IOP Conf. Series: Materials Science and Engineering **196** (2017) 012043 doi:10.1088/1757-899X/196/1/012043

Photonic jet µ-etching: from static to dynamic process

A Abdurrochman[4], S Lecler[1], J Zelgowski[1], F Mermet[2], J Fontaine[3] and B Y Tumbelaka[5]

[1] ICube-IPP, Université de Strasbourg, CNRS, Illkirch, Strasbourg, France
[2] IREPA LASER, Illkirch, Strasbourg, France
[3] INSA de Strasbourg, Boulevard de la Victoire, Strasbourg, France
[4] Department of Physics, UniversitasPadjadjaran, Jl. Raya Bandung-Sumedang KM. 21, Jatinangor, Sumedang 45363, Indonesia
[5] Department of Electronics Engineering, UniversitasPadjadjaran, Jl. Raya Bandung-Sumedang KM. 21, Jatinangor, Sumedang 45363, Indonesia

E-mail: a.andri@phys.unpad.ac.id, sylvain.lecler@unistra.fr

Abstract. Photonic jet etching is a direct-laser etching method applying photonic jet phenomenon to concentrate the laser beam onto the proceeded material. We call photonic jet the phenomenon of the localized sub-wavelength propagative beam generated at the shadow-side surfaces of micro-scale dielectric cylinders or spheres, when they are illuminated by an electromagnetic plane-wave or laser beam. This concentration has made possible the laser to yield sub-µ etching marks, despite the laser was a near-infrared with nano-second pulses sources. We will present these achievements from the beginning when some spherical glasses were used for static etching to dynamic etching using an optical fiber with a semi-elliptical tip.

1. Introduction

The photonic jet was coined in 2004 to designate a phenomenon in the vicinity of a dielectric particle when it was illuminated by an electromagnetic plane-waveλ. This phenomenon was observed first in the shadow-side of a micro-cylinder base on the calculation of the resulting electric field obtained through high-resolution of *finite-difference time-domain* (FDTD) computational solution of Maxell's equations [1]. For microspheres, the solution was given by implementing an exact Eigen function series solution using the *Mie theory*[3]. If λ_0 is the wavelength, a photonic jet has five important properties [4]: (1) It propagates as a non-evanescent beam beyond the particle along a length ℓ_{FWHM} that can extend more than $2\lambda_0$ with a subwavelength full-width at half-maximum (FWHM). (2) Its FWHM can be smaller than the diffraction limit, ($<\lambda_0/2$). (3) It is not a resonant phenomenon. (4) It has a high intensity that exceeds significantly the intensity of the illuminating wave. (5) Putting a nano-particle within a photonic jet will generate a perturbation of far-field backscattered power of the illuminated particle that is much higher than its initial Rayleigh scattering, which can be used to reveal the presence of nano-particles. Heifetz et.al has summarized some important applications of photonic jet such as: photonic jet microscopy, small propagation losses waveguide, photonic jet surgery, fluorescence enhancement, nano-particle detector, optical tweezers and optical data storage. This manuscript, especially, will present the application of photonic jet for micro- and submicro-etching. The achievements began with some glass spheres used for static etchings until the success of using an optical fiber with a semi-elliptical tip for dynamic etchings.

2. Parameters of photonic jet to consider for µ-etching

In our researches, we find that four parameters may be considered for photonic jet µ-etching[5]. They are:

- I_{max}: the highest photonic jet intensity generated beyond the sphere.
- f_c: the focal point of photonic jet from the highest intensity localization to the sphere surface.
- Γ_{FWHM}: the photonic jet lateral size as FWHM.
- ℓ_{FWHM}: the photonic jet length where the intensity is at a half maximum $½I_{max}$.

These parameters must be adapted for the photonic jet µ-etching application.

3. Photonic jet static-etching

Many articles have suggested using microspheres for material's surface processing and especially laser direct-etching. They have reported lateral feature sizes of etching smaller than a half of the incidence wavelength ($D_{etch} \leq \lambda_0/2$), that was in ultraviolet region. These experiments are done on for different purposes, especially to improve the lateral resolution or to obtain mask-less patterning. Most of them practice a normal directive scheme to realize photonic jet static-etching (figure 1). Our preliminary works also adopted this scheme with some adaptations to meet our experiment-setup [6]. The microspheres were placed at a defocused position of the laser. We used nanosecond pulses of near-IR lasers (28 ns pulses of a 1064 nm Nd:YAG laser and 160 ns pulses of a 1060 nm YLIA laser), four different sizes of glass-microspheres (diameter of 4, 6, 24 and 35 µm) on a silicon wafer plate [6-8].

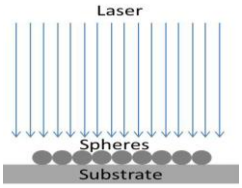
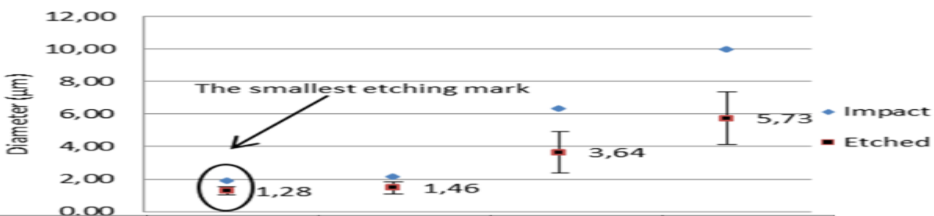


Figure 1. The normal directive laser illumination

Even though we managed to achieve sub-micron etching marks on silicon, our calculations revealed that these etching marks were not yielded by the highest intensity peak at the focal point (Figure 2). They were etched by fluence on the sample surface under the microsphere; with $F_{sur} < F_{PJ}$. Thus, to add a distance and put the material at the focal point of photonic jet will be better to allow the maximum photonic jet fluence etches the material. However, it is not an easy task with microspheres. Therefore, we have proposed applying photonic jet out of curved-tip of a waveguide. In addition to be able to control the sample-sphere distance, it may be possible to move the waveguide above the material to engrave. And so we will perform photonic jet dynamic-etching.



D_s (µm)	4	6	24	35	µ-sphere diameter
Γ_{FWHM} (µm)	0.7	0.6	0.7	0.8	PJ diameter
f_c (µm)	0.15	0.4	3	5	PJ focal point
F_{pj} (J/cm²)	48	96	511	773	Max. PJ fluence at focal point
F_{sur} (J/cm²)	33	41	123	97	Max. beam fluence on the surface

Figure 2. The photonic jet static-etching on silicon is smaller than computational photonic jet diameter. They are produced by the beam on the surface which has the fluence smaller than photonic jet fluence at the focal point

IOP Conf. Series: Materials Science and Engineering **196** (2017) 012043 doi:10.1088/1757-899X/196/1/012043

4. Photonic jet dynamic-etching

There are two technical issues in applying photonic jet for dynamic etching: (1) how to generate photonic jet out of curved-tip waveguide; (2) how to select the photonic jet parameters for µ-etching. The first technical issue has been solved analytically and observed experimentally in microwave frequency [9, 10]. It is possible to generate photonic jet out of a tipped parallel plate waveguide. We have reported the analytical and experimental works concerning photonic jet out of tipped-end optical fiber [5, 11, 12], as shown in figure 3, which led to consider the second technical issue: how to select the photonic jet parameters for laser µ-etching.

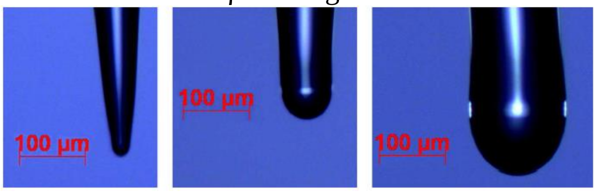
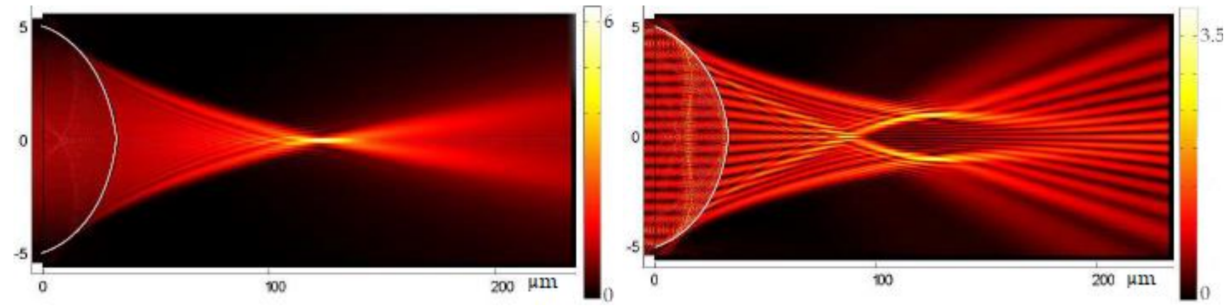


Figure 3. Different shaped tips and core sizes of fibers realized by *Lovalite©*.



a. b.

Figure 4. Intensity maps computed around the shaped tip of the 100 µm core diameter silica waveguide in 2D with (a) the fundamental mode excitation and (b) the 19th mode excitation.

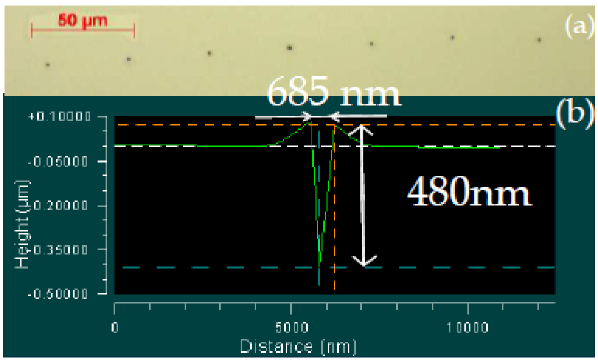


Figure 5. Etching marks on silicon made by photonic jet out of a 100 µm core optical fiber: (a) series of marks observed by an optical microscope and (b) profile measured by an optical profile-meter.

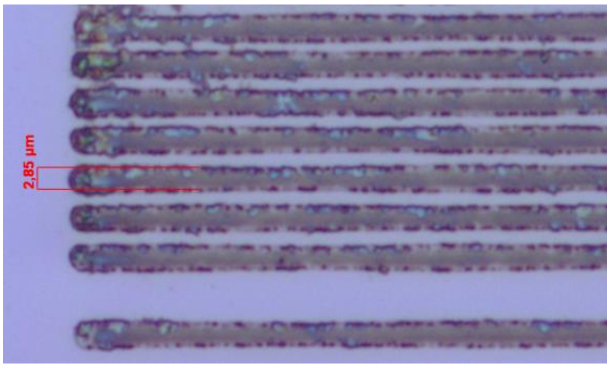


Figure 6. Grating of lines with a period of 5 µm etched on silicon by photonic jet out of a 100 µm core optical fiber.

We identify two main parameters which must be considered in order to have the optimum photonic jet parameters for µ-etching: (1) the optical fiber parameters and (2) the mode of electromagnetic wave (laser beam). We have used a finite element method with, respectively, the silica optical fiber tips, perfectly matched layer absorbing boundary condition around free space and scattering boundaries in the optical fiber cladding. Two optical fiber parameters must be selected to achieve optimum photonic jet parameters for µ-etching: the diameter of the fiber core and the shape of the tip [5]. Large core diameter has more guided electromagnetic modes; the photonic jet is concentrated further from the tip with larger beam spot (Γ_{FWHM}). Elliptical elongated tips generate higher photonic jet concentration closer to the tip than circular-shape or obtuse tip. Figure4 shows optical fibers which have been tested, with diameter respectively of 20, 50 and 100 µm, shaped tip and different curvatures. These optical fibers were placed in our experimental scheme in [5]. And we learn that the energy distribution on electromagnetic modes must be taken into account in optical fiber [5, 12]. Illustrated in figure 4, a fundamental mode is focused at the focal point, while higher mode (the 19th mode) is spread around the focal point.

Our first etching marks on silicon, with too many energy, were not as small as the photonic jet diameter in simulation (figure 5a); especially for the larger fiber core, since only the fundamental mode was taken into account in our simulations. In multimode fiber, the whole propagated energy is not used to ablate the material but is spread around the focal point as in figure 5b.
Naturally, a 100 µm core fiber is multimode at 1064 nm (around 70 groups of modes can propagate inside the fiber). Nevertheless, we made static etchings with a diameter of 685 ± 5 nm (figure6) using 35 pulses of laser VGEN ISP 1-40-30 (1064 nm, 100 ns) and 64 µJ injected in to the 100/140 all silica fiber[11]. The same fiber has been used to perform dynamic etchings, showing the interest to use optical fiber for such a photonic jet etching. A grating of lines with a period 5 µm is presented figure 6. In dynamic, due to the overlapping the line width measures around 2 µm.

5. Conclusion

The development of photonic jet static-etching processes using microspheres, and photonic jet dynamic-etching processes using shaped tip optical fiber have been reviewed and discuss, including the influence of the different parameters. We have shown that sub-wavelengthµ-etching can achieve with a nanosecond near infrared laser. It is possible to engrave lines using the overlapping of the etching-marks in line, since we used an optical fiber with three-axis motorized micro-stage.

Acknowledgments: SATT-Conectus Alsace projects of France and the scholarships of Directorate General of High Educations of Indonesia in 2011-2015.

References

[1] Chen Z, Taflove A and V. Backman 2004 *Op. Exp.***12**1214
[2] Li X, Chen Z, Taflove A and V. Backman 2005 *Op. Exp.***13**526
[3] Lecler S, Takakura Y and Meyrueis P2005 *Op. Lett.***30**2641
[4] Heifetz A, Kong S C, Sahakian A V, Taflove A and Backman V 2009 *J. Comp. Theor. Nanosci*. **6**1979
[5] Abdurrochman A, Zelgowski J, Lecler S, Mermet F, Tumbelaka B Y and Fontaine J 2016 *AIP Conf. Proc.***1712**030001
[6] Abdurrochman A, Lecler S, Mermet F, Tumbelaka B Y, Serio B and Fontaine J 2014 *App. Op.* **53**7202
[7] Abdurrochman A, Lecler S, Fontaine J, Mermet F, Meyrueis P, Tumbelaka B Y and Montgomery P 2014 *Proc. SPIE Phot. Europe* Ed. Mackenzie J I *etal* (Brussels) **9135** 913523
[8] Abdurrochman A, Lecler S, Mermet F, Fontaine J and Tumbelaka B Y 2014 *Int. Con. Phys.* (Yogyakarta,Indonesia) doi:10.2991/icp-14.2014.2
[9] Halaq H, Lecler S, Takakura Y, Robert S and Sauviac B 2010 *Workshop EM IEEE* (Saint-Malo, France)
[10] Ammar N, Aguili T, Baudrand H, Sauviac B and Ounnas B. 2015 *IEEE Transactions on Antennas and Propagation***63**4857
[11] Zelgowski J, Abdurrochman A, Mermet F, Pfeiffer P, Fontaine J and Lecler S 2016 *Op. Let.***41** 2073
[12] Zelgowski J, Lecler S, Abdurrochman A, Pfeiffer P, Mermet F, Fontaine J and Tumbelaka B Y 2016 *SPIE-Photonic Europe* (Brussels)