IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684, p-ISSN: 2320-334X
PP 58-64
www.iosrjournals.org

Rapid Prototyping-An Insight Through TPS

Manikandan.S[1], Biju B Thomas[2], M.Puviyarasan[3]
[1,2] *B.E., Mechanical Engineering, Iv Year Students, Panimalar Engineering College, Chennai-123*
[3]*Assistant Professor, Mechanical Engineering, Panimalar Engineering College, Chennai-123*

ABSTRACT: *Rapid Prototyping(RP) is a simple manufacturing process where a 3D physical model is fabricated directly from a Computer-Aided Design (CAD), in which the ideas of designers and engineers take a three dimensional form. In the current trend where cost-saving strategy becomes a key to stay competitive, RP aims at reducing the development and the time involved. Some of the current issues related to RP technology are the less desirable properties of the moulding materials, high prices of the equipments and product development tool, and the single moulding process techniques. There has been tremendous growth in RP technology in the past 10 years. Two Photon Stereolithography a real 3D fabrication technique illustrated by Maruo et al. in 1997 is based on the absorption of two photons. Diffusion-assisted Two Photon Steriolithography is an alternative method to improve the resolution by adding a quencher in the photopolymerizable system. In presence of quencher, the photo induced radical can be quenched which consequently prevents polymerization. By this way, it has been shown that the radical diffusion can be controlled resulting in the confinement of the polymerization region. However, the concentration of quenching molecules has to be much larger than those of radical produced in order to result in an effective deactivation. Kawata and coworkers demonstrated the multi-focal strategy in 2005 (Kato, 2005) by combining TPS with a micro lens array for boosting fabrication speed while avoiding geometric limitations associated with molding.*

This paper presents an insight into rapid prototyping through TPS. The developed build time analysis mathematical models and adaptive speed strategies for RP print heads can be used to optimize build time towards a minimum target. However, the field is still in its infancy, with continuous efforts being taken to ameliorate its reliability and precision. Thus this could rightly be the field which bears enormous potential to bring in some appreciable change in the manufacturing sector.

Keywords: *Rapid prototyping; Product development; Machine design.*

I. INTRODUCTION

Until recent times, skilled model makers are needed to construct the archetypes from 2D engineering drawings, which is a time-consuming and expensive process. Prototypes are now being rapidly produced from 3D computer models with the advent of new layer manufacturing and CAD/CAM technologies.

In product development and manufacturing cycle required for assessing the form, fit and functionality of a design, prototyping plays an integral part. Prototypes were often handmade by skilled craftsmen, stretching the product development time. Owing to this, a very few design changes could be made in the pre-production stage, resulting in parts being seldom optimized and futile. The term rapid prototyping (RP), enclosing a range of novel technologies for producing accurate parts from CAD models in a beeline, needs no human intervention. Here designers have the freedom to produce physical models of their drawings, check its assembly and functioning and discuss an array of manufacturing issues with a pellucid prototype. Eventually, errors, product development costs and lead times are substantially reduced. It has been claimed that RP can cut new product costs by up to 70% and the time to market by 90%.[1]

2. WHAT IS RAPID PROTOTYPING?

Rapid Prototyping is the fabrication of a 3D physical model directly from a Computer-Aided Design (CAD). This is a simple manufacturing process where the ideas of designers and engineers take a three dimensional form. The RP process provides a fast and inexpensive alternative for producing prototypes and functional models as compared to the conventional routes for part production [2]. RP is defined by *Wohler's Report 2000* as: a special case of machine technology that quickly produces models and prototype parts from 3-D data using an additive approach to form the physical models. [3]

In RP processes, the solid physical part is completed by placing very thin cross sections of the part, one above of the other. In other words, two-dimensional slices are being created and stacked together to form the solid parts. For instance, stacks of various sized "circles" are built consecutively in the RP machine to create a "sphere" with ease.

3. RP FUNDAMENTALS

Several features are shared in common by the prototypes made through current and emerging processes. A solid or surface CAD is made of sections which define the shape of the part collectively. The model is electronically sectioned into layers of predetermined thickness. Information about each section is then electronically transmitted to the RP machine layer by layer. Subsequent layers are sequentially processed until the part is complete. This sequential, layered, or lithographic approach of manufacturing defines RP.[4]. Fig 1 depicts the process cycle in RP.

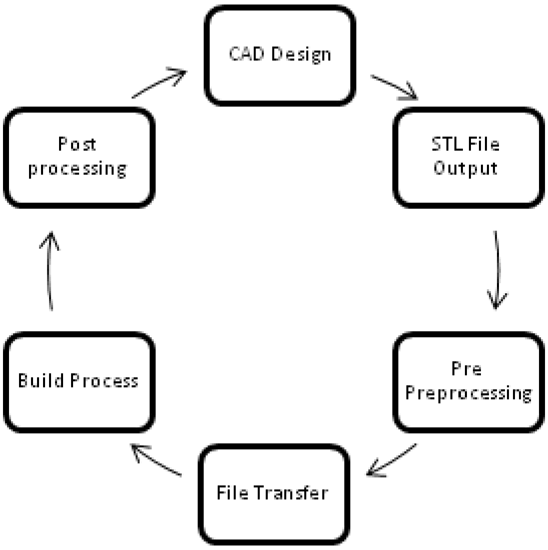

Figure 1 The Rapid Prototyping Cycle [5]

II. DEVELOPMENT OF RP SYSTEMS

Currently, there are numerous novel technologies that are available in RP which allow the “automatic” production of prototype parts directly from a solid model. Some of the commonly used methods are:
Stereolithography Process
Selective Laser Sintering
Laminated Object Manufacturing
Fused Deposition Modeling
Hrd-Tip Soft-Spring Lithograph
Micro And Nano Lithograpy
Two Photon Steriolithography

With various researches being carried out in these processes the most promising advancements are found to be with the Two Photon Stereolithography (TPS). The process of TPS and the various improvisations over it are discussed below

5. Two Photon Steriolithography (TPS)

In conventional Stereolithography techniques the polymerization is based on the absorption of a single photon. Two Photon Stereolithography a real 3D fabrication technique illustrated by Maruo et al. in 1997[6] is based on the absorption of two photons. TPS provides the feasibility to fabricate real three- dimensional (3D) microstructures beyond the resolution of focal size. Two Photon Absorption (TPA) has been generalized as Multi Photon Absorption with the advent of lasers in this technology.

III. WORKING PRINCIPLE OF TPS

TPA is the absorption of two photons leading to the excitation of a molecule from a lower energy electronic state to a higher energy electronic state. [7]The total energy of the two photons is equal to the energy difference between the involved lower and upper electronic states of the molecule.
TPA takes place by two common mechanisms
Sequential excitation

Simultaneous two-photon excitation.

Considering TPS, only the simultaneous two- photon excitation mechanism is involved. In this mechanism, a virtual transitional state referred as the intermediate state is formed by the interaction between the molecules of the material and the photon that is absorbed first. The second photon should be absorbed within the short lifetime of the intermediate stage in order to reach the first real excited state. In order to increase the probability of such a non-linear absorption process, the density of photons available should be high. The density of photon could be increased by using short pulse laser beams and objectives having high numerical aperture (NA).

IV. EXPERIMENTAL SETUP OF TPS

The TPS setup as shown in Fig 2 is composed of three integral parts: (i) Excitation source, (ii) CAD system and (iii) Scanning method.

Focusing of the laser beam using microscopic objective lens is highly significant in the entire fabrication system. It has been demonstrated by Baldeck and coworkers that a cheap Nd-YAG microlaser operating at 532 nm could be used in a TPS process. However the most commonly used laser is the Ti: Sapphire laser operating at 800 nm. (Wang et al. 2002)[8].The mechanical resistance of the final structure and the writing time are influenced by trajectories the CAD system is chosen cautiously.

The scanning method will have an influence over the output of the writing process. Galvano mirrors can be used for horizontal scanning along with a piezoelectronic stage for vertical scanning enabling high speed scanning. In this, the spherical aberration due to the usage of objective lens with high numerical aperture limits the horizontal range of the optical system to an order of few micrometers. This could be overcome by using a piezoelectric stage for scanning in all three directions(x, y, z). However the scanning speed of this system tends to be low.

Shutters are used to control the intensity of the laser beam. The shutter used may be of mechanical type or optical type. The beam is expanded before being introduced into the microscope. It is then followed by the focusing of the laser beam into a multiphoton absorbing material. This induces a photo polymerization within a volume that is less than the volumetric pixel. In common practice the samples are placed over a piezoelectric stage which could be moved above the fixed laser beam by using CAD. Polymerization takes place on the areas that are exposed to the beam and the required structure can be attained by removing away the unsolidified photoresist.

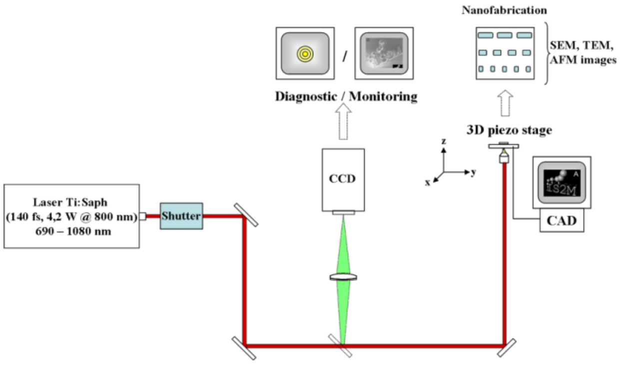

Figure 2 Experimental Setup of a Two Photon Stereolithography Process [9]

V. PROCESS PARAMETERS

The TPS process is governed by various process parameters of which the prominent features are discussed in the forthcoming section.

8.1 Pulse Energy

The advancements in the laser technology have made significant contribution to the TPS process. For example, the energy of a single pulse can be increased by an order of four through pulse regeneration process. Hence it becomes easy to attain the polymerization threshold of almost all resins. [11]Considering a Ti: Sapphire laser, for a laser beam of 80 MHz with average input power of 1W the single pulse energy is 12.5 nJ. When this beam is subjected to pulse regeneration process the single pulse energy becomes 1 mJ with the repetition rate as 1 KHz and the average power remaining unchanged. The increase in the single pulse energy of a photon multiplies photon flux density by the same order (>10^4), and the TPA probability is squared (10^8). The high single pulse energy value enables the polymerization of a number of UV curable resins by TPA.

However, intense damage is caused in the material when the laser irradiation is beyond a certain value. This phenomenon is called laser-induced breakdown. A thermal process dominates such breakdown. The multi photon absorption process does not depend on the laser induced breakdown but [12] photo polymerization depends on it [13].

8.2 Resolution

With rapid improvement in TPS resolution, the resolution should be defined and measured in a suitable way. Resolution corresponds to the lateral and/or axial features size of single voxel or single line. Several methods such as ascending scan method (Sun et al. 2002)[[14], suspending bridge method (DeVoe et al. 2003) have been proposed to improve the precision in the measurements. However, the truncation effect and the influence of materials shrinkage elimination is difficult with these. The resolution of an optical lithography system should be determined by taking into account the role of the photopolymer. The methods involved in improving the resolution includes the design of a high efficiency photoinitiator (Xing et al. 2007) [15] and using shorter wavelengths (Haske et al. 2007)[16]

8.3Numerical Aperture

The objective lens strongly redistributes the beam energy. The distribution of laser intensity at the focal region depends on NA. Figure 3 shows two-photon PSF of different NAs in both x and y directions (Fig. 3a), and along the optical axis, the z direction (Fig. 3b). The refractive indices value of cover glass and the resin was taken as, 1.518 and 1.52, respectively, and the laser is assumed to polarize along the x direction. The incident power before the apertures which have variable sizes is assumed to be identical in each case. The peak power increase with NA is natural, due to the increase of convergence angle. Spatial resolution is improved at high NAs.

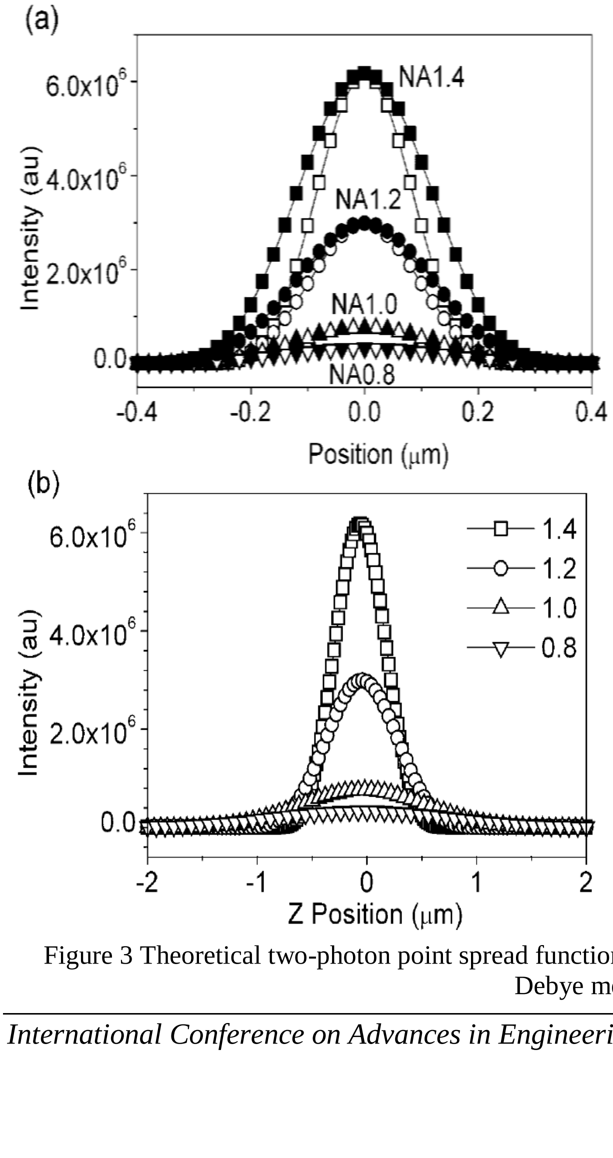

Figure 3 Theoretical two-photon point spread function of different NA focusing calculated using vectorial Debye method [14]

It is seen from the figure that regardless of the absolute intensity level, low NA tends to give larger feature sizes in both lateral and longitudinal directions. The above result is consistent with that predicted in imaging theories.[14]

8.4 Viscosity of resins

In TPS, in order to fix the polymerized structures the scanning is to be done from the surface. If the contact area of the surface tends to be small then the adhesion might be less strong during the post- fabrication washing. This could be overcome by pre-casting a thin layer of the same resin material and polymerizing this layer by a photon absorption process. The adhesion between polymer-polymer tends to be stronger than polymer-glass. In the fabrication of real 3D structures, the structures that were formed earlier may tend to move or float due to the spreading of resin or the vibrations in the surrounding. This is a major drawback of using liquid droplets. This drawback was solved by selecting resins of relatively high viscosity [17-20]. By reducing the concentration of the monomers considerably high viscosity could be attained. For some commercial resins the viscosity could be improved by a pre-polymerization method [21]. This involves partly exposing the resin via single-photon absorption before TPA fabrication to induce short-chain photopolymerization, which equivalently increased the viscosity of resins.

8.5 Speed of the process

Process speeds of several 100 µm/s have been reported for under-100 nm resolution. Until recently, Fourkas's group has realized the fastest demonstration of microstructures with micrometric resolution using a very sensitive photoinitiator (Kumi et al. 2010) [22]reporting a speed of 1 cm/s. Around March 2012, it is reported that it took only four minutes to fabricate a F1 race car of 300 µm length by TPS retaining micrometric resolution. This indicates a speed of 5 m/s involved which is almost in agreement with the time used in laser based processes. [23]

9. ADVANTAGES

The two-photon photopolymerization system is similar to a laser scanning microscope, which does not require vacuum condition and is easy to operate and maintain.

As it directly converts computer-designed patterns into matter structure there is no requirement for mask, mold, or stamp for fabrication The rapid fabrication turnaround time helps to quickly iterate and modify design.

In addition to its intrinsic ability to produce 3D structures, the long wavelength chosen for TPA has less scattering and less absorption giving rise to the deep light penetration; intense nonlinear processes can be started with the use of ultra short pulses at relatively low average power, without damaging the samples thermally.[14]

10. LIMITATIONS

TPS is based on a serial process (i.e. point-by-point writing) thereby affecting mass production.

Resolution achievable by TPS is still 1 or 2 order of magnitude lower.

Low-throughput of the process[9]

11. IMPROVEMENTS IN TPS

In the forthcoming section, different approaches can be discussed to address these specific points and highlight some recent developments which overcome these drawbacks and promise a brilliant future to TPS.

11.1 DIFFUSION ASSISTED TPS

An alternative method to improve the resolution is to add a photo polymerizable quencher. Quenching the photoinduced radical consequently prevents polymerization. It has been shown that the radical diffusion can be controlled by this way, resulting in the confinement of the polymerization region (Tanaka et al. 2005)[24]. In order that an effective deactivation should be obtained, the concentration of quenching molecules has to be much larger than those of radical produced. Therefore, a novel photoinitiator was designed by Lu and coworkers with a radical quenching moiety (Lu et al. 2011)[25]. In this case, an intramolecular radical deactivation leads to a more efficiently control of radical diffusion than in the case of an intermolecular type. As a result, finer features can be formed but however no sub-diffraction gaps between two lines have been demonstrated, and only small effects on the feature size have been observed.

Sakellari and coworkers proposed to add a mobile quencher to control the extent of the polymerization region (Sakellari et al. 2012)[26] since a nondiffusing quencher results only in an increase of the polymerization threshold. Contrary to other works (Tanaka et al. 2005, Lu et al. 2011) the quencher used in this work is an amine-based monomer which interacts with other monomer or become part of the polymer backbone without compromising the mechanical stability of the structure.

A future metallization or further chemical functionalization is allowed by amine functions. By this method, for the first time a single beam can be used to fabricate woodpile structures with 400 nm intralayer period. Moreover, this 400 nm intralayer period has to be compared with the best result obtained by STED-like lithography, i.e. 375 nm intralayer period (Fischer et al. 2011). Interestingly, comparable resolution are obtained in both cases as single beam is used in the frame of this diffusion assisted high resolution TPS. While this method is easier to implement in laboratory and in order to get such impressive resolution, the scan speed is intrinsically low to allow diffusion of the quencher into the scanned area and should be around 20 $\mu m.s^{-1}$

11.2 MULTI-FOCAL TPS

Kawata and coworkers demonstrated the multi-focal strategy in 2005 (Kato, 2005)[28] by combining TPS with a micro lens array for boosting fabrication speed while avoiding geometric limitations associated with molding. More than one hundred identical and individual 3D objects have been written simultaneously resulting in a two-order increase in the fabrication yield compared to single beam TPS. In 2006, Kawata et al. succeeded to write in parallel more than 700 hundred identical structures (Formanek, 2006)[29] illustrating the high potential for large scale production.

A more general approach of multi-focal TPS was proposed by Ritschdorff et al. to allow parallel but independent writing of different objects (Ritschdorff et al. 2012)[30]. In the frame of this recent work, a proof-of-concept has been illustrated with the construction of biocompatible networks by using two independent sub-beams. The main beam is directed through a dynamic mask (typically a spatial light modulator) in order to control each beam separately. With the requirement of high-power lasers, this work opens the doors to numerous and more flexible applications.

However there are some factors that have to be taken in consideration to use it as a tool in laboratory or industries. In order to provide enough energy after each lens or dynamic mask, an amplified femtosecond laser should be made use of. Moreover, in order to deliver the same amount of energy for each lens and to fabricate uniform structures, the laser beam intensity distribution has also to be perfectly controlled. Another factor is the precise control of alignment of the hundred forming laser beams with respect to the plan of the substrate. A tilt of less than 1° of the substrate will result in the fabrication of inhomogeneous structures which is unacceptable from a metrology point of view in industries.

VI. CONCLUSION

Thus structural resolution and high-output have been provided by the rapid technical development of TPS. All these improvements and promising advances should enable the limitations for mass production to be overcome and ameliorate the application of TPS in industries. Finally, due to its current rapid expansion and the array of concepts involved with it, TPS should definitely be a field where major research works could be expected.

REFERENCES

D.T.Pharn ,R.S.Gault, A Comparison of Rapid Prototyping Technologies, International Journal of Machine Tools & Manufacture, 38, 1998,1257-1287

Venkat Deepak Kolar , Application of Reverse Engineering and Rapid Prototyping to Casting, Jawaharlal Nehru Technological University, India, 2004.

Patri K Venuvinod , Weiyin Ma, Rapid Prototyping-Laser Based and Other Technologies(Kluwer Academic Publishers,2004) Rafiq Noorani, Rapid Prototyping: Principles and Applications (John Wiley & Sons,Inc.,2006)

Ali K.Kamrani , Emad Abouel Nasr, Rapid Prototyping : Theory and Practice (Springer Science + Business Media Inc., 2006)

Maruo, S, & Ikuta. K, Submicron Stereolithography for the production of freely movable mechanisms by using single-photon polymerization. Sensors and Actuators,A: Physical, A100, 2002, 70-76.

Goeppert-mayer. M, Über Elementarakte mit zwei Quantensprüngen, Annalen der Physik, 401, 1931, 273-294.

Wang. I, Bouriau. M, Baldeck. P. L, Martineau. C & Andraud. C, Three-dimensional microfabrication by two-photon-initiated polymerization with a low-cost microlaser. Optics Letters, 27, 2002, 1348-1350.

Arnaud Spangenberg, Nelly Hobeika, Fabrice Stehlin, Jean-Pierre Malval, Fernand Wieder, Prem Prabhakaran, Patrice Baldeck and Olivier Soppera, Updates in Advanced Lithography, Recent Advances in Two-Photon Stereolithography,2 (InTech, 2013)

Witzgall G, Vrijen R, Yablonovitch E, Doan V, Schwartz BJ , Opt Lett 23:1745, 1998

Hong-Bo Sun, Satoshi Kawata, Two-Photon Photopolymerization and 3D Lithographic Microfabrication (170:169-273, DOI 10.1007/b94405, Springer-Verlag 2004.) vonderLinde D, Schuler H . J, Opt Soc Am B 13:216, 1996

Belfield KD, Schafer KJ, Liu YU, Liu J, Ren XB, Van Stryland EW J Phys Org Chem 13:837, 2000

Sun, H. B, Tanaka, T, & Kawata, S., Three-dimensional focal spots related to two-photon excitation. Applied Physics Letters, 80, 2002, 3673-3675.

Xing, J. F, Dong, X. Z, Chen, W. Q, Duan, X. M, Takeyasu, N, Tanaka, T, & Kawata, S. Improving spatial resolution of two-photon microfabrication by using photoinitiator with high initiating efficiency, Applied Physics Letters, 90, 2007,131106.

Haske, W, Chen, V. W, Hales, J. M, Dong, W. T, Barlow, S, Marder, S. R, & Perry, J. W., nm Feature sizes using visible wavelength 3-D Multiphoton lithography.Optics Express, 15, 2007, 3426-3436.

Odian G , Principles of polymerization(3rd edn. Wiley, New York, 1991)

Fouassier JP, Rabek JF , Lasers in polymer science and technology (CRC Press, Boca Taton, FL, 1990)

Reiser A ,Photoreactive polymers: The science and technology of resists(Wiley,New York,1989)

Fouassier JP, Rabek JF , Radiation curing in polymer science and technology,Elsevier, London, 1993
Sun HB, Kawakami T, Xu Y, Ye JY, Matsuo S, Misawa H, Miwa M, Kaneko R, Opt Lett 25:1110, 2000
Kumi, G, Yanez, C. O, Belfield, K. D, & Fourkas, J. T., High-speed multiphoton absorption polymerization: fabrication of microfluidic channels with arbitrary crosssections and high aspect ratios. Lab on a Chip, 10, 2010, 1057-1060.
Vienna, 2012. http://amt.tuwien.ac.at/projekte/2pp/.
Formanek, F, Takeyasu, N, Tanaka, T, Chiyoda, K, Ishikawa, A, & Kawata, S., Three-dimensional fabrication of metallic nanostructures over large areas by twophoton polymerization. Optics Express 14, 2006, 800-809.
Lu, W. E, Dong, X. Z, Chen, W. Q, Zhao, Z. S, & Duan, X. M., Novel photoinitiator with a radical quenching moiety for confining radical diffusion in two-photon induced photopolymerization. Journal of Materials Chemistry, 21,2011, 5650-5659.
Sakellari, I, Kabouraki, E, Gray, D, Purlys, V, Fotakis, C, Pikulin, A, Bityurin, N, Vamvakaki, M, & Farsari, M. , Diffusion-Assisted High-Resolution Direct Femtosecond Laser Writing, ACS Nano, 6, 2012,2302-2311.
Fischer, J, Ergin, T, & Wegener, M., Three-dimensional polarization-independent visible-frequency carpet invisibility cloak. Optics Letters, 36, 2011, 2059-2061.
Kato, J, Takeyasu, N, Adachi, Y, Sun, H. B, & Kawata, S., Multiple-spot parallel processing for laser micronanofabrication. Applied Physics Letters, , 86, 2005
Formanek, F, Takeyasu, N, Tanaka, T, Chiyoda, K, Ishikawa, A, & Kawata, S., Three-dimensional fabrication of metallic nanostructures over large areas by twophoton polymerization. Optics Express, 14, 2006, 800-809.
Ritschdorff, E. T, Nielson, R, & Shear, J. B, Multi-focal multiphoton lithography. Lab on a Chip, , 12, 2012, 867-871.