Define and measure the dimensional accuracy of two-photon laser lithography based on its instrument transfer function

Gaoliang Dai\textsuperscript{1,*}, Xiukun Hu\textsuperscript{1}, Julian Hering\textsuperscript{2,3}, Matthias Eifler\textsuperscript{2,4,*}, Jörg Seewig\textsuperscript{4} and Georg von Freymann\textsuperscript{3,5}

\textsuperscript{1} Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
\textsuperscript{2} Opti-Cal GmbH, 67663 Kaiserslautern, Germany
\textsuperscript{3} Department of Physics and Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
\textsuperscript{4} Lehrstuhl für Messtechnik & Sensorik, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
\textsuperscript{5} Fraunhofer Institute for Industrial Mathematics ITWM, 67663 Kaiserslautern, Germany

\* Author to whom any correspondence should be addressed.

E-mail: gaoliang.dai@ptb.de

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Abstract

Two-photon polymerization (TPP) is a powerful technique for direct three-dimensional (3D) micro- and nanomanufacturing owing to its unique ability of writing almost arbitrary structures of various materials. In this paper, a novel method is proposed to quantitatively define and measure the dimensional accuracy of TPP tools based on the concept of instrument transfer function (ITF). A circular linear-chirp pattern is designed for characterizing the ITF. Such a pattern is arranged in a linear chirp function with respect to its radial distance $r$ from the pattern centre, thus, well representing a signal with a quasi-flat amplitude over a given spectral bandwidth. In addition, the pattern is rotational symmetric, therefore, it is well suited for characterizing the ITF in different angular directions to detect angular-dependent asymmetries. The feasibility of the proposed method is demonstrated on a commercial TPP tool. The manufactured pattern is calibrated by a metrological large range atomic force microscope (AFM) using a super sharp AFM tip, thus the dimensional accuracy and angular-dependent anisotropy of the TPP tool have been well characterized quantitatively. The proposed method is easy to use and reveals the dimensional accuracy of TPP tools under real manufacturing conditions, which concerns not only the optical focus spot size of the exposing laser but also influencing factors such as material shrinkage, light–matter interaction and process parameters.

1. Introduction

Two-photon polymerization (TPP) \cite{1} is a powerful three-dimensional (3D) micro- and nanofabrication technique based on nonlinear light–matter interaction. In TPP processing, femtosecond laser pulses are focused into a photosensitive material, where two-photon absorption \cite{2} and subsequent polymerization in an extremely localized focal volume (voxel) is induced. By scanning the laser focus with respect to the photoresist, e.g. by a galvanometric mirror scanner, TPP allows for ultra-fast structuring in a layer-by-layer process. Due to its flexibility and high resolution while reaching feature sizes into the sub-100 nm region \cite{3}, TPP enables research in many fields, e.g. photonic crystals \cite{4,5}, topological insulators \cite{6,7}, biological cell-scaffolds \cite{8–10}, photonic and mechanical metamaterials \cite{11,12}, as well as industrial relevant applications, like micro-optical elements \cite{13–16}, and material measures \cite{17–19}.

Resolution and writing speed (i.e. the manufacturing throughput) have been tremendously improved in recent years. However, an objective comparison between different TPP devices or different materials with respect to structural quality and fabrication yield is still difficult. With increasing industrial applications, such a comparison is highly sought after, as it supports the decision which type of material might yield the...
best results on a certain type of TPP device. Furthermore, it might support the development of smart algorithms, which automatically optimize the writing strategies for arbitrary structures. So far, structures are optimized following a trial-and-error route, based on the experience of the user. For most of the structures, going to the physical limits of the device and material is often not necessary. For example, for the application of printing highly accurate micro-lenses using stimulated emission depletion (STED) inspired TPP [20], the dimensional accuracy is the more important quality criteria than resolution. However, resolution is the quantity which is most often found in literature to define the performance of TPP. Although TPP resolution has been rapidly improved in the past decade [20–23], resolution alone tells nothing about the overall structural quality reached. Furthermore, resolution is often confused with feature size, for which the lateral and/or axial size of a single voxel is typically applied [1]. A single voxel might be measured using, e.g. the ascending scan method [24, 25] or the suspending bridge method [23]. The measurement of the voxel shape may suffer from the so-called truncation effect [24], impacting the measurement accuracy. Furthermore, the feature size does not reveal the true resolving capability of a TPP tool, because the resolution of a TPP process depends not only on the focal spot size of the laser, but also on the nonlinear interaction of light-matter, the material’s shrinkage, diffusion, deformation of the structure as well as the process parameters (e.g. the distance between two adjacent lines during fabrication, the writing speed, etc). To measure resolution, the accepted way is to measure the distance between two lines or more generally two features, which can be done either laterally or axially. While lateral resolution down to 120 nm [22] has been demonstrated along these lines using STED-inspired TPP, this again does not tell too much about the fabrication capability of complex structures, as the writing process of adjacent features can be strongly affected due to the consumption of photoinitiators and diffusion of various species (photoinitiators, scavengers) [26]. Fischer et al suggested to fabricate a 3D periodic unit, e.g. a woodpile photonic crystal for determining both axial and lateral resolution of a given photopolymerizable system [20]. While it is advantageous for characterizing the lateral and axial resolution of the tool simultaneously, it needs either a relatively complex spectral evaluation route, which only indirectly measures the resolution or it requires a combination of focussed ion beam (FIB) slicing and electron beam microscopy to retrieve the parameters.

In this paper, we propose a novel method for quantitatively characterizing the dimensional accuracy of a TPP tool and the used material based on its instrument transfer function (ITF). For characterization, an atomic force microscope (AFM) is sufficient, which does not have to reach atomic resolution and allows for characterization at much lower cost than FIB/electron-beam or spectral characterization. The ITF generally describes the response of a system in terms of the frequency components between its input and output signals and has been investigated in the field of optical microscopy [27]. In a TPP process, such an ‘input signal’ represents the designed 3D model of a structure applied to a TPP tool for printing, while the ‘output signal’ is the manufactured 3D structure. In such a way, the ITF can be understood as the printing capability of a TPP tool as a function of the object’s spatial frequency components. This concept has the advantage that it is consistent with the ISO standardization in the geometrical product specification, namely the ISO 25178 parts 600 [28] and 70 [29], defining the material measures and metrological characteristics for, e.g. the resolution of optical areal surface topography measuring instruments based on their ‘topography fidelity’.

2. Method

To test the dimensional accuracy of TPP tools, we design a circular linear-chirp pattern. Two main ideas are implemented in this design. First, sample features are arranged in a linear chirp function with respect to its radial distance \( r \) from the pattern center. Such a linear chirp function profile represents a 3D surface topography with a quasi-flat amplitude over a given bandwidth, which is preferable for characterizing the ITF. Second, the pattern is rotationally symmetric, thus it is ideal to evaluate angular-dependent asymmetries of TPP tools by characterizing the ITF features in different angular directions. This radial arrangement tests the scanning axis of the TPP tool, as well as certain asymmetries introduced by aberrations/polarization. While the chirp directly tests the achievable dimensional accuracy in lateral direction, the request for constant surface modulation tests the dimensional accuracy in axial direction as well as the power dependent cross-linking density.

Mathematically, a linear chirp function can be described as

\[
z(r) = \frac{H}{2} \sin\left(\Phi_0 + 2\pi r \left( f_0 - \frac{\Delta f}{2R} r \right) \right),
\]

where \( H \) is the feature height; the pattern has a linearly changing spatial frequency with respect to \( r \), i.e. \( f(r) = f_0 - \frac{r}{R} \Delta f \); \( R \) is the radius of the outermost borders of the pattern; \( f_0 = 1/\lambda_{\text{topo}} \) is the initial topographic frequency; and \( \Delta f \) is the bandwidth of the structure.
Figure 1. (a) SEM images of a chirped pattern fabricated by TPP similar to the one measured in (c); (b) schematic diagram showing the principle of the radial scanning strategy applied in measuring the pattern; (c) AFM image taken by the radial scanning strategy shown as raw measurement data after 1st order levelling. Each radial profile is scanned with 48001 pixels and a pixel distance of 2 nm; (d) radial profiles of \( \theta = 0^\circ \) (blue) and \( \theta = 135^\circ \) (red) at the marked positions in (c) and the design profile (black).

\[
\Delta f = \frac{1}{\lambda_{\text{topo}}^{\text{min}}} - \frac{1}{\lambda_{\text{topo}}^{\text{max}}},
\]

where \( \lambda_{\text{topo}}^{\text{min}} \) denotes the minimum radial spatial wavelength and \( \lambda_{\text{topo}}^{\text{max}} \) denotes the maximum radial spatial wavelength.

To get the accurate knowledge of the ‘output signal’ — the 3D geometry of the manufactured pattern, exemplarily shown as SEM image in figure 1(a) — a 3D microscopic technique, which possesses better resolution than the TPP tool has to be applied. A very suitable candidate tool for this purpose is AFM, which is widely applied for characterization of various nanostructures with both a high lateral resolution (down to a few nm determined by the AFM tip geometry) and a high vertical resolution (at sub-nm level). In this study, we measure the manufactured pattern by a metrological large range AFM (Met. LR-AFM) developed at the Physikalisch-Technische Bundesanstalt — the national metrology institute of Germany. The details of this tool can be found elsewhere [30–33].

During AFM measurements, one has to consider the tip dilation effect. The image obtained by the AFM is the dilated result of the measured feature with the tip shape [34], which will consequently bias the spectrum of the calibrated data sets. To mitigate the tip dilation effect, super sharp AFM tips (SSS-NCLR, NANOSENSORS\textsuperscript{TM}) are applied in this study.

The so-called radial scanning strategy used here is schematically illustrated in figure 1(b) and was first designed for measuring rotation symmetrical structures, such as Rockwell indenters [35]. In measurements, profiles are measured in a radial direction through the center of the pattern. The advantages of this measurement strategy are two-fold. First, the measurement time can be reduced significantly, as the number of needed measurement profiles can be reduced. Second, the pixel density along the radial profiles can be increased without impacting the needed measurement time, thus enhancing the sampling frequency of the reference data.

The TPP pattern is manufactured by a commercial TPP tool (Photonic Professional GT+, Nanoscribe GmbH) equipped with a 63× objective lens with a nominal numerical aperture (NA) of 1.4 (Carl Zeiss Microscopy GmbH) and with a galvanometric mirror scanner with a scan speed of 20 mm s\(^{-1}\). The built-in fibre laser is specified with a central wavelength of 780 nm, a repetition rate of 80 MHz and a pulse duration
Figure 2. (a) SEM image of the SSS-NCLR AFM tip after being applied in AFM measurements. The contour of the tip is evaluated as the tip geometry, showing a tip radius of about 14 nm; (b) reconstructed result (red) of the measured profile (black) ($\theta = 270^\circ$ in figure 1) by the tip geometry determined in (a); (c) detailed zoomed-in views showing the raw profile (black), reconstructed profile (red) and the tip geometry (crosshatched blue) at the marked positions I and II.

of roughly 100 fs. All manufacturing processes have been performed in an air-conditioned room at 21 $^\circ$C and <30% relative humidity. The sample material is IP-L 780 photo resist due to its specified high resolution properties. The test pattern is printed with a size of 100 $\mu$m $\times$ 100 $\mu$m with a topographic wavelength range of $\lambda_{\text{topo}}^{\text{min}} = 0.6 \mu$m to $\lambda_{\text{topo}}^{\text{max}} = 20 \mu$m and has a nominal feature height $H$ of 1.0 $\mu$m. Exemplary SEM and AFM images are illustrated in figures 1(a) and (c), respectively, where the former shows a similar structure, which has been sputter coated for SEM. In the AFM measurement, each radial profile has a length of 96 $\mu$m and is sampled with 48001 pixels, representing a very fine sampling distance of 2 nm pixel$^{-1}$. The pattern is measured by 60 profiles, representing an angular resolution of 3$^\circ$/profile. The figure is shown as the raw measurement data without any noise filtering after applying the 1st order levelling, which is used to remove the effect introduced by sample tilting in its mounting. Figure 1(d) depicts two radial profiles along the angular direction of $\theta = 0^\circ$ (blue) and $\theta = 135^\circ$ (red), together with the design profile (black). It can be seen that the printed features have higher amplitude at the outer region (with lower spatial frequency) than the features at the inner region (with higher spatial frequency), which indicates the limit of the printing capability of the TPP technique for the chosen structure.

To be sure that the results are not influenced by the tip geometry of the AFM, the AFM tip geometry is measured by using a scanning electron microscope (FEI Helios), as shown in figure 2(a). The contour of the tip is evaluated, showing a radius of approximately 14 nm at its apex. To correct the tip effect in the measurement data, the measured profile is eroded by the determined tip geometry. Figure 2(b) depicts the raw profile and tip-corrected profile in black and red, respectively. It can be seen that the two profiles overlap very well, indicating that the applied AFM tip can well resolve the printed structures. For clarity, detailed zoomed-in views are further given in figure 2(c) at the marked positions 'I' and 'II' of figure 2(b). The position 'I' is selected at the region where the structure has a larger spatial wavelength, thus has been well printed; while the position 'II' is selected at the region with a shorter wavelength whose printed amplitude is reduced. It can be seen in the zoomed-in figure of the position 'II', the raw profile and tip-corrected profile do have slight differences. However, the applied tip can still well resolve the bottom of the printed feature.
Figure 3. (a) Amplitude curves calculated by Fourier transformation of the designed profile and two measured radial profiles along the angular direction of $\theta = 0^\circ$ and $\theta = 135^\circ$; (b) evaluated (open circles) and fitting (solid lines) ITF curves of the TPP tool along two angular directions; (c) evaluated dimensional accuracy along different angular directions, which is defined as the wavelength of the printed profile where the gain is dropped to $-6$ dB.

Based on the aforementioned theory, the ITF of the TPP tool can be evaluated as

$$\text{ITF}(\theta, f) = \frac{F_m(\theta, f)}{F_d(\theta, f)} \left[\frac{\text{FFT} \{V_m(r, \theta)\}}{\text{FFT} \{V_d(r, \theta)\}}\right]$$

where $\text{ITF}(\theta, f)$ denotes the ITF in polar coordinates; $F_m(\theta, f)$ and $F_d(\theta, f)$ are the Fourier transformation results of the measured profile $V_m(r, \theta)$ and the designed profile $V_d(r, \theta)$ in the orientation of $\theta$ in polar coordinates.

Figure 3(a) depicts the amplitude curves calculated by Fourier transformation of the designed profile and the measured radial profiles along two angular directions of $\theta = 0^\circ$ and $\theta = 135^\circ$ shown in black, red and blue, respectively. After applying equation (3), the ITF curves of the TPP tool along these two angular directions can be calculated, as plotted in figure 3(b) (open circles). It can be seen that the ITF keeps almost constant at low spatial frequencies. It indicates that the features, which have lower spatial frequencies than the dimensional accuracy of the TPP tool can be well printed. However, the gain of the ITF curves starts to decay when the spatial frequency is increased from 0.4 to 1.6 $\mu$m$^{-1}$, indicating the loss of printed features due to reaching the dimensional accuracy limit of the TPP tool as well as feeling the influence of proximity and other material related effects. Thus, the ITF curve can well represent the dimensional accuracy of the TPP tool.

To achieve a better evaluation stability, we fit the evaluated ITF curve to the function:

$$G(f) = \frac{k}{1 + (m \cdot f)^n}$$

where $G$ denotes the gain and $f$ denotes the spatial frequency; the parameter $k$ is introduced to represent the z-scaling factor; the parameters $m$ and $n$ are introduced to describe the bandwidth characteristics of the instrument. The fitting curves are shown as solid lines in figure 3(b).

To have a quantitative definition, we define the dimensional accuracy limit of the TPP tool as the value of the wavelength where the gain of the ITF curves drops to $-6$ dB, as shown in figure 3(b). At this wavelength,
the amplitude of the printable feature drops at the half of the designed amplitude. For the example shown in the figure 3(b), the dimensional accuracy limit is evaluated as 0.83 and 0.67 µm for the two angular directions of $\theta = 0^\circ$ and $\theta = 135^\circ$, respectively. After calculating the ITF and its corresponding dimensional accuracy at all angular directions ranging from $\theta = 0^\circ$ to $\theta = 360^\circ$ as mentioned above, we obtain the angular-dependent dimensional accuracy of the tool, as plotted in figure 3(c). It has rather a quasi-elliptical shape than a circular shape, which may be owing to the optical aberrations of the microscopic set up. Besides, a non-perfect circular polarisation of the excitation laser beam distorts the theoretical round shape of the focus within the $xy$-plane, thus resulting in additional asymmetries regarding the lateral dimensional accuracy. Another reason can be assumed by the unidirectional fabrication of the structure along the angular direction of $\theta = 90^\circ$ (hatching direction). This was carried out to avoid angular-direction-dependent non-synchronizations of laser power ramping and galvo-mirror positioning during the polymerization process, which was found in previous experiments.

One may wonder why the dimensional accuracy value evaluated in our proposed method is much larger than, e.g. the diffraction limit of the applied optical microscope ($\lambda/(2\,\text{NA}) = 0.278\,\mu\text{m}$) or higher resolutions reported with these commercial devices. But having in mind the complex interplay of optics and materials in TPP, these differences do not surprise at all. The very best resolution results for two separated lines are a very special case with not too much relation to actual structures printed. Along these lines it is reassuring that the practical specifications given for the used TPP device are close to the values found by the proposed method. Therefore, the proposed method can indeed provide a quantitative measure for the dimensional accuracy reachable for an actual structure under certain fabrication conditions and not only the physical limitation based on optical diffraction effects.

3. Application

The ITF method introduced above has advantages of characterizing the dimensional accuracy of TPP manufacturing including the contributions not only from the optics, but also from the light–matter interaction and the printing process. Furthermore, the method can be well applied to investigate the influence of process parameters on the dimensional accuracy of TPP tools. For instance, by printing the test patterns with varied process parameters, the dependency of the dimensional accuracy on the process parameters can be obtained, which could thus offer a basis for the process optimization. In general, this will speed up the process for structure optimization as a very good set of starting parameters can be easily determined. Of course, this will not yet replace optimization in detail, if one wants to work at the physical limits of the tool.

To demonstrate such an application, in this study we investigate the impact of laser power on the dimensional accuracy. We designed another pattern with a wavelength range of $\lambda_{\text{topo}}^{\text{min}} = 0.3\,\mu\text{m}$ to $\lambda_{\text{topo}}^{\text{max}} = 0.9\,\mu\text{m}$, a feature height of $H = 300\,\text{nm}$ and a radius of the outermost borders of the pattern of $R = 50\,\mu\text{m}$. A number of patterns are printed with varying pre-defined power levels, ranging from 34% to 73% of the maximal laser power ($P_{\text{max}} \sim 50\,\text{mW}$ at the entrance pupil of the objective). This generalized...
Figure 5. (a) Evaluated (open circles) and fitting (solid lines) ITF curves of the TPP tool along $\theta = 90^\circ$ at three power levels $P$ of 40% (black), 50% (red) and 71% (blue), respectively; (b) evaluated printing dimensional accuracy values along different angular directions for three different power levels $P$ of 40% (black), 50% (red) and 71% (blue), respectively; (c) dependence of evaluated printing dimensional accuracy values on the power level at $\theta = 60^\circ$; (d) height ratio of the printed profile ($z_{\text{exp}}$) to the design value ($z_{\text{design}}$) at $\lambda_{\text{topo}} = 0.83 \, \mu m$ which corresponds to the last peak position of the designed curve in figure 4.

power level is set by multiplication of two variables: the so-called ‘power scaling’ and ‘laser power’. While the power scaling variable has to be fixed for the complete structure, the laser power variable can be adjusted spatially within the designed pattern to achieve, e.g. an equal exposure dose at all printing positions. This was used to realize an overall constant height of the chirp’s amplitudes. Exemplary SEM images of sputter coated patterns fabricated with 50% and 60% of the maximal laser power are shown in figure 4(a). The radial profiles of many un-sputtered patterns printed with varying power levels measured by AFM are compared in figures 4(b)–(e) along the angular direction $\theta$ of $0^\circ$, $90^\circ$, $180^\circ$, $270^\circ$, respectively. The designed radial profile is shown at the bottom of figures 4(b)–(e). As can be seen in figure 4(c), the amplitude of the printed features reduces significantly when the spatial frequency of the signal increases, indicating that the tool cannot well print the designed structures at higher spatial frequency due to the limit of its dimensional accuracy. In addition, the printed profiles show different behaviour at different power levels. For instance, the amplitudes of the printed features increase when the power level is increased from 34% to 50% and then decrease for higher power levels of 52% to 73%. It indicates the impact of the laser intensity on the dimensional accuracy of the TPP. At first sight this seems anti-intuitive, since higher power levels are expected to worsen the resolution, due to the increasing voxel size and proximity effect. Of course, increasing the overall laser intensity is not what is usually done for reaching the highest resolution. But for dimensional accuracy, this is exactly the expected behaviour. Too low power levels result in low cross-linking density and, hence, in reduced structural stability, so that well defined features are not possible to reach. This behaviour is well
Figure 6. (a) Illustration of the target bowl-containing structure; (b)–(d) scanning electron microscopic images of the corresponding fabricated structures with power levels below, equal and greater than 50%; (e) illustration of the target woodpile structure with rod distances of \(0.8 \, \mu m\); (f)–(h) scanning electron microscopic images of the corresponding fabricated structures with power levels below, equal and greater than 50%.

represented in the ITF evaluation as shown in figure 5(a), where the evaluated ITF curves (open circles) together with the fitting curves (solid lines) along \(\theta = 90^\circ\) of three selected power levels \(P\) of 40\%, 50\% and 71\% are plotted in black, red and blue, respectively. The curves indicate that the conformity of the structure's amplitude is of great importance. For low power levels, e.g. \(P = 40\%\), this amplitude is getting lower, too. Consequently, the −6 dB drop is already reached at low topographic frequencies (\(\sim 1.4 \, \mu m^{-1}\)), leading to the observed worsened dimensional accuracy value. On the other side, for considerable higher power levels, e.g. \(P = 71\%\), the voxel size, proximity effect, etc become the limiting factors. In the end, the optimal power level appears to be about 50\% in this experimental scenario.

Furthermore, the printed profiles shown in figure 4 are also angular dependent. For instance, the amplitude of the printed signal at \(\theta = 0^\circ\) is significantly smaller than that of other angular directions. The reason can be found in the way of fabrication: in contrast to the example shown in section 2, the patterns now are manufactured by circular movements of the laser focus around the center with increasing \(r\), starting at \(\theta = 0^\circ\) and ending at \(\theta = 359^\circ\), respectively. Thereby, we expect an overall improvement in dimensional accuracy, because there are way less power ramping procedures during such a ‘hatching circle’, thus, leading to less fabrication errors, compared to a hatching line along the angular direction of \(\theta = 90^\circ\). As a disadvantage, around \(\theta = 0^\circ\), these non-perfect adoptions of the laser focus’ acceleration/deceleration with regard to the required power level lead to the observable stronger deviation of the structure’s amplitude around this angle. The angular dependence of the evaluated printing dimensional accuracy of the patterns are shown in figure 5(b). For sake of clarity, again, only the results of patterns printed at three power levels \(P\) of 40\%, 50\% and 71\% are shown in black, red and blue, respectively. It can be seen from figure 5(b) that the dimensional accuracy of the three patterns has a similar quasi-elliptical shape. The printing process achieves the best result near \(\theta = 45^\circ\) while it has the worst dimensional accuracy near \(\theta = 135^\circ\). Since the elliptical shape is flipped with regard to the results in section 2 (see figure 3(c)), we can neglect the impact of the laser focus’ non-symmetrical shape and optical aberrations, as they did not change at all. Instead, the way of hatching and the resulting diffusion of photoinitiator and scavenger molecules, hence, the proximity effect, seem to be generally much more critical for the fabrication results. Further optimizing the way of hatching can possibly move this elliptical shape towards a circle and can be investigated in future research.

Figure 5(c) depicts the dependence of evaluated dimensional accuracy (along \(\theta = 60^\circ\)) with respect to the power level. It can be clearly seen that the TPP tool achieves the best dimensional accuracy of about 0.51 \(\mu m\) at the power level of 50\%. In addition, to show the dependence of the printed feature height on the power level, the height ratio of the printed profile (\(z_{\text{exp}}\)) to the design value (\(z_{\text{design}}\)) is plotted in figure 5(d). It can be seen that the printed structure reaches the highest amplitude also near the power level of 50\%. Both plots show excellent agreement with the expected tendency of the overall materials response, as mentioned above. These values should now give a rough guideline for the fabrication of any other structures: a power level of about 50\% is expected to give a good conformity of the targeted and fabricated structures. Indeed, this can be found experimentally as shown by a bowl-containing structure, illustrated in figures 6(a)–(d). Too low power levels (25\%) lead to significantly unwanted deformations due to the weak crosslinking density, whereas too high power levels (55\%) already result in micro-explosions.
Regarding the above determined dimensional accuracy limit of the TPP tool, one can conclude from the long main axis of the resolution ellipse in figure 5(b), that, e.g. line distances of roughly 0.8 \( \mu m \) should be resolvable. Therefore, we fabricated woodpile photonic crystals with a respective nominal rod distance of 0.8 \( \mu m \) as benchmarks. Here, we found again the best structure conformity at a power level of 50\%, with clearly distinguished rods (figures 6(e)–(h)). Low power levels (40\%) result in dramatic shrinkage and deformation of the woodpiles due to the aforementioned reasons, whereas too high power levels (75\%) lead to adhesion between neighboring rods. Thus, those woodpiles can not be considered as resolved structures any more.

While the circular chirp structure does not spare the user the fine-optimization, it allows for a rough prediction of critical fabrication parameters like the power level or the resolution limit of the 3D printing devices in use and might help in chosing the right material/parameter combination as well as guide the development of automatic optimization algorithms.

4. Conclusions

In summary, we have proposed and demonstrated a new approach for characterizing the dimensional accuracy of TPP tools based on the concept of ITF, which is consistent to the ISO 25178 and has been investigated to describe the transfer behaviour of optical surface topography measuring instruments. Using this approach, a TPP tool under investigation is commanded to print circular linear-chirp patterns. The manufactured patterns are then measured by, e.g. an AFM tool to get its real feature topography. Based on the designed 3D model of the pattern which represents the ‘input signal’ and the measured topography which represents the ‘output signal’, the ITF of the TPP tool can be evaluated as the ratio between the Fourier transformation results of the input and output signals. In this study, the circular linear-chirp pattern is designed as a ‘signal’ for two folds of reasons. First, a signal in a linear chirp function could well represent a surface topography with a quasi-flat amplitude over a given bandwidth, which is preferable for characterizing the ITF. Second, the pattern is rotationally symmetric, thus it is ideal to characterize the ITF features in different angular directions for detecting angular-dependent asymmetries of TPP tools.

Compared to previous methods which characterize device resolution only, our method could reveal the overall dimensional accuracy of the TPP tool, including the contributions not only from the optics, but also from the light–matter interaction and the printing process. Furthermore, the method can be well applied to investigate the influence of process parameters on the dimensional accuracy of TPP tools. For instance, by printing the test patterns with varied process parameters, our method could thus offer a basis for the process optimization. As an example, the proposed method is applied in investigating the impact of the general power level of a TPP tool on its dimensional accuracy, showing promising results.

The proposed method so far presents a first step towards better comparability of different TPP devices by an objective measurable criterion, which is achievable without using FIB cross sections or spectral analysis of complex 3D structures. Furthermore, using AFM for mechanical load experiments could possibly allow to extract even more information about the polymer network, e.g. the local cross-linking density. Here, further investigations in the future will allow even better statements about the right fabrication parameters.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

Gaoliang Dai  
https://orcid.org/0000-0002-1611-0074
Matthias Eifler  
https://orcid.org/0000-0001-6628-7284
Georg von Freymann  
https://orcid.org/0000-0003-2389-5532
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