SPIE Proceedings vol. 6458, Proc. Photonics West LASE 2007, paper no. 645818

Pulsed Laser Processing of Shallow Micro-Optical Structures

J.E.A Pedder[1], A.S. Holmes[2]
[1]Oerlikon Optics UK Ltd, Oxford Industrial Estate, Yarnton, Oxford, OX5 1QU, UK
[2]Imperial College London, EEE Department, Exhibition Road, London, SW7 2AZ, UK

ABSTRACT

Pulsed UV laser machining is an established method for production of 2.5D and 3D features in a wide variety of materials. In addition to direct laser patterning by ablation, exposure of photoresist using pulsed lasers can eliminate the need for large area contact photomasks. Half-tone machining, either by ablation or exposure, allows the production of high quality shallow features where the surface roughness from other laser machining techniques would be unacceptable. Such features could be used as anti-reflection surfaces for mobile display devices. Features produced by lithography typically exhibit low surface roughness but have more complex fabrication processes. Here, the surface roughness of shallow features produced by half-tone lithography and half-tone ablation is investigated for a photoresist. Similar surface profiles are achieved for each technique and roughness levels are comparable for both.

1. INTRODUCTION

Material processing using lasers has become an established part of many industrial production lines. Industrially robust lasers operating with nanosecond pulse lengths are used to process a wide variety of materials[1]. Unlike femtosecond laser machining, where the high peal power available allows normally transparent materials to be ablated through multi-photon absorption, nanosecond machining requires strong single-photon absorption in the target material. However, the extensive range of wavelengths available from modern lasers allows a broad of materials to be processed. Furthermore, laser processing systems typically have small footprints, making them ideal for compact production lines.

Highly coherent laser beams such as those produced by diode pumped solid-state (DPSS) lasers are easily focused to a small, intense, spot. Additionally, pulsed DPSS lasers typically operate at several kHz repetition rate, making them suitable for rapid beam scanning techniques. Recently, thin film processing with DPSS lasers for photovoltaic components has become widespread due to increased market demand[2]. Also, patterning of transparent conductive oxide (TCO) layers on flat panel display components by DPSS mask projection has recently been reported[3].

High precision laser micromachining using excimer lasers has been widely reported as a reliable method of processing a variety of materials[4,5]. High pulse energies, usually several hundred mJ, make them ideal for parallel processing of multiple parts over large areas. Additionally, the low repetition rate typical of excimer lasers enables image separation using high precision motion stages. This is very useful for single shot processes such as TCO patterning and multi-shot processes such as those used to make micro-electromechanical systems (MEMS)[6].

1.1. MICRO-OPTICAL FEATURES

Micro-optical structures such as microlens arrays are widely used in the front elements of rear projection televisions. Combining a microlens array and a patterned black matrix screen can improve the contrast of the screen. Typically, a micromachined master is replicated by electroforming and hot embossing or injection moulding. This type of mass replication process reduces the cost per part from several thousand dollars to a few dollars or less. Several complementary technologies are available to produce the master, notably diamond turning, greyscale lithography and laser ablation.

Where it is necessary to machine microlenses directly into a hard material such as glass, diamond turning offers the only viable option[7]. In this case, a circularly symmetric diamond tip is ground into the substrate to the desired depth. Simple x-y stages are used to generate large area arrays of repeating lenses with the same diamond tip. Although tool wear can be an issue when machining hard materials, repeatable results with good uniformity have been demonstrated. This technique is capable of machining lens features with lateral sizes from 50μm to several mm and with surface roughness values less than 15nm rms.

Alternatively, if smaller lenses are required and a lithography step is acceptable, greyscale lithography followed by transfer of the photoresist profile into a harder material is possible. This technique allows the use of true greyscale masks such as those made with high-energy beam-sensitive (HEBS) glass[8]. Prior knowledge of the photoresist exposure rate is required before the mask design step. Furthermore, transfer of the resist pattern into glass by anisotropic techniques such as reactive ion etching (RIE) requires detailed knowledge of the relative etch rates. Such transfer can only be done over the etching system's region of uniformity and is subsequently limited to small, wafer sized, areas. Although outstanding surface quality has been demonstrated for the greyscale lithography process, the use of non-standard masks increases the cost to the user.

Rapid processing of lens arrays over large areas is desirable when a single master mould is required for a large display screen. Laser ablation of polycarbonate using UV excimer lasers has been proven as an alternative technique to fabricate microstructures on large area substrates[9]. In addition to linear features such as v-grooves and cylindrical lenses, 2-D arrays of closely packed microlenses are quickly and easily fabricated by laser ablation. A technique known as synchronized-image-scanning (SIS) has been developed as an efficient tool for machining large arrays of repeating microstructures[10]. Recently, we have reported on the use of halftone imaging combined with SIS to manufacture microlenses with outstanding surface quality. Figure 1 shows an SEM picture of a series of microlenses fabricated by halftone-SIS using a UV excimer laser. This type of laser machined feature normally exhibits surface roughness around 10nm Ra.

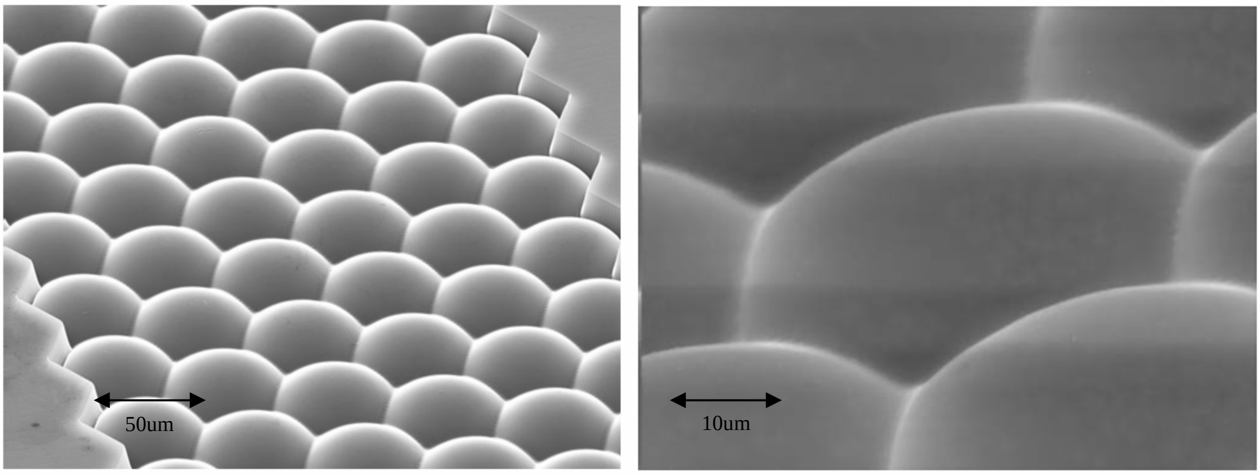


Fig. 1. Microlenses machined into polycarbonate with a UV excimer laser using halftone-SIS. Surfaces exhibit low surface roughness, <10nm Ra in the lens centre.

1.2. ANTI-REFLECTION SURFACES

Anti-reflection surfaces are a vital component of mobile display devices. Surface glare from ambient light can reduce the visibility of the backlit screen and lead to excessive power consumption. To reduce these effects, both polarized films and micro-textured surfaces have been used. However, it is important to reduce surface reflectivity whilst maintaining the viewing angle and contrast of the display. Whilst polarized surfaces can result in modest reductions in reflection coefficient, textured surfaces such as moth-eye arrays can virtually eliminate reflection of ambient light[11]. However, moth eye arrays can result in a very narrow viewing angle and are unsuitable for many mobile devices. Shallow micro-optical features with surface height around the wavelength of visible light can be included in the anti-reflection stack. If a suitable refractive index is used for the micro-optical layer, then a significant reduction in reflectivity can be achieved while the viewing angle of the screen is maintained.

Micro-textured surfaces with such shallow structures are too small to prototype using mechanical techniques and reflow techniques with patterned photoresist are limited to convex surfaces by surface tension effects. Laser micromachining with binary masks is more suitable for deeper structures since typical material removal rates are a few hundred nm per shot. Half-tone laser processing, either by ablation or exposure, offers an alternative to greyscale lithography for creating such shallow structures. Such techniques would be used to create a master that could be replicated by electroforming and hot-embossing. Here, we investigate whether similar results can be obtained through halftone lithography and ablation, the aim being to establish the most appropriate technique for a typical microstructure.

2. EXPERIMENTAL TECHNIQUE

An Exitech PPM601excimer laser machining system, with a Lambda Physik LPXPro laser operating at 248nm wavelength, was used as the exposure and ablation tool for these tests. The machine has large x-y stages with Generation 6 processing area (1.5m x 2m). A floating optical head ensures that the image plane of the system projection lens (x5 reduction) remains in focus with the substrate over the entire chuck area. An example of a typical optical setup in an excimer laser micromachining system is shown in figure 2. A suitable resist, Shipley SPR220-7, was chosen for favorable exposure and ablation characteristics at 248nm.

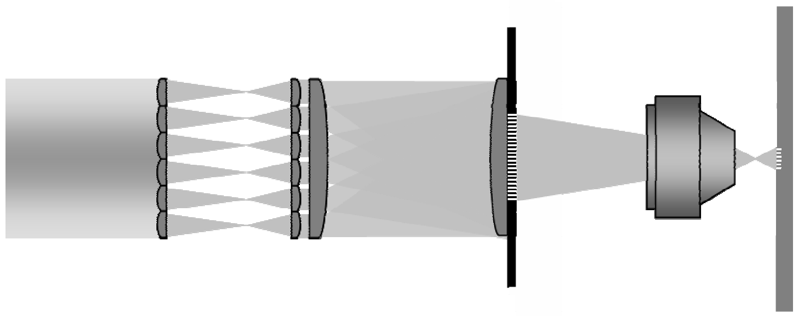
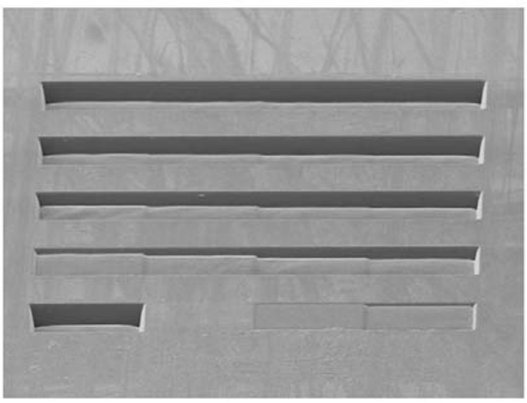


Fig. 2. Optical arrangement in a typical excimer laser micromachining system. Beam forming optics are used to homogenize the raw laser beam and illuminate a photomask. A projection lens reduces the mask pattern to image onto the workpiece.

Accurate reproduction of the desired surface profile requires prior knowledge of the material response before the mask design phase. For shallow structures, where the surface gradient is low, it is only necessary to calibrate the exposure and ablation rates for normal incidence. A halftone calibration mask, where regions of different transmission are illuminated in parallel, has previously been used to measure the ablation curve of SU-8 photoresist and polycarbonate[12]. An SEM picture of a typical calibration feature is shown in figure 3.



80%	85%	90%	90%
60%	65%	70%	75%
40%	45%	50%	55%
20%	25%	30%	35%
90%	5%	10%	15%

Fig. 3. Typical multi-level calibration pattern in SU-8 from 50 laser shots at F_o=1J/cm^2. A discrete number of transmission steps are used to calibrate the ablation/exposure curve of the target material.

2.1. ABLATION OF SPR220

Shallow structures such as those under investigation here require only a few laser shots to achieve the desired surface profile. Incubation effects are observed when ablating polymers with few shots at modest fluence levels due to the formation of a thin layer of modified material[13]. In this case, the ablation depth of the first shot can be significantly lower than for subsequent shots. It is therefore necessary to measure the ablation curve of the material in this low shot regime to minimize errors in the fabricated shape. Ideally, a range of ablation curves would be measured to provide a comprehensive data set of the material response. Figure 4 shows the ablation curve for SPR220 measured using a similar calibration pattern to that shown above but only using 5 laser shots with a fluence level at 100% mask transmission of $F_0 = 0.5 J/cm^2$

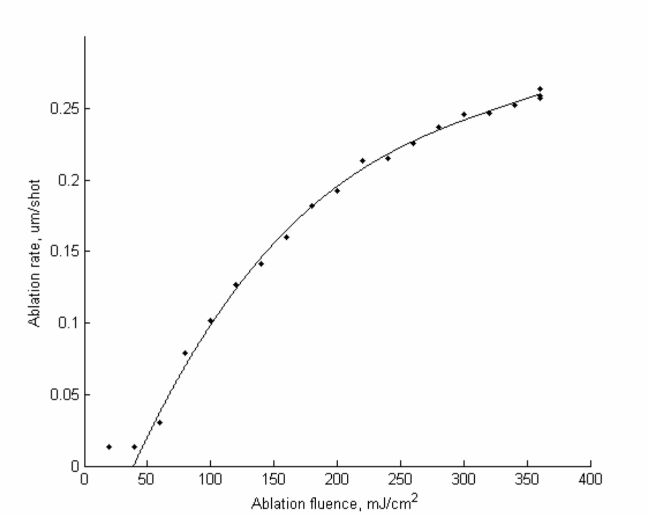


Fig. 4. Ablation curve for SPR220 photoresist at 248nm with polynomial fit (solid line). Significant deviations are observed for 5% and 10% transmission levels due to errors in the mask fabrication.

Prior knowledge of the material response can be used to calculate the local mask transmission required to achieve a desired surface. This operation is described in detail elsewhere[14], but for the case of shallow structures a simple inversion of the ablation curve equation is sufficient once the number of shots required has been estimated.

2.2. EXPOSURE OF SPR220

Unlike in ablation, where much of the exposed material is ejected during each shot, with conventional lithography the exposed material remains in place until development, and consequently modifies the exposure of the underlying resist. This effect is exacerbated by the use of shorter wavelengths, where the absorption coefficient of the exposed material is typically higher than that at longer wavelengths. Furthermore, significant incubation effects are observed for pulsed lithography making multi-shot processes difficult to predict. Accurate knowledge of such behavior is therefore more important for lithography, especially when the number of shots required is small.

Figure 5 shows the measured material exposure rate (depth after development divided by number of shots) for 1 and 4 shots with F_0 of $20 mJ/cm^2$. Considerable incubation is observed for exposure at lower fluence levels and multiple pulses are required to expose a significant amount of material below $12 mJ/cm^2$. A comprehensive range of data would hence be required to ensure accurate reproduction of a desired surface shape. It should be noted that similar processing rates are achievable with fluence levels 25 times lower than those required for ablation. However, the non-zero absorption coefficient of the exposed material limits the depth of the structures to less than 1μm in this case.

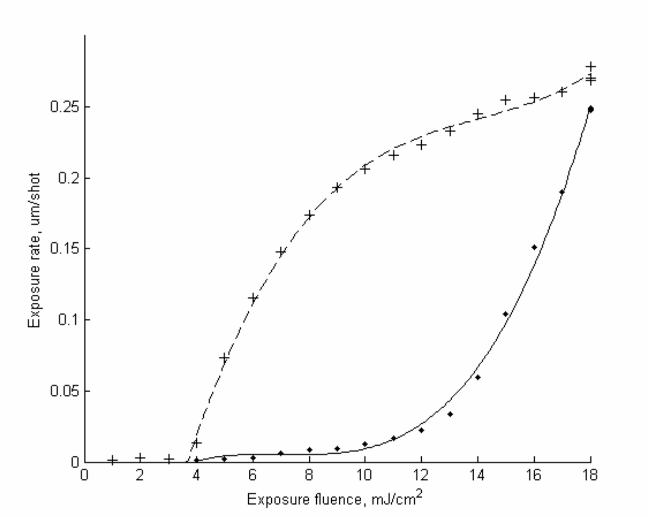


Fig. 5. Exposure rate for SPR220 at 248nm. Polynomial fit is shown for 4 shots (broken line) and 1 shot (solid line).

2.3. FABRICATION OF TEST STRUCTURES

A simple convex surface feature with a depth around 200nm was used to compare the exposure and ablation techniques in SPR220. The same mask pattern was used for both processes and the number of shots adjusted until similar surface profiles were achieved. This approach ensured the fabrication of similar surfaces while not requiring detailed knowledge of the exposure and ablation characteristics before the mask design step. Figure 6 shows a 2-D map of the designed mask transmission function. Factors such as the mask critical dimension and writing grid limit the number of 'grey' levels available and impose a maximum and minimum transmission level.

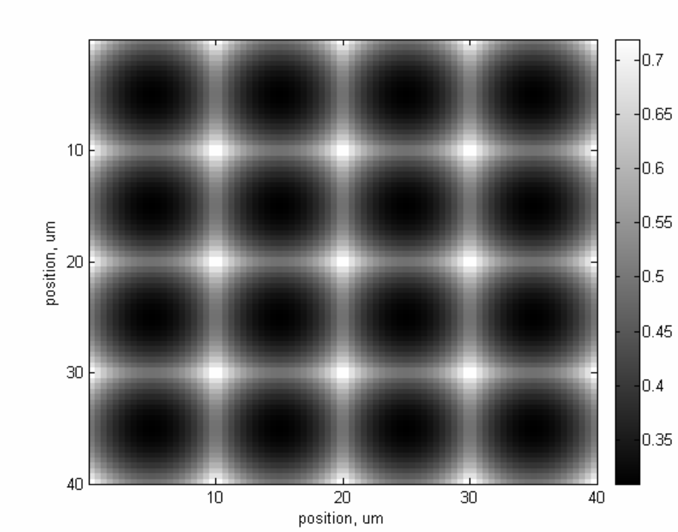


Fig. 6. Transmission profile of pattern used to fabricate the test structures. Halftone pixels are on a 3µm grid at the mask, giving local fluence regions (in the image plane) on a 600nm pitch. The resulting structures are in a square, close-packed array on a 10µm pitch.

An F_0 level of 500mJ/cm^2 was used for the ablation testing, maintaining a minimum fluence above 150mJ/cm^2. Ensuring the fluence level remains above the material ablation threshold in this way prevents the formation of undesirable surface roughness from debris. However, as a consequence additional material has to be removed in order to leave the desired surface shape. Figure 7 shows the surface profile from a test structure ablated into SPR220 photoresist with 3 laser shots, together with the result from exposure with 4 shots at an F0 level of 20mJ/cm2 followed by development.

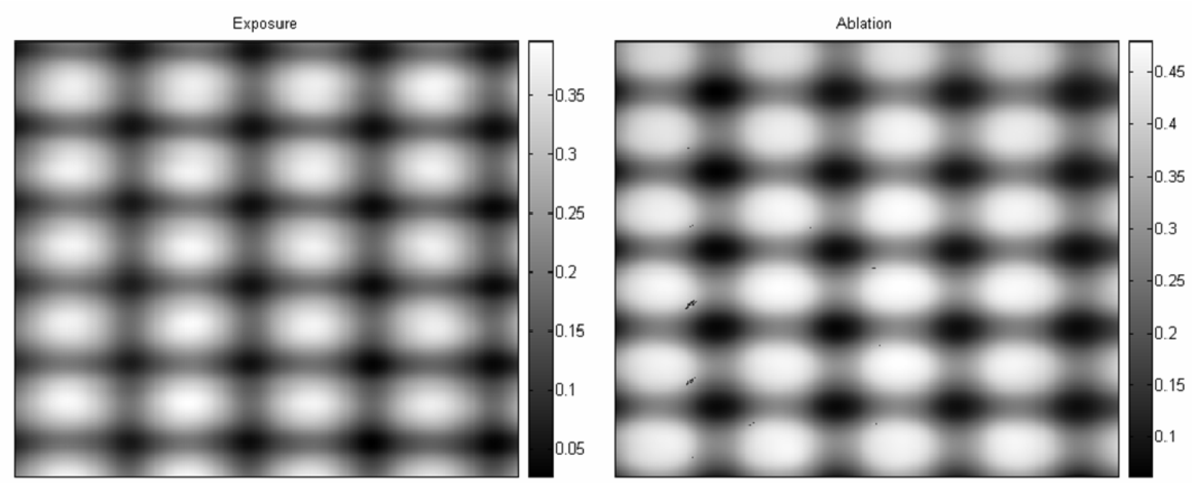


Fig. 7. Surface profile measurements for test samples from exposure and ablation taken with a Zygo white light interferometer. Similar lens shapes have been achieved with the same mask pattern.

A cross-sectional profile of a single feature is shown in figure 8. Similar profiles have been achieved with the same mask by adjustment of the fluence and number of shots. However, the sample produced by exposure and development exhibits some fine structure not present on the ablated feature. Currently, we cannot explain the origin of the additional surface roughness; however, we expect that it has formed from an interference effect due to partial coherence in the laser source. Localized reflow may have prevented the formation of the fine structure on the ablated sample. In both cases the Ra value is a few Å which would have a minimal effect on wave propagation.

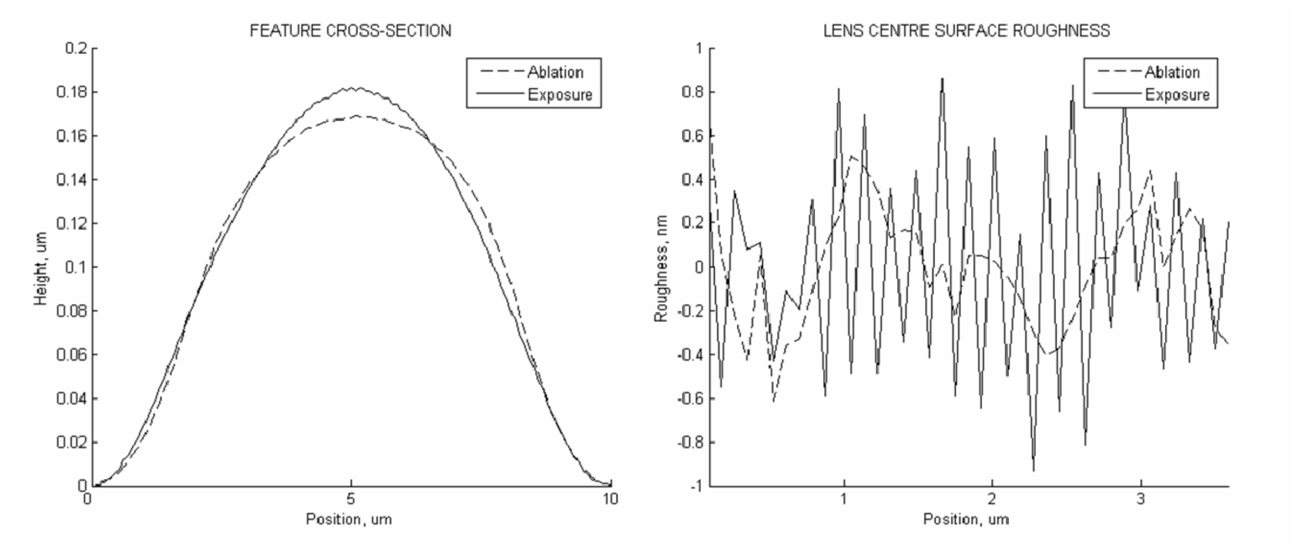


Fig. 8. Surface profiles (left) and roughnesses (right) of individual micro-optical features produced by ablation and exposure. Periodic fine structure is evident on the exposed sample.

3. CONCLUSION

Halftone laser machining has been introduced in recent years as an alternative technique for producing a variety of laser machined structures. Outstanding surface roughness has been demonstrated for laser ablated features several microns deep, and this has recently been extended to large area surfaces by combination with techniques such as SIS. In this paper we have investigated the production of even shallower features in SPR220 photoresist both by ablation and by exposure and development. Unexplained fine structure was observed in samples produced by exposure that was not present in ablated features; however, the resulting effect on device performance would be minimal. Similar surface profiles are achievable with both techniques, while exposure requires 25 times less energy than ablation. On the basis of these results, it appears that the choice of technique for a given industrial application is likely to be dominated by other factors, for example economic and environmental considerations. In particular, exposure is expected to be cheaper in terms of laser processing, but requires wet chemical processing which has an associated cost and environmental impact.

4. REFERENCES

1. M.C. Gower, Industrial Applications of Laser Micromachining, Optics Express, Vol. 7, No. 2, July 2000, pp 56-57.
2. H.J. Booth, Recent applications of pulsed lasers in advanced materials processing, Thin Solid Films, Vol. 453-454 , April 2004, pp 450-457.
3. M. Henry, Laser Direct Write of Active Thin-Films on Glass for Industrial Flat Panel Display Manufacture, Proc. 4th Int. Congress. Laser Adv. Mat. Processing, Kyoto, 2006, Paper No. 06-16.
4. N.H. Rizvi, P. Apte, Developments in Laser Micro-Machining Techniques, J. Mat. Proc. Tech., Vol. 127, No. 2, Sept. 2002, pp 206-210.
5. M.C Gower, Laser micromachining for manufacturing MEMS devices, Proc. SPIE, Vol. 4559, Oct. 2001, pp 53-59
6. A.S. Holmes et al, Laser profiling of 3-D microturbine blades, SPIE Vol. 5063, Proc. 4th Int. Symposium on Laser Precision Microfabrication (LPM2003), Munich, Germany, 21-24 June 2003, pp 152-156.
7. A.Y. Yi, L. Li, Design and fabrication of a microlens array by use of a slow tool servo, Optics Letters, Vol. 30, July 2005, pp 1707-1709.
8. W. Daschner et al, General aspheric refractive micro-optics fabricated by optical lithography using a high energy beam sensitive glass gray-level mask, J. Vac. Sci. Tech. B, Vol. 14, Nov. 1996, pp 3730-3733.
9. K.L. Boehlen et al, Advanced Laser Micro-Structuring of Super-Large Area Optical Films, Proc. SPIE, Vol. 5720, Jan. 2005, pp 204-211.
10. K.L. Boehlen, I.B.Stassen Boehlen, Laser micromachining of high-density optical structures on large substrates, Proc. SPIE, Vol. 4760, July 2004, pp 118-127.
11. H. Kikuta et al, Optical elements with subwavelength structured surfaces, Optical Review, Vol. 10, 2003, pp 63-73.
12. J.E.A. Pedder, A.S. Holmes, Excimer laser micromachining of polymers using half-tone masks: mask design and process optimization, Proc. 6th International Symposium on Laser Precision Microfabrication (LPM2005), Williamsburg VA, USA, 4-7 April 2005, pp 215-218.
13. J. Kruger et al, Investigation of excimer laser ablation threshold of polymers using a microphone, App. Surf. Sci., Vol. 197, 2002, pp 800-804.
14. A.S. Holmes, Excimer laser micromachining with half-tone masks for the fabrication of 3D microstructures, IEE Proc. Sci. Meas. & Technol., Vol. 151, No. 2, 2004, pp. 85-92.