only 3 GHz offset that is equivalent to 1% error. The two-pole filter provided two clear reflection zeros (transmission poles) while one of them was at the designed frequency of 300 GHz. The insertion loss of the filters was 0.8 dB.

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