PHYSICS AND MATHEMATICS

3D LASER FABRICATION OF CONICAL FIBER TIPS

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ABSTRACT
This paper investigates the 3D laser fabrication of microoptics with sharp conical tips as focusing elements that can control the focusing of light below the diffraction limit. The conical tips were obtained by 3D laser lithography method and two-photon photopolymerization in a photosensitive resin. The processing time and the scanning path were optimized by a Python code that we developed. The light propagation through the optical microstructure was simulated with the aid of the COMSOL Multiphysics software within the Electromagnetic Waves, Frequency Domain approximation. The propagation of the light was visualized and analyzed from the spatial distribution of the intensity of light traversing an optical fiber with conical fiber tips.

Keywords: 3D laser lithography, conical fiber tips, near-field scanning optical microscopy, two-photon polymerization, evanescent waves, COMSOL Multiphysics.

1. Introduction

Using near-field scanning optical microscopy (NSOM), a spatial resolution better than the diffraction limit can be obtained. In aperture-NSOM (a-NSOM), the scanning probe microscopy (SPM) technique is performed with the help of an optical fiber with nanoscopic aperture through which light is either sent or collected, a technique which makes the topic of the present paper. Despite the NSOM importance in optics that we will focus on, this method is also renowned in research and applications of semiconductors, organic layers, membranes, as well as biological materials. [1-4]

With 3D Laser Lithography, a Laser Direct-Writing (LDW) technique based on Two-Photon Polymerization (TPP) effect in photoresists, one can fabricate such aperture to then engage in near-field optical microscopy operations. With applications in micro-optics and photonic integration, microfluidics, biotechnology and more, Two-Photon Polymerization is viewed in scientific literature as an ‘equivalent for 3D printing on the micron scale’, treating the resin with femtosecond laser pulses in the visible to near-infrared spectrum. [5,6]

In our research, a high-resolution Nanoscribe 3D printer was employed for the fabrication of the conical fiber tips. With 3D lithography, we ensure complete control over the geometry so as to obtain the desired design. [7] Also, by using Python programming to plot mathematical equations and thus obtain the trajectory followed by the laser, we guarantee an increase in the quality of the geometry. Another novelty we propose is connected to the optimization of the code in terms of density of points on both the exterior and interior of the conical structure, aiming for two aspects: obtaining solid structures, both straight and parabolic-edge cones with minimum losses, as well as ensuring a reasonable fabrication time.

2. Theory

Laser processing and characterization is possible below optical diffraction limit using the evanescent waves that propagate in the proximity of some optical structure with features size comparable with the light wavelength [8]. Meaning ‘tending to vanish’, evanescent waves are those with an intensity that decays exponentially with distance from the interface at which they are formed. In optics, an optical waveguide can confine an optical field within a specific region. For instance, in an optical fiber, light can be confined to its core. Still, the light partially extends into the fiber cladding with a rapid decrease in amplitude as it moves away from the core.

These evanescent waves can be effectively utilized in fiber couplers. These waves facilitate the coupling of light from one core to a neighboring core, which can be achieved by using two single-core fibers together over a short length, creating a tiny distance between the cores. In such cases, the phenomenon of ‘total internal reflection’ occurs, although the term can be quite misleading, as the reflection no longer reflects all optical power.

Another important concept is that of scattered light, which can have both traveling and evanescent components. However, in an ordinary optical microscope, evanescent components cannot contribute to image generation, they can be accessed only with the help of near-field microscopes that often achieve superior image resolution.

3. Fabrication Method. Experimental Setup.

The fabrication of the microscopic cones was optimized thanks to a Python code we wrote that then generated the trajectory to be followed by the 3D Laser lithography equipment from Nanoscribe GmbH. To achieve this, we used Python libraries such as NumPy and Matplotlib, as well as mathematical principles and equations.

The strategy was to split the geometrical object into three parts: the base, the exterior surface of the structure and the interior volume, so that the different point density for each of them will lead both to an optimal fabrication time and good solidity.

For obtaining the base of the cone, our approach was to generate spiral hatching with an ever-decreasing radius, aiming for the smoothness of the created path. Several drawbacks have been overcome regarding the optimal laser scanning path, such as scanning strategy and even numerical errors. Thus, optimizations such as using the math.pi constant instead of an approximation or implementing a gradual increment between segments of the same spiral loop enabled us to go from the initial fragmented and deviated object as shown on the left side of the Figure 1 to the smooth base obtained on the right site of the same Figure.

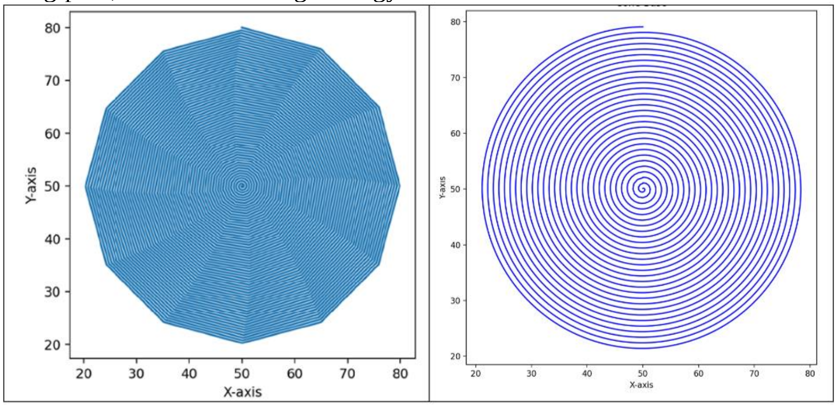

Figure 1: Base optimizations

The same technique was used for the exterior surface of the cone, except for the fact that, this time, each time we would increase with a set step in the Z direction, calculated so as to reach the designated height of the cone when the radius decreases towards zero at the cone tip. Also, we first tried a simultaneous implementation of both the exterior and the interior, but then opted for a separation due to the different aimed point density.

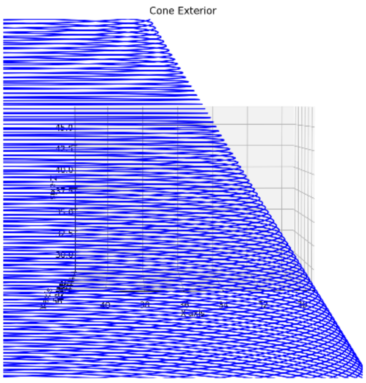

Figure 2: Close-up

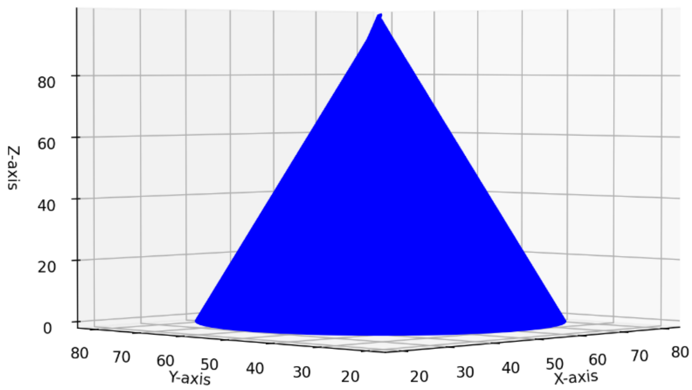

Figure 3: Conical Structure

The biggest challenge was creating a structure for the cone interior volume that would be both solid and feasible for a reasonable fabrication time. The initial idea was to continue with the concentric circles, using the same algorithm as for the exterior surface, but 'filling' every level as the base. The issue with this was that by opting for a lower point density that would optimize the fabrication time, there would be gaps in the structure affecting both mechanical stability and the optical propagation properties of the structure. Thus, we came up with the idea of alternating two different hatching paths: the first one – a spiral hatching, and the second one – ellipses superimposed in the center of the corresponding circle. In this way, two consecutive Z levels have a different structure, therefore ensuring solidity. Figure 4 shows the applied scanning strategy as described above. The picture is represented intentionally with a much larger step in order for visualization to be easier. Also, we made sure to gradually decrease the ellipse radii accordingly to the corresponding decrease of the circle radius so as for the ellipses levels not to oversize the circles levels (Figure 5).

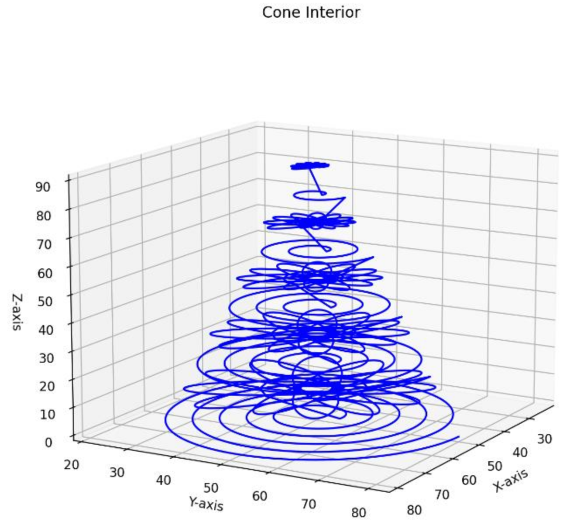

Figure 4: Circles and ellipses

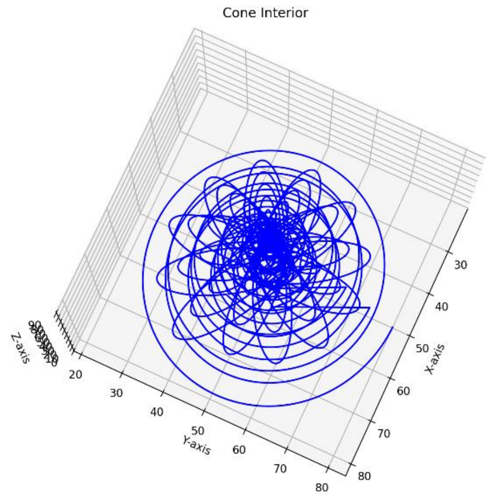

Figure 5: Top view

The Python code we developed is available on GitHub [9].

4. Results

The first part of the results section regards the scanning images, representing the mapping of the XY signal.

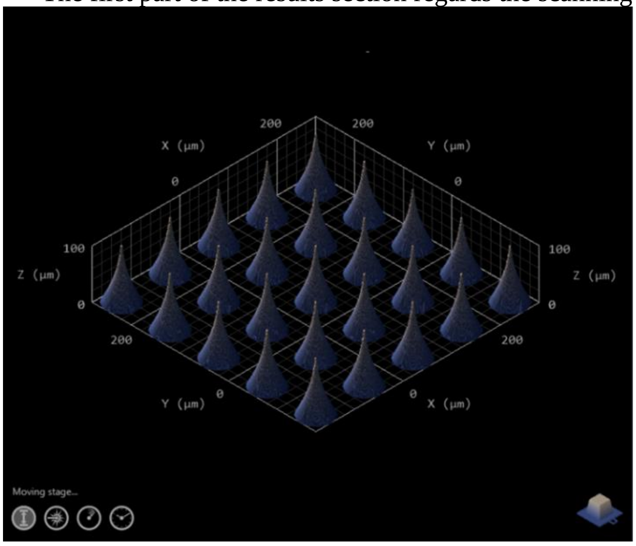

Figure 6: Cones matrix

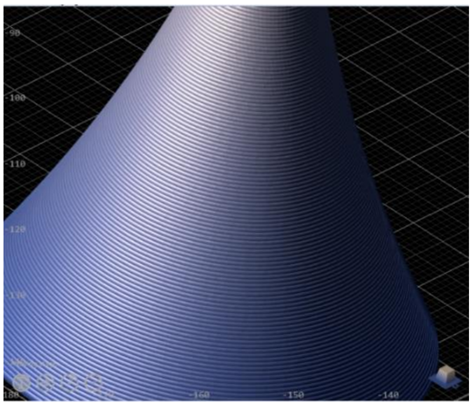

Figure 7: Cone Close-up

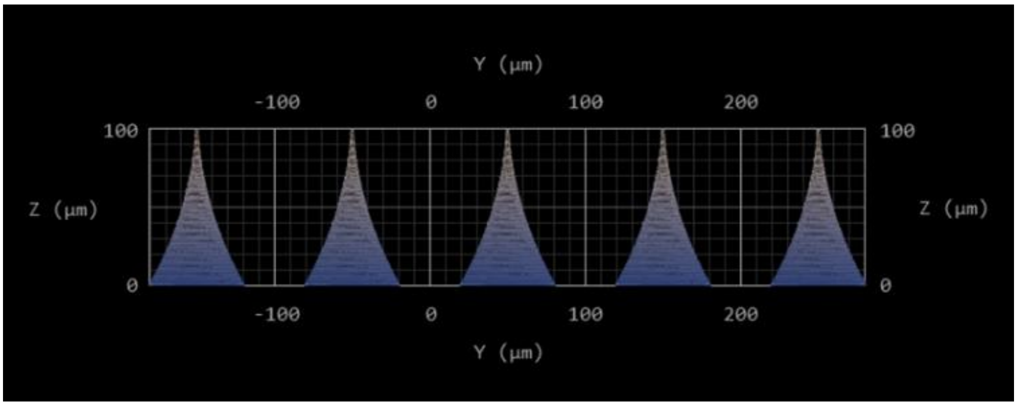

Figure 8: Cones Front View

The second part of the results focuses on the microscopy images of the conical fiber tips. One takeaway from our first batch of developed conical tips was that the power of the Nanoscribe printer had to be closely monitored, because if the power is too big, the shape of the cone gets ruined.

Figure 9: Arrays of microstructures printed on glass.

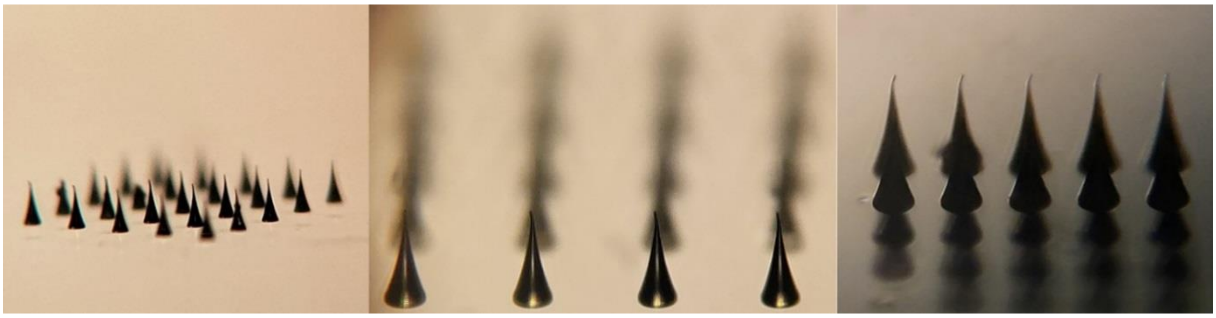

Figure 10: Conical Fiber Tips Batch – printed by 3D laser lithography.

To validate this fabrication strategy, our paper will also include a numerical simulation of light propagation through the cone tips. For this purpose, we have employed the COMSOL Multiphysics software using the Electromagnetic Waves, Frequency Domain approximation. Our demonstration aims to produce a heatmap of the light intensity (from a source) as the light enters an optical fiber, travels through the core, concentrates in and then exits through the conical fiber tip built by us.

We started the numerical design by building the geometry and then tweaking it according to the real-life dimensions and refractive indices. Therefore, we have plotted the fiber core, fiber cladding and the tip, which is in an environment of air. We have then selected the inlet and outlet ports to specify the way the light is propagating – from left to right, as it can be seen in the Figure 11.

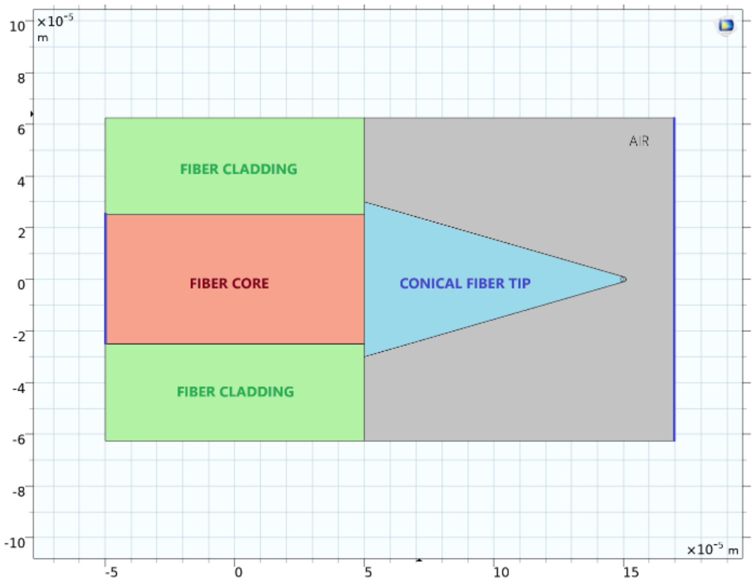

Figure 11: Simulated Geometry in COMSOL Multiphysics software.

We began by creating a heatmap of the intensity of light traversing just an optical fiber, without the tip. In the resulting graphics below, we can see the concentration of light in the core of the fiber, decreasing gradually from the center of the core towards the cladding, where light no longer penetrates.

It is also notable to mention the difference when inputting different values for the core and cladding height. For instance, the image on the left side of the

Figure 12 corresponds to a multimode fiber, in which the decrease in light intensity appears more gradual, while in the image on the right side, with a small core and large cladding corresponding to a monomode fiber, the decrease seems more abrupt. We have computed the propagation of the light through the bare fibers for the two general cases: multimode and monomode fibers, in order to have these data as reference for the fibers with cone structures fabricated on their ends.

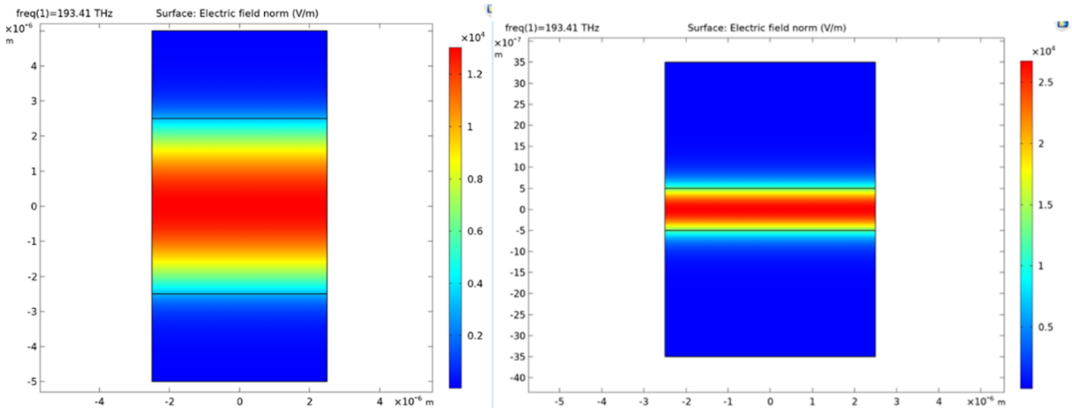

Figure 12: Simulations of light intensity traversing optical fibers

We then proceeded to represent the further propagation through the conical fiber tip. Except for the cone with the small circular top, we also had to add an air environment in order to follow the propagation of the light outside the cone tip.

In the Figure 13 are shown two outputs of our study with the following steps: Boundary Mode Analysis – Inlet, Boundary Mode Analysis – Outlet, and Frequency Domain. The first one is a benign version of our simulation, while the second one is a more refined one in order to resemble a real-life fiber tip our Python code produces after Nanoscribe development.

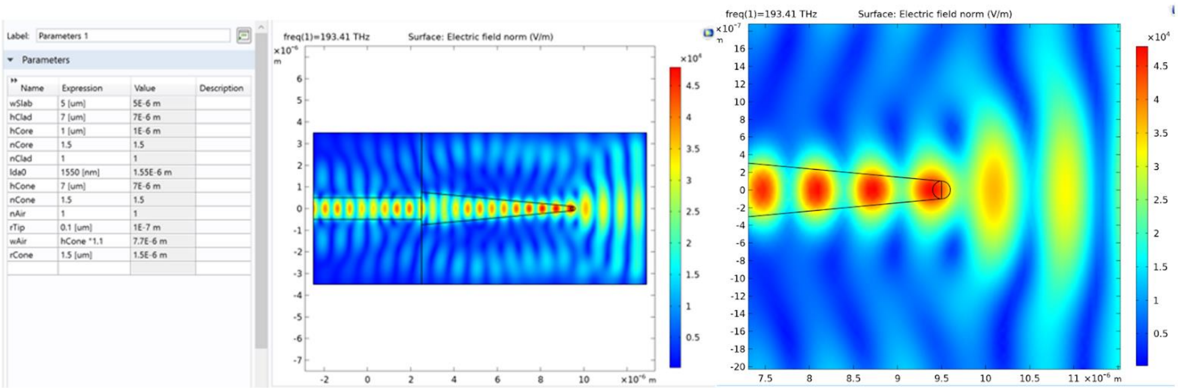

Figure 13: COMSOL Simulation with tip – first model

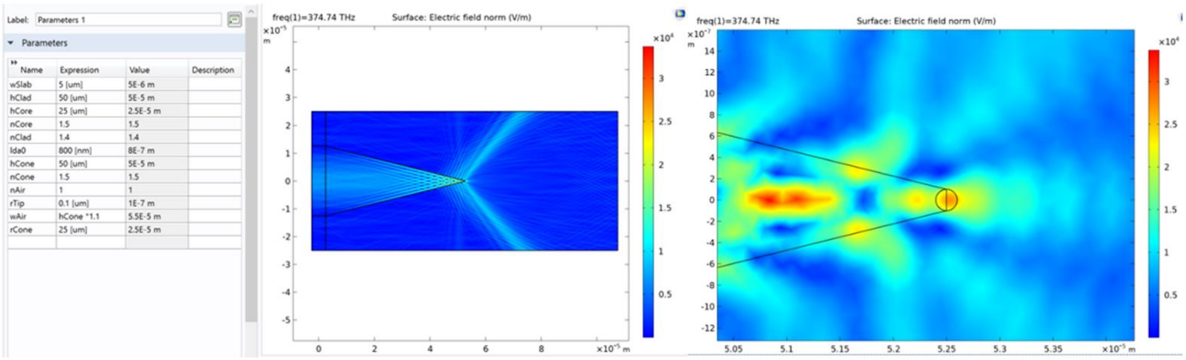

Figure 14: COMSOL Simulation with tip – optimized model

It is, however, clear that in both cases the light passes through the core, traverses the conical tip, and reaches maximum intensity in the vertex of the fiber tip (represented in the heatmap as dark orange / red). The light then propagates with a decreasing intensity from the vertex outwards, up to our defined outlet.

Tweaking the parameters of this simulation will be particularly useful for future improvements of the production of such fiber tips to be used as NSOM probes. Depending on the NSOM measuring conditions, it is possible to modify the geometry, add parabolic-shaped margins for the cone, and implement other optimizations to be able to see the effects of such an experiment.

5. Conclusions

The production of conical fiber tips will be especially useful for future endeavors regarding research and technology, thanks to their ability to manipulate light at the nanoscale. Some future applications include but are not limited to NSOM (to achieve subwavelength spatial resolution imaging), fiber-optic sensors (as sensing elements), optical tweezers (for manipulating and trapping microscopic particles), fiber-probe spectroscopy (for collecting and analyzing emitted or scattered light on a small surface), photonic crystal fibers (to enable light coupling between conventional optical fibers and special fibers), nano-optomechanics (for investigating mechanical vibrations at the nanoscale), nanolithography and nanofabrication (as nanoscale light sources, for high-precision fabrication), quantum optics experiments (to couple single photons or other quantum states to nanoscale devices) and biomedical imaging (for endoscopic imaging or minimally invasive medical procedures).

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9. Our open source Python code available on GitHub: https://github.com/vioneers/3D-Laser-Fabrication-of-Conical-Fiber-Tips.git .