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Research Article

Fabrication of two-dimensional photonic quasi-crystals with 18- and 36-fold by holography for solar application

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Abstract: Holographic lithography has been widely used to the realisation of complex photonic structures such as photonic crystal and quasi-photonic crystals. Dual-beam multi-exposure holographic technique was adopted for the fabrication of 18-fold and 36-fold sub-microscopic rotational symmetric structures; the fabricated photonic quasi-crystals examined by laser diffraction pattern, optical and scanning electron microscopes. Here, the authors have fabricated photonic quasi-crystals in photoresist and the structure was transformed into metal, the transferred structure in metal could act as a substrate/or back reflector for the thin film solar cell. Further work on concentration of solar light by photonic quasi-crystals is progressing.

1 Introduction

A material with a periodic order was different from conventional crystal due to its atomic arrangement was discovered and named a quasi-crystal [1]. A quasi-photonic crystal (QPC) has a rotational symmetry other than those allowed for crystals, i.e. one-, two-, three-, four- and six-fold symmetries and higher rotational symmetry than conventional photonic crystals (PC). It has a long-range order and the long-range order is non-periodic [2–8].

We have fabricated highly rotational symmetric QPC structures by using holography. Depending on the number of laser beams and their arrangements, one can fabricate different symmetries of two-dimensional (2D) and 3D PC and QPC. For example, multi-beam interference of laser beams with single exposure technique [9, 10]. By using three or four beams interference method, one can create 2D hexagonal or square structures [11–13]. Umbrella such as central and side laser beam multiple interference technique and the 4 + 1 configuration has been proposed for the holographic fabrication of 3D PCs [11, 14–17]. Experimentally, five diffracted laser beams generated by using phase masks [18, 19], flat-top prisms [20, 21], two beam interference, four beam interference, special prism and combined holographic gratings as beam splitter (BS) have been involved in the fabrication of PCs by interference holographic lithography [22]. However, by using two beam multi-exposure interference technique [23, 24] has many advantages over the commonly used multi-beam interference technique; such as experimental simplicity, easy fabrication of different structures with long range and high contrast of structures [25] are few examples.

If number of interfering beams is more than six, one can fabricate QPCs [26, 27]. The 8-fold, 10-fold and 12-fold QPC fabrication technique by holographic method reported by many research groups, but a very few groups [28] recently published 18-fold symmetry. The 18- and 36-fold QPCs by using holography two beams multi-exposure method is elaborated here.

The concept of solar concentration by diffraction grating and periodic structures have been reported [29–34], also the solar light absorbance enhancement and improving efficiency of silicon (Si) solar cell by PC [35–37] have been reported. Another class of high rotational symmetric QPC and its pivotal role of enhancement of Si solar cell were reported [38]. Here, we have adopted a dual-beam multi-exposure technique for the fabrication of 18- and 36-fold QPC structures in photoresist (PR) and in metal. Its advantage over other method is of easy replication and low cost for mass production. Hence, we select this technique for the fabrication of QPC and periodicity gets inspected by laser diffraction pattern, optical and scanning electron microscopy. The fabricated periodic structures transferred to metal and the same is used as substrate for the fabrication of PN junction thin film solar cell. The already published works are generally based on Si solar cell efficiency enhancement. Here, we have selected cadmium telluride (CdTe) solar cell for our work. The absorbance enhancement is mainly due to the higher-order rotational symmetry in QPC structures, which leads to the presence of additional, resonant modes, the broadening of existing modes and the reduction of surface reflectance. Our future work is focusing on QPC fabrication in three different substrates such as glass, metal and polycarbonate. On the basis of these structures, solar light absorbance and efficiency enhancement of the solar cell is progressing.

2 Experimental arrangement

A dual-beam multi-exposure holographic experimental arrangement for the fabrication of 2D PCs structures is shown in Fig. 1. A beam of wavelength 442 nm emitted from 100 mW Helium – Cadmium (He-Cd) laser divided into two by variable density beam splitter (BS) and it is used to control the beam ratio. The separated beams are expanded and spatially cleaned by spatial filter SF1 and SF2. Both expanded and spatially cleaned beams are collimated by using lenses L1 and L2. A double-iris and wave plates are used to select two laser beams of the same profile, same polarisation and same intensity. The collimated laser beams to be interfered at photoresist (PR) which is placed in plate holder PH are guided by two front coated aluminium mirrors M1 and M2. The angle between two laser beams is denoted as θ [39] and could be easily controlled by two mirrors M1 and M2. We have used PR for the formation of QPC structures; PRs are light-sensitive organic polymers, which form imaged relief patterns on exposure and development. The exposed areas of positive PR and unexposed areas of negative PR become soluble and dissolve away during the developmental process [40–42].

In this paper, the AZ-4620 positive PR (8 µm thickness) exposed by He–Cd laser with wavelength of 442 nm for the fabrication of QPC, PR is placed in a rotation stage with stepper motor arrangement for precise control of rotation between exposures. The Uniblitz computer control VCM D1 (model number) shutter driver and LS series model high-speed electronic shutter is used to organise the accurate laser exposures. The

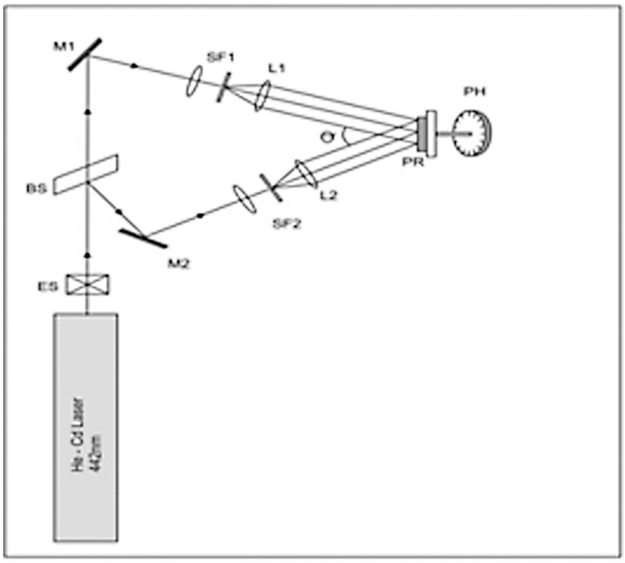

Fig. 1 *Holographic dual-beam multi-exposure experimental arrangement for the fabrication of 2D quasi PC*

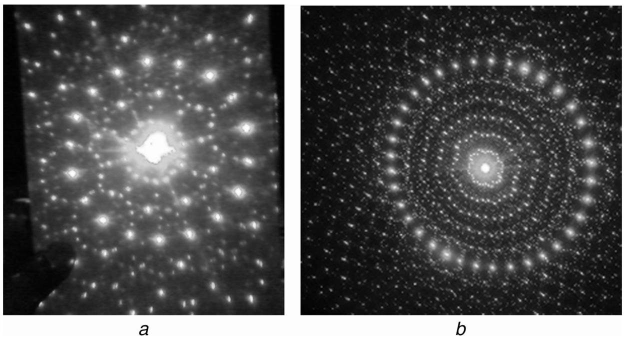

Fig. 2 *Laser diffraction patterns of circular periodic 2D quasi periodic* ***(a)*** 18-Fold, ***(b)*** 36-Fold symmetries

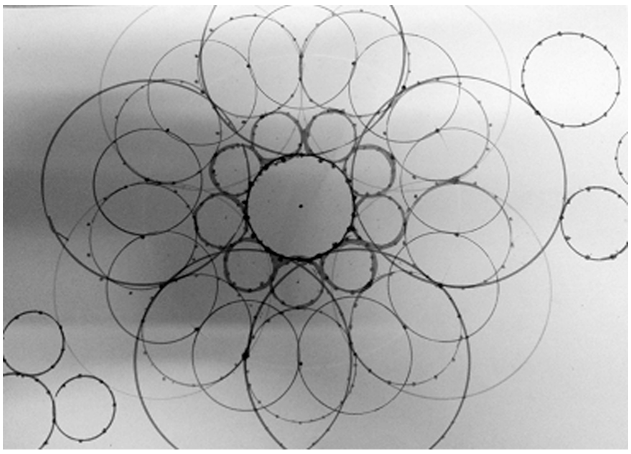

Fig. 3 *2D QPC with 18-fold rotation symmetry diffraction spots are converted into solid lines for eye guidance*

exposure energy was ~150 mJ/cm^2. The intensity ratio of the two beams is 1:1. The sodium hydroxide (NaOH) 1.5% is used as the developer and the developing time is about 15 s.

3 Result and discussion

A dual-beam multi-exposure holographic technique was adopted for the fabrication of rotation symmetric 2D QPCs with 18- and 36-fold. The ratios between the beams are maintained 1:1 by adjusting the variable density BS, the interfered two collimated beams angle (θ) 21° was controlled by the two mirrors (M1 and M2). The two beams get interfered in PR was fixed at angular rotational stage Plate Holder (PH) and it was connected to the stepper motor for accurate control of the rotation (not shown in Fig. 1). First, the high diffraction grating was recorded and its exposure time was optimised in order to calculate the multiple exposures time for 18 and 36 exposures to generate 18- and 36-fold QPCs, respectively. The optimised exposure sensitivity was in the range of 150 mJ/cm^2. From this value, we have adjusted the exact exposure time for multi-exposures. After 18 and 36 exposures in the PR, laser exposed PR underwent for a chemical development by using 1.5% of NaOH as developer and the typical developing time for our experiment was about 13–15 s and the chemically processed plate was washed in running water for 5 min and dried by cool air. The developed 2D QPC with periodic symmetry of 18-fold and 36-fold 2D was examined by its laser diffraction patterns as shown in Figs. 2*a* and *b*, respectively.

A 532 nm green emitted by diode pumped frequency doubled solid state laser passed directly on the fabricated QPC, the diffraction pattern is detected by a paper screen and recorded by a digital camera as shown in Fig. 2. As shown in Fig. 2, the 18-fold and 36-fold rotational symmetries of the diffraction pattern are displayed clearly. The first-order spots of uniform intensity distribution confirmed the 18- and 36-fold QPCs are in Figs. 2*a* and *b*, respectively. The intensity variation of the diffraction order shown in Fig. 2 is useful to identify the different periodic order. The uniform intensity of the first-order spots reveal the information that the multiple exposure in photosensitive plate was exactly calculated.

Each first-order spots themself again act as a centre of another rotation periodicity, in order to deep analyse 18-fold circular periodicity, we have joined all the diffracted order spots and indicated as solid line for eye guidance as shown in Fig. 3. To obtain the detail analysis of the symmetric periodic structure, we have examined the five-fold 2D PC structure by scanning electron microscope as shown in Fig. 4.

Already fabricated QPC with 18- and 36-fold symmetries in PR was converted in metal through electroforming technique. The replicated QPC in metal acts as a master hologram for producing similar QPC structures without altering the uniformity and quality; thus, it is very important aspect for cost reduction and fast production in terms of mass production. Here, we have used this metallic QPC structure as substrate for the fabrication of CdTe-based PN junction solar thin film by using chemical vapour deposition method. The thin film of *P*-type of CdTe and *N*-type of indium (In):zinc oxide (ZnO) layer successfully coated on the top of metallic rotational symmetric 2D QPC structure as an initiation of further development. The metallic QPC could act as a back reflector. The fabricated thin film PN junction solar cell by using 2D quasi-PC is shown in Fig. 5.

After PN material thin film layer formation on the top of metallic QPC, it was examined by optical microscope and the presence of the same QPC structure was confirmed in PN layer and

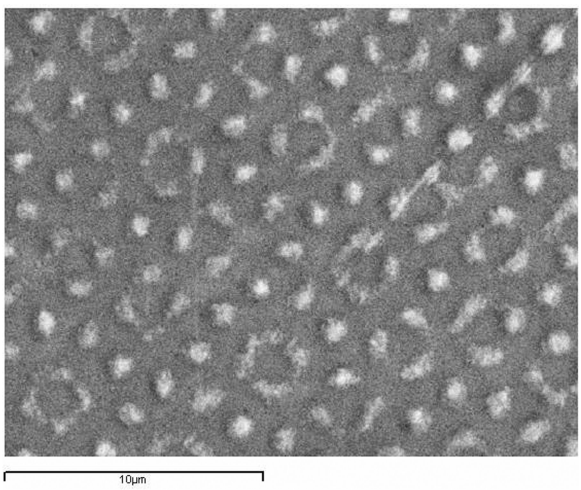

Fig. 4 *Scanning electron microscopic image of the five-fold 2D PC structure*

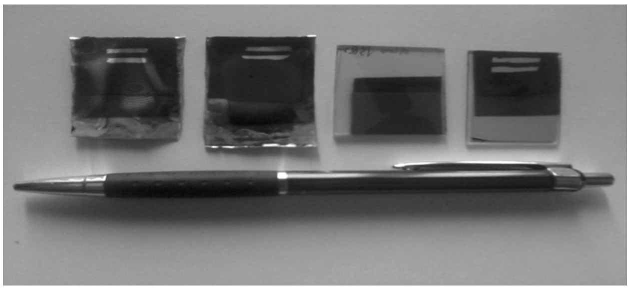

Fig. 5 *Thin film solar cell fabricated by using 2D QPC*

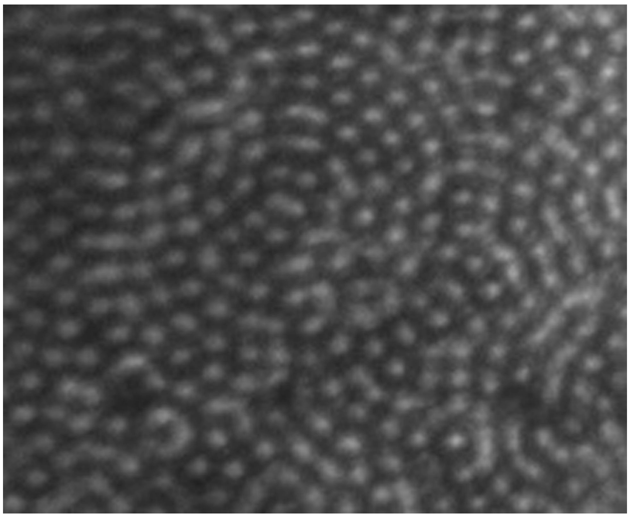

Fig. 6 *Optical microscopic image of the PN junction CdTe type thin film material coated on 36-fold circular periodic 2D QPC*

was shown in Fig. 6. The same kind of fabrication on glass substrate is also shown on the right side of Fig. 5 and tested by another research group. Further work is to be the formation of same structures in polycarbonate sheets by using same metal master with the help of pressure and heat transfer technique. The comparison study of these three kinds of substrates performance in solar concentration application is our future work. Enhancement of optical absorption and photon resonances within absorbing electrodes are responsible for the light harvesting enhancement in PC-based solar cells.

4 Conclusion

A dual-beam multi-exposure technique was involved for the fabrication 2D QPC with circular symmetry. The recorded structures were examined by diffraction pattern, scanning electron microscopic image and it was shown in Figs. 2 and 4. The recorded 2D QPC structures were converted into metal through electroforming technique; the same metallic structure used as substrate for *P*-type CdTe and *N* type In:ZnO thin film coating by vapour deposition method and the structure was analysed by optical microscope. Thus, the experiment has provided guidance for the large area and fast production of QPC structures with high quality and with low cost. The QPC structures exhibit more absorption peak in long wavelength range. Higher-order rotational symmetry should support additional resonant modes compared with periodic structures which is responsible for absorption enhancement in solar cell. Further work in this direction is progressing.

5 References

[1] Shechtman, D., Blech, I., Gratias, D., *et al.*: 'Metallic phase *with* long-range orientational order *and* no translational symmetry', *Phys. Rev. Lett.*, 1984, **53**, pp. 1951–1953

[2] Xiao, H.S., Yulong, W., Wen, L., *et al.*: 'Fabrication of ten-fold photonic quasi-crystalline structures', *AIP Adv.*, 2015, **5**, p. 057108

[3] Tiorduer, M.: 'Penrose type graded photonic quasi-crystal for light manipulation'. ICTON, 17th Int. Conf., 2015, pp. 1–4

[4] Zito, G., Priya Rose, T., Gennaro, E.D.: 'Bandgap properties of low-index contrast aperiodically ordered photonic quasi crystals', *Microw. Opt. Technol. Lett.*, 2009, **51**, (11), pp. 2732–2737

[5] Wang, X., Xu, J., Lee, J.C.W., *et al.*: 'Realization of optical periodic quasicrystals using holographic lithography', *Appl. Phys. Lett.*, 2006, **88**, (5), p. 051901

[6] Sun, X.H., Liu, W., Wang, G.L., *et al.*: 'Optics design of a top-cut prism interferometer for holographic photonic quasi- crystals', *Optics Communications*, 2012, **285**, pp. 4593–4598

[7] Sen, K., Jiang, G., Wang, Michael R.: 'Eight-fold photonic quasi-crystal fabricated by prism assisted holographic lithography'. Proc. SPIE, 2013, p. 8632OG

[8] Gao, Y., Liu, M.: 'Design of two-dimensional 7-, 8-, 9-, 10-, 14-, 16-fold penrose-tiled photonic quasicrystals and mixed honeycomb', *Opt. Eng.*, 2013, **52**, (5), pp. 053401 -1–053401 -5

[9] Campbell, M., Sharp, D. N., Harrison, M. T., *et al.*: 'Fabrication of photonic crystals for the visible spectrum by holographic lithography', *Nature*, 2000, **404**, (6773), pp. 53–56

[10] Jun, H. M., Shu, Y.: 'Creating periodic three dimensional structures by multi-beam interference of visible laser', *Chem. Mater.*, 2002, **14**, (7), pp. 2831–2833

[11] Wang, X., Xu, J. F., Su, H. M., *et al.*: 'Three dimensional photonic crystals fabricated by visible light holographic lithography', *Appl. Phys. Lett.*, 2003, **82**, (14), pp. 2212–2214

[12] Kondo, T., Matsuo, S., Juodkazis, S., *et al.*: 'Multiphoton fabrication of periodic structures by multibeam interference of femtosecond pulses', *Appl. Phys. Lett.*, 2003, **82**, pp. 2758–2760

[13] Lin, Y., Herman, P.R., Abolghasemi, E.L.: 'Proposed single-exposure holographic fabrication of microsphere-type photonic crystal through phase mask techniques', *J. Appl. Phys.*, 2005, **97**, (9), p. 096102

[14] Miklyaev, V. Yu., Meisel, D. C., Blanco, A., *et al.*: 'Three-dimensional face-centered-cubic photonic crystal templates by laser holography: fabrication, optical characterization, and band-structure calculations', *Appl. Phys. Lett*, 2003, **82**, (8), pp. 1284–1286

[15] Berger, V., Gauthier, O., Costard, E.: 'Photonic band gaps and holography', *J. Appl. Phys.*, 1997, **82**, pp. 60–64

[16] Chan, T.Y.M., Toader, O., John, S.: 'Photonic band-gap formation by optical-phase-mask lithography', *Phys. Rev. E, Stat.*, 2006, **73**, (4), p. 046610

[17] Lin, Y., Harb, A., Rodriguez, D., *et al.*: 'Fabrication of two-layer integrated phase mask for single-beam and single-exposure fabrication of three-dimensional photonic crystal', *Opt. Express*, 2008, **16**, (12), pp. 9165–9172

[18] Chanda, D., Abolghasemi, L. E., Haque, M., *et al.*: 'Multi-level diffractive optics for single laser exposure fabrication of telecom-band diamond-like 3-dimensional photonic crystals', *Opt. Express*, 2008, **16**, (20), pp. 15402–15414

[19] Ohlinger, K., Zhang, H., Lin, Y., *et al.*: 'A tunable three layer phase mask for single laser exposure 3D photonic crystal generations: bandgap simulation and holographic fabrication', *Opt. Mater. Express*, 2011, **1**, (5), pp. 1034–1039

[20] Xu, D., Chen, K. P., Harb, A., *et al.*: 'Phase tunable holographic fabrication for three-dimensional photonic crystal templates by using a single optical element', *Appl. Phys. Lett.*, 2009, **94**, (23), p. 231116

[21] Pang, Y.K., Lee, J.C., Ho, C.T., *et al.*: 'Realization of woodpile structure using optical interference holography', *Opt. Express*, 2006, **14**, (20), pp. 9113–9119

[22] George, D., Lutkenhaus, J., Gomard, G., *et al.*: 'Holographic fabrication of 3D photonic crystals through interference of multi-beams with 4 + 1, 5 + 1 and 6 + 1 configurations', *Opt. Express*, 2014, **22**, (19), pp. 22421–22431

[23] Vadivelan, V., Shaji, S. T. L., Sholly, J., *et al.*: 'Fabrication of metallic 2-D photonic crystal by holography'. Proc. of SPIE 2008, China, 2008, vol. **6832, no**. 683206, pp. 1–6

[24] Gauthier, R.C., Ivanov, A.: 'Production of quasi-crystal template patterns using a dual beam multiple exposure technique', *Opt. Express*, 2004, **12**, (6), pp. 990–1003

[25] Lai, N.D., Liang, W.P., Lin, J. H., *et al.*: 'Fabrication of two- and three-dimensional periodic structures by multi-exposure of two beam interference technique', *Opt. Express*, 2005, **13**, (23), pp. 9605–9611

[26] Levinac, D., Steinhardt, P.: 'Quasicrystals: a new class of ordered structures', *Phys. Rev. Lett.*, 1984, **53**, (26), pp. 2477–2480

[27] Vrdeny, Z.V., Nahata, A., Agarwal, A.: 'Optics of photonic quasicrystals', *Nat. Photonics*, 2013, **7**, pp. 177–187

[28] Wei, R., Xu, Z., Wang, X.: 'Epoxy-based azo polymer for photofabricating surface-relief quasi-crystal structures', *Opt. Mater. Express*, 2015, **5**, (6), pp. 1349–1355

[29] Mellor, A., Tobías, I., Martí, A., *et al.*: 'Upper limits to absorption enhancement in thick solar cells using diffraction gratings', *Prog. Photovolt. Res. Appl.*, 2011, **19**, (6), pp. 676–687

[30] Mellor, A., Tobías, I., Martí, A., *et al.*: 'A numerical study of bi-periodic binary diffraction gratings for solar cell applications', *Sol. Energy Mater. Sol. Cells*, 2011, **95**, (12), pp. 3527–3535

[31] Rothemund, R., Umundum, T., Meinhardt, G., *et al.*: 'Light trapping in pyramidally textured crystalline silicon solar cells using back-side diffractive gratings', *Prog. Photovolt. Res. Appl.*, 2013, **21**, pp. 747–753

[32] Peters, M., Rüdiger, M., Hauser, H., *et al.*: 'Diffractive gratings for crystalline silicon solar cells-optimum parameters and loss mechanisms', *Prog. Photovolt. Res. Appl.*, 2012, **20**, (7), pp. 862–873

[33] Song, Y.M., Yu, J.S., Lee, Y.T.: 'Antireflective submicro meter gratings on thin-film silicon solar cells for light-absorption enhancement', *Opt. Lett.*, 2010, **35**, (3), pp. 276–278

[34] Hossain, M.M., Gu, M.: 'Fabrication method of three dimension periodic metallic nano/micro structures for photonic applications', *Lasers Photonics Rev.*, 2014, **8**, (2), pp. 233–249

[35] Dewan, R., Marinkovic, M., Noriega, R., *et al.*: 'Light trapping in thin-film silicon solar cells with submicron surface texture', *Opt. Express*, 2009, **17**, (25), pp. 23058–23065

[36] Bermel, P., Luo, C., Zeng, L., *et al.*: 'Improving thin-film crystalline silicon solar cell efficiencies with photonic crystals', *Opt. Express*, 2007, **15**, (25), pp. 16986–17000

[37] Park, Y., Drouard, E., Daif, O. E., *et al.*: 'Absorption enhancement using photonic crystals for silicon thin film solar cells', *Opt. Express*, 2009, **17**, (16), pp. 14312–14321

[38] Meng, X., Drouard, E., Gomard, G., *et al.*: 'Absorbing photonic crystals for silicon thin-film solar cells: design, fabrication and experimental investigation', *Sol. Energy Mater. Sol. Cells*, 2011, **95**, pp. S32–S38

[39] Ren, H., Du, Q.G., Ren, F., *et al.*: 'Photonic quasi crystal nano patterned silicon thin film for photovoltaic applications', *J. Opt.*, 2015, **17**, (3), pp. from 035901 (6 pages)

[40] Chemisana, D., Collados, M., Qunitanillla, M., *et al.*: 'Holographic lenses for building integrated concentrating photovoltaics', *Appl. Energy*, 2013, **110**, pp. 227–235

[41] Smith, H.M.: '*Holographic recording materials*' (Springer Verlag, Berlin, 1977, 1st edn.), pp. 209–227

[42] Sekkat, Z., Kawata, S.: 'Laser nanofabrication in photoresist and azopolymer', *Laser Photonics Rev.*, 2014, **8**, (1), pp. 1–26