Two-photon lithography of fluorescence-encoded quick-read micro-code for anti-counterfeiting applications

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Abstract

Anti-counterfeiting tags are a simple and easy way to avoid duplication/forgery of valuable products; however, counterfeiting has evolved over time, with the help of newer technologies to clone and reproduce exact signatures, tags, barcodes, etc that are difficult to identify. To prevent such counterfeiting, it is imperative to obtain advanced and encoded anti-counterfeiting technologies with constant research and innovation. With this motivation, we have designed a sub-micron-scale patterned, fluorescent anti-counterfeiting tag based on an emissive layer embedded in a non-emissive polymer layer. The fabrication of the embedded structure is achieved using step-by-step writing of emissive and non-emissive layers using two-photon lithography. Interestingly, the encoded message is visible under ultraviolet illumination, and the structure is invisible under white light illumination. The proposed method can be extended for multilayer patterning with spatial positioning of different encoded messages along the height of the structure to incorporate layered security.

1. Introduction

Fake and inferior replicas of high-value products such as currency, legal documents, pharmaceuticals, electronic components, etc have caused severe financial damage and imposed social security threats globally. With increased instances of counterfeiting, the development of advanced and encoded anti-counterfeiting means is of utmost importance to prevent the cloning and reproduction of such anti-counterfeiting tags. The past decade has witnessed rapid development in anti-counterfeiting technology. Widely used advanced technological means are anti-counterfeiting tags that include luminescent printing on fluorescent readouts [1–3], photonic watermarks [4, 5], plasmonic labels [6–9] and so forth [10–15]. In particular, luminescent nanoparticle-based inks have been extensively utilized in anti-counterfeiting applications. These inks are based on a variety of luminescent materials, such as semiconductor nanomaterials, metal nanoclusters and complexes [12, 16–22]. However, the luminescent inks are prone to detection and can be copied due to the deterministic nature of encoding based on the single color readout. Additionally, the identification related to such tags is visible to counterfeitters, and hence can be easily cloned and reproduced. To avoid duplication of such fluorescent tags, the encoded structures can be hidden/embedded within a matrix, hence rendering invisibility to the tags under white light illumination. To achieve this goal, the two-photon lithography technique can be implemented to generate sub-micron-scale patterned encoded anti-counterfeiting tags embedded within a photopatternable matrix.

Two-photon lithography is based on the non-linear interaction of materials with ultrashort laser pulses. This interaction allows single-step modification in sub-diffraction volumes, on and within the photopatternable resin, and hence is used widely for the generation of micro/nano-patterned structures for a wide variety of applications, including photonics, biomedical and microelectromechanical systems, among
others. Two-photon lithography has also been used for the fabrication of fluorescent structures using semiconductor nanocrystals, metallic nanoclusters and carbon quantum dots for photonic and biomedical applications, but their applications in developing anti-counterfeiting means have not been explored much. Liu et al demonstrated plasmonic security labels fabricated using two-photon lithography [9]. These plasmonic labels provided layered security, but the readouts were based on surface-enhanced Raman spectroscopy, and post-fabrication processing was required, making the system complex. Here, we propose a layered security with an easy fluorescent readout, where a sub-micron-scale patterned fluorescent tag is embedded in a non-emissive polymer layer, making it invisible to counterfeiters. Moreover, the cloning and duplication of such intricate structures require strong technical proficiency, thereby increasing the difficulty level in counterfeiting.

We have devised an anti-counterfeiting method based on a sub-micron-scale patterned fluorescent structure embedded in a non-emissive polymer matrix. An acrylate-based two-photon polymerizable resin (TPPR) was formulated, and microwave-synthesized nitrogen-doped carbon quantum dots were doped in the resin to include emissive characteristics to the TPPR. As a proof of concept, a quick response (QR) code was fabricated using two-photon lithography and, further, a non-emissive cuboid was fabricated over the QR code. This encapsulation provides long-term stability to the fluorescent tag by avoiding any wear and tear in the environmental conditions. Instantaneous readouts were obtained from the fluorescent images of the cloaked micro-QR codes when images were scanned using the Google Lens scanner on a smartphone. The typical time taken by QR code scanners is ∼5 s, and our codes were read within that time frame, so the fabricated structures qualify as a QR code [23]. The cuboid fabricated in the non-emissive layer serves as a cloaking layer as well as an encapsulation for the original QR code. The proposed method can be extended toward ‘layered security’ by adding multi-emissive carbon dots (CDs) or by using 3D encoding based on layer-by-layer stacking of information in the z (height/depth) direction.

2. Experimental methods

2.1. Synthesis of carbon quantum dots
Nitrogen-doped carbon quantum dots were prepared using microwave-assisted pyrolysis, as reported in our previous work [24]. Briefly, citric acid and urea (U) at a 1:3 mass ratio were mixed in deionized (DI) water to obtain a clear solution. The solution was exposed to microwave irradiation using a domestic microwave source to obtain a brownish solution. Then, the solution was allowed to cool at room temperature and the sample was collected in DI water and subsequently washed at 8000 rpm. The sample was lyophilized and stored in a vacuum desiccator for further use. The structural, chemical and optical characterizations of the CDs used in this work were reported previously [24]. The CDs were found to be oval-shaped, with a size distribution in the range 2 nm–5 nm. Fourier transform infrared absorption and emission spectroscopies were performed to obtain the chemical structure and the optical properties of the CDs, respectively. The synthesized CDs exhibited excellent emissive traits, and the presence of C–N and N–H groups indicated nitrogen doping in the CDs.

2.2. Formulation of resin
The photopatternable resin solution was prepared by mixing two different triacrylate monomers, tris (2-hydroxyethyl) isocyanurate and ethoxylated (6) trimethylolpropane triacrylate in a 1:1 ratio, and 10 wt % of commercially available photoinitiator ethyl-2,4,6-trimethylbenzoyl phenylphosphinate was added to the solution to obtain non-emissive resin (NER). One weight (wt %) of powdered CDs was added to the NER resin, and the mixture was sonicated to obtain emissive resin (ER). The formulated resins were stored in a vacuum desiccator and placed in the dark for further use.

2.3. Fabrication of sub-micron scale patterned structure
A schematic of the step-by-step fabrication process is shown in figure 1. A thin film of ER was spin-casted on a glass coverslip and the sample was mounted to an xyz precision stage assembly, coupled to an inverted microscope. Ultrashort laser pulses (140 femtoseconds) from a laser source (Coherent Chameleon Ultra I), operating at 80 MHz, were focused into the resin using a 100×, 0.9 numerical aperture objective, inducing pinpoint polymerization in the resin. The average laser power at the input of the microscope objective was set to 80 mW, and the sample scan speed was set to 500 μm s⁻¹ for all experiments. To write QR codes, the sample was translated in the x and y directions with reference to a predefined origin. After exposure, the unpolymerized resin was washed away using dimethyl formamide (DMF) and allowed to dry in air. Further, NER was spin-casted over the fabricated structure, and a cuboid in the NER was written over the structure using the protocol discussed above. To obtain a cloaking layer restricted/confined only over the emissive
Figure 1. Schematic of step-by-step process of fabrication of an emissive microstructure embedded in a non-emissive layer. ER was spin-coated over a glass substrate and the QR code was fabricated over it using two-photon polymerization. Unexposed resin was washed away using N,N dimethyl formamide. Further, a layer of NER was coated over the sub-micron scale-patterned QR code and a cube was fabricated over it. The final structure appeared to be opaque under white light illumination and the hidden code was visible under ultraviolet light due to the fluorescence of the structure.

Figure 2. (a) A binary QR code is fabricated in the emissive ER layer. (b) The sample is then developed in DMF, and (c) a new layer of NER resin is spin coated over the ER. The NER is written by two-photon polymerization to form a solid structure that hides the code. (d) the absorption and emission spectrum of the ER resin shows a peak at 400 nm and an emission at 450 nm, respectively. (e) SEM image of the fabricated micrograting. (f) A zoomed view of the micrograting element. (g) A fluorescent image of the final structure.

3. Results and discussion

The optical properties of both the resins (ER and NER) were investigated using ultraviolet and photoluminescence spectroscopy, and it was observed that the resins were transparent at the writing wavelength of 800 nm. The absorption spectra of the ER shown in figure 2(d) depicts a distinct absorption peak centered around ~400 nm; this can be attributed to the superposition of the absorbance of the photoinitiator and the surface states of the CDs. The peaks at ~300 nm and ~280 nm can be ascribed to the $\pi \rightarrow \pi^*$ transition arising from the carbonaceous core of the CDs and the absorption by the vinyl moieties of the acrylic resin, respectively. Both the resins were transparent to the illumination wavelength and for ER, emission centered on ~450 nm was obtained due to the emissive properties of the CDs present in the resin.

The operating wavelength for fabrication was set at 800 nm (double the absorption wavelength of the photoinitiator), and the fabrication parameters (e.g. writing speed and laser power) were kept constant for writing the structures (see section 2). The mechanism of two-photon polymerization can be found in our previous reports [26–28]. The set of microgratings was fabricated in the ER and characterized using scanning electron microscopy (SEM) to test the uniformity of the structures fabricated in the ER. The SEM images of the fabricated microgratings and a zoomed view of a line element of the micrograting are shown in figures 2(e) and (f), respectively. The embedded emissive sub-micron-scale patterned structure was fabricated in two steps. Initially, the QR code was fabricated in the ERs over a dimension of 100 $\mu$m × 100 $\mu$m as shown in figure 2(a). Subsequently, the sample was developed in DMF and the NER was spin-casted over the structure, and a cuboid was fabricated over the QR code with layer-by-layer writing. The fabrication was monitored live and it was observed that a single layer of polymerized NER was not able to hide the emissive structure under visible illumination, as shown in figure 2(b), so multiple layers of the polymerized NER were fabricated over the QR code. After writing five layers, a cuboid of 100 $\mu$m × 100 $\mu$m × 5 $\mu$m was formed over the emissive QR code, and it exhibited invisibility under optical illumination, as shown in figure 2(c).
Figure 2. Optical microscope images of (a) QR code of our lab webpage (NEMO Lab, IIT Bombay) fabricated over 100 µm × 100 µm area, (b) QR code covered by a cuboid of NER (100 µm × 100 µm × 1 µm), and (c) QR code covered by a multiple layered cuboid of NER (five layers, 100 µm × 100 µm × 5 µm). The scale bars for (a)–(c) correspond to 50 µm. (d) UV-visible absorption spectrum and emission spectrum of the resin. (e) SEM image of grating with subwavelength resolution fabricated in ER, and (f) Zoomed view of single line element of grating showing resolution of ∼560 nm.

Figure 3. (a) Image of a QR code from our lab webpage (QR code adopted from QR-code-generator.com). (b) Optical microscope image of QR code covered by a thick layer of polymer film of ∼5 µm. (c) False-color fluorescent readout of the fabricated QR code under UV light (360–380 nm) excitation. (d) and (e) QR readouts from image (b) and image (c), respectively, when scanned using Google Lens. Scale bar in (b), (c) corresponds to 50 µm.

The final structures were inspected under illumination of UV radiation at wavelengths in the range 360–380 nm. It was noticed that the QR code embedded under the polymer bed was visible under UV illumination, as shown in figure 3(c). Interestingly, the addition of the polymer layer rendered invisibility to the structure under white light illumination. The images obtained from the cloaked structure under UV illumination (360–380 nm) were scanned using Google Lens, and we were able to obtain the link to our laboratory webpage from the scanned QR code successfully, as shown in figure 3(e). No signal/information was obtained when the optical microscope image of the cloaked structure was scanned using Google Lens, as shown in figure 3(d). We can clearly state that the intricate details of the QR code were successfully
transferred to the micro-QR code fabricated in the ER, and the fluorescent readout from the cloaked structure provided an image with good contrast and high fidelity present.

To transfer this technique from the laboratory to real-world applications, the end product (i.e. the cloaked micro-QR code) should exhibit features such as high reproduction fidelity, scalability and long-term environmental stability. Two-photon assisted fabrication is well known for its reproduction fidelity, and as a test case multiple QR codes with the same structural attributes were fabricated under similar experimental conditions. The end products were found to exhibit good correlation in terms of the structural details and precision of fabrication. Optical microscopic images of two identical micro-QR codes, each fabricated over an area of 100 µm × 100 µm, are shown in figure 4(a), and the replication of the QR codes can be clearly observed in the image. To investigate the intricate details of the structure, fabricated micro-QR codes were imaged using SEM. The top view of one of the micro-QR codes of figure 4(a) is shown in figure 4(b), and the finer details can be seen in the zoomed view shown in figures 4(c) and (d). The zoomed view was captured at a tilt angle of 30 degrees. The sub-micron complex three-dimensional features present in the QR codes add an additional layer of security as these features are not easy to copy and reproduce until the exact parameters used for their fabrication are known to the counterfeits. These sub-micron-scaled features offer a good level of security against cloning, and hence the micro-QR codes fabricated in the NER can be directly implemented toward the development of anti-counterfeiting tags for high-end products.

The QR codes are available in several versions; each version stores different amounts of data and hence they are different sizes. The smallest QR code is QR code version 1, with 21 rows and 21 columns; version 2 has 25 × 25 elements, whereas version 40 stores the maximum data with 177 × 177 columns [29]. Each
element can be represented by a single voxel; hence, the smallest/largest possible QR code depends on the voxel size that can be obtained for the ER,

\[
\text{Size of smallest QR code} = 21 \times 21 \times \text{smallest voxel size} \tag{1}
\]

\[
\text{Size of largest QR code} = 177 \times 177 \times \text{largest voxel size}. \tag{2}
\]

The systematic evaluation of the variation of voxel size is out of the scope of this study. The literature suggests that sub-micron-scaled polymer voxels serve as building blocks for structures in two-photon polymerization-assisted fabrication [30–36]. For complex 2D structures, we have already reported \(~\sim200\) nm resolution and \(~\sim140\) nm for linear structures [27, 28]. Assuming the smallest voxel to be \(~\sim200\) nm, the smallest QR code can be written over an area of 4.2 \(\mu\)m \(\times\) 4.2 \(\mu\)m. The smallest QR code cannot be reduced below the size defined in equation (1). Interestingly, upscaling of the largest QR code beyond the size defined in equation (2) is possible by representing a single array element by a combination of multiple voxels. In order to examine the scalability of the fabrication process, a micro-QR code was fabricated over an area of 50 \(\mu\)m \(\times\) 50 \(\mu\)m. The SEM image shown in figure 4(d) represents the top view of the downscaled structure. It is interesting to note that downsizing the scale of the micro-QR code provides the added benefit of high-density data, as the area required for fabrication was reduced to a quarter, and the same data were stored in the micro-QR code. The long-term stability and photo bleaching were also examined for the fluorescent tags. For a sample stored for three months in ambient lighting conditions, no noticeable variation in structural attributes was observed. A fluorescent image for such a sample is shown in figure 4(e), and the intended message was also successfully read out from the fluorescent image, as shown in figure 4(f). The sample was kept under continuous UV irradiation for 30 min to examine the photo-stability of the micro-QR code. No significant reduction in emission intensity was observed, as shown in the average emission intensity plot in figure 4(g), obtained from the micro-QR code along a horizontal axis passing through the center of the structure, highlighted in figure 4(e). The proposed cloaked micro-QR codes are almost invisible to the naked eye. Even if it is discovered, the cloaking layer covers the real code. These micro-QR codes can be used as unclonable QR code on high-end equipment, luxury brands, integrated circuits, pharmaceuticals, etc. Current technology implements fluorescent stamps that are easy to clone due to the simplicity of design and obvious visibility of the anti-counterfeiting tags. We use polymer-based sub-micron-scaled codes, which are robust, weather-proof and difficult to clone. Additionally, the long-term environmental stability, ease of fabrication and scalability offered by TPL make this technique a potential candidate in the development of tags with higher security standards/layers. The combination of two-photon polymerization and spatially selective placement of the emissive layer provides an innovative means to develop encoded fluorescent anti-counterfeiting tags with enhanced security.

4. Conclusions

We have demonstrated an innovative means to generate fluorescent anti-counterfeiting tags. Two-photon assisted writing of emissive and non-emissive structures provides an effective means to generate encoded tags with higher security. The fluorescent readout obtained from the embedded QR code was able to communicate the intended message. The negligible photo-bleaching and absence of changes in the structural attributes and emission of the sample stored under ambient conditions demonstrate the longevity and robustness of the micro-QR codes. We envision that this technique can be extended toward the development of other higher layered security tags for anti-counterfeiting applications in several ways, such as the addition of multi-emissive particles or the addition of information stacked along the height of the structure.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest
Authors declare no conflict of interest.

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References

[1] Hajiali M, Keyvan Rad J, Ghelzelsefose S and Mahdavian A R 2020 Solvent-free and anti-counterfeiting fluorescent inks based on epoxy-functionalized polyacrylic nanoparticles modified with rhodamine B for cellulosic substrates J. Ind. Eng. Chem. 92 287–96
[2] Chen B, Xie H, Wang S, Guo Z, Hu Y and Xie H 2019 UV light-tunable fluorescent inks and polymer hydrogel films based on carbon nanodots and lanthanide for enhancing anti-counterfeiting Luminescence 34 437–43
[3] Zuo M, Qian W, Li T, Hu X Y, Jiang J and Wang L 2018 Full-color tunable fluorescent and chemiluminescent supramolecular nanoparticles for anti-counterfeiting inks ACS Appl. Mater. Interfaces 10 39214–21
[4] Hu H, Zhong C, Chen C and Chen Q 2014 Magnetically responsive photonic watermarks on banknotes J. Mater. Chem. C 2 3695–702
[5] Chen K, Zhang Y and Ge J 2019 Highly invisible photonic crystal patterns encrypted in inverse opaline macroporous polyurethane film for anti-counterfeiting applications ACS Appl. Mater. Interfaces 11 45256–64
[6] Zhang Y, Jiang C, Ng S H, Lu Y, Han F, Bach U and Gooding J J 2016 Unclonable plasmonic security labels achieved by shadow-mask-lithography-assisted self-assembly Adv. Mater. 28 2330–6
[7] Cheng H, Lu Y, Zhu D, Rosa L, Han F, Ma M, Su W, Francis P S and Zheng Y 2020 Plasmonic nanopapers: flexible, stable and sensitive multiple PUF tags for unclonable anti-counterfeiting applications Nanoscale 12 9471–80
[8] Cui Y, Fang Y, Lee Y H, Lee M R, Zhang Q and Ling X Y 2015 Multiplex plasmonic anti-counterfeiting security labels based on surface-enhanced Raman scattering Chem. Commun. 51 5363–6
[9] Liu Y, Lee Y H, Lee M R, Yang Y and Ling X Y 2017 Flexible three-dimensional anti-counterfeiting plasmonic security labels: utilizing z-axis-dependent SERS readouts to encode multilayered molecular information ACS Photonics 4 2529–36
[10] Cui Y, Hegde R S, Pang I Y, Lee H K and Ling X Y 2014 Encoding molecular information in plasmonic nanostructures for anti-counterfeiting applications Nanoscale 6 282–8
[11] Bae H J, Bae S, Park C, Han S, Kim J, Kim I N, Kim K, Song S-H, Park W and Kwon S 2015 Biomimetic microfingerprinting for anti-counterfeiting strategies Adv. Mater. 27 2083–93
[12] Jiang K, Zhang L, Lu J, Xu C, Cai C and Lin H 2016 Triple-mode emission of carbon dots: applications for advanced anti-counterfeiting Angew. Chem. 128 7347–51
[13] Jiang Y, Li G, Che W, Liu Y, Xu B, Shan G, Zhu D, Su Z and Bryce M R 2017 A neutral dinuclear Ir(III) complex for anti-counterfeiting and data encryption Chem. Commun. 53 3022–5
[14] Deng J, Deng L, Guan Z, Tao J, Li G, Li Z, Li Y and Zheng G 2020 Multiplexed anticounterfeiting meta-image displays with single-sized nanostructures Nano Lett. 20 1830–8
[15] Mayer F, Richert S, Hübner P, Jabbour T and Wegener M 2017 3D fluorescence-based security features by 3D laser lithography Adv. Mater. Technol. 2 1700212
[16] Li F, Wang X, Xia Z, Pan C and Liu Q 2017 Photoluminescence tunability in stretchable PDMS film grafted doped core/multishell quantum dots for anti-counterfeiting and data encryption Adv. Funct. Mater. 27 1700051
[17] Xu Y et al 2016 Two-photon-pumped perovskite semiconductor nanocrystal lasers J. Am. Chem. Soc. 138 3761–8
[18] Smith A F, Patton P and Skrabak S E 2016 Plasmonic nanoparticles as a physically unclonable function for anti-counterfeit nanofingerprints Adv. Funct. Mater. 27 1600318
[19] Park K, Jung K, Kwon S J, Jang H S, Byun D, Han I K and Ko H 2016 Plasmonic nanowire-enhanced upconversion luminescence for anti-counterfeit devices Adv. Funct. Mater. 26 7836–46
[20] Xu L, Chen J, Song J, Li J, Xue J, Dong Y, Cai B, Shan Q, Han B and Zeng H 2017 Double-protected all-inorganic perovskite nanocrystals by crystalline matrix and silica for triple-modal anti-counterfeiting codes ACS Appl. Mater. Interfaces 9 26556–64
[21] Jiang K, Wang Y, Cai C and Lin H 2017 Activating room temperature long afterglow of carbon dots via covalent fixation Chem. Mater. 29 4866–73
[22] Žukauskas A, Malinauskas M, Kontenis L, Purlys V, Paipulas D, Vengris M and Gadonas R 2010 Organic dye doped microstructures for optically active functional devices fabricated via two-photon polymerization technique Lith. J. Phys. 50 55–61
[23] Tarjan L, Šenk I, Tegeljía S, Stankovski S, Ostojic G and Readability A 2014 Analysis for QR code application in a traceability system Comput. Electron. Agric. 109 1–11
[24] Jaiswal A, Singh G P, Shejale K P, Saxena S and Shukla S 2020 Synthesis of oval nitrogen doped carbon quantum dots for anticounterfeiting applications Adv. Electron. Mater. 6 113457–62
[25] Cicha K, Li Z, Stadlmann K, Osvianikov A, Markut-Kohl R, Liska R and Stämpfli J 2011 Evaluation of 3D structures fabricated with two-photon-photopolymerization by using FTIR spectroscopy J. Appl. Phys. 110 064911
[26] Chaudhary R P, Ummeathala G, Jaiswal A, Hawal S, Saxena S and Shukla S 2016 One-step, subwavelength patterning of plasmonic gratings in metal-polymer composites RSC Adv. 6 113457–62
[27] Chaudhary R P, Jaiswal A, Ummeathala G, Hawal S R, Saxena S and Shukla S 2017 Sub-wavelength lithography of complex 2D and 3D nanostructures without two-photon dyes Addit. Manuf. 16 30–40
[28] Ummeathala G, Jaiswal A, Chaudhary R P, Hawal S, Saxena S and Shukla S 2017 Localized polymerization using single photon photoinitiators in two-photon process for fabricating subwavelength structures Polymer 117 364–9
[29] Tiwari S 2016 An introduction to QR code technology Int. Conf. Inf. Technol., Institute of Electrical and Electronics Engineers (IEEE) pp 39–44
[30] Kawata S, Sun H R, Tanaka T and Takada K 2001 Finer features for functional microdevices Nature 412 697–8
[31] Vyatskikh A, Ng R C, Edwards B, Briggs R M and Greer J R 2020 Additive manufacturing of high-refractive-index, nanoarchitected titanium dioxide for 3D dielectric photonic crystals Nano Lett. 20 3513–20
[32] Zakhurdaeva A, Dietrich P, Hölscher H, Koos C, Korvink J G and Sharma S 2017 Custom-designed glassy carbon tips for atomic force microscopy Micromachines 8 285
[33] Saha S K, Wang D, Nguyen V H, Chang Y, Oakdale J S and Chen S C 2019 Scalable submicrometer additive manufacturing Science 366 105–9
[34] Hering J, Eifler M, Hofherr I, Ziegler C and Seewig J 2020 Two-photon laser lithography in optical metrology Advanced Fabrication Technologies for Micro/Nano Optics and Photonics XI p 1054412
[35] Li Z, Hu P, Zhu J, Gao Y, Xiong X and Liu R 2018 Conjugated carbazole-based Schiff bases as photoinitiators: from facile synthesis to efficient two-photon polymerization J. Polym. Sci. A 56 2692–700
[36] Marino A, Barsotti J, De Vito G, Filippeschi C, Mazzolai B, Piazza V, Labardi M, Mattoli V and Ciofani G 2015 Two-photon lithography of 3D nanocomposite piezoelectric scaffolds for cell stimulation ACS Appl. Mater. Interfaces 7 25574–9