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Tailoring the longitudinal electric fields of high-order laser beams and their direct verification in three dimensions

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Abstract

We demonstrate the tailoring of longitudinal electric fields that arise from tight focusing of spatially phase-shaped high-order laser beams, and verify their spatial distribution in three dimensions. To tailor the three-dimensional (3D) spatial distribution of longitudinal electric fields, we precisely control the relative phase delay between the two lobes of a HG₁₀ laser beam using a spatial light modulator (SLM) before tight focusing. To verify the longitudinal electric fields in the focal volume, we employ 3D microscopic mapping of second-harmonic generation (SHG) from a single semiconductor nanowire that is extremely sensitive to the orientation of the longitudinal electric field. The technique is direct, general and expected to be useful in harnessing and in probing longitudinal electric fields with arbitrary spatial intensity distributions in the 3D focal volume.

Keywords: Second-harmonic generation, 3D microscopy, Semiconductor nanowire, Polarization, Longitudinal electric field

1. Introduction

There has been much interest in the syntheses and applications of complex light shapes, i.e., beams that exhibit unconventional or nonuniform amplitude, phase and polarization properties. This interest is anticipated to further bloom thanks to the availability of spatial light shaping devices such as liquid crystal-based spatial light modulators (SLMs), deformable membrane mirrors and digital micromirror devices. Such instruments provide remarkable levels of

versatility that open new ways to perform optical trapping [1–3], microfabrication [4,5], microscopy [6–10], vector beam engineering [11–13] and many other applications.

The interest in engineered vector beams and especially their unique focusing properties is also increasing. In fact, the focal fields of vector beams (excluding azimuthally polarized beams) can contain nonvanishing electric field components that are parallel to the propagation axis (so-called longitudinal electric fields) [14]. These longitudinal fields have opened significant new ways to improve the sensitivity and performance of many optical systems [15,16]. Also, the longitudinal electric fields were found to be critical in the interpretation of many fundamental light–matter interactions [17]. In the context of nonlinear optics, such longitudinal electric fields have been shown to influence strongly the efficiency of second-harmonic generation (SHG) from individual nanostructures [18]. Thus, being able to tailor and to study the polarization components of optical fields in the focal volume or a particular optical field component like the longitudinal electric field is important.

To date, complete characterization of 3D vectorial field distributions, especially those that arise from the tight focusing of unconventional light shapes, remains a fundamental challenge. This capability is hindered by the shortage of techniques to probe directly and reliably these beams or their longitudinal electric fields in the 3D focal volume. For example, previous techniques to probe and study longitudinal electric fields have been restricted by the inherent challenges in the implementation of near-field experiments including the physical properties of near-field probes [19–21], applicability of nanoscale surface deformations in photosensitive materials [22–24], availability of specialized electromagnetic filters placed before the detector [25], and complexity and implementation of indirect nanotomography for focal fields reconstruction [26,27]. Recently, we have shown the possibility of directly mapping the longitudinal electric fields of spatially phase-shaped HG_{10} beam along the transversal focal plane using far-field second-harmonic generation (SHG) from a single semiconductor nanostructure [28]. We aim to develop this work further in order to improve the control of longitudinal electric fields, allowing, for example, full tunability of nonlinear optical generation in a single nanostructure.

In this work, we present a general approach to tailor the spatial distribution of the longitudinal electric fields that arise from a tightly focused spatially phase-shaped high-order laser beam, and verify their spatial distribution in three dimensions. Spatial phase shaping of a

Fig. 1. Schematic diagram of the point-scanning SHG microscope consisting of a femtosecond laser, half-wave plates (HWP), polarizing beamsplitter (PBS), beam

dump (BD), mirrors (M), lenses (L), pinholes (P), mode converter (MC), analyzer (A), spatial light modulator (SLM), microscope objective (OBJ), 3D piezo-scanning stage (PZ), dichroic filter (DF), shortpass filter (SP), bandpass filter (BP) and cooled photomultiplier tube (PMT).

In order to achieve a raster-scanned SHG map, the SHG from the sample is collected pixel-by-pixel, i.e., as a function of its relative 3D position with respect to the focused beam. This is accomplished using a custom-designed LabVIEW program. All scans in the present work were acquired at a collection time of 50 ms and pixel resolution of 0.1 μm . An average power of 1 mW before the microscope objective was used for all these experiments. The average power of the laser beam was controlled using a half-wave plate and a polarizing beamsplitter that are positioned right after the laser.

In order to access different vector beams in our setup such as radially or azimuthally polarized beams, a commercial doughnut mode converter (ARCOptix S.A.) is used. It is well-known that a radially polarized beam can be formed by the linear superposition of orthogonally polarized HG modes [17,36]. To generate a HG_{10} beam, a polarizer was used to analyze the synthesized radially polarized beam. Shown in Fig. 2 are the experimental 2D intensity profiles of the radially polarized beam and the extracted HG_{10} beam taken with a beam camera.

Fig. 2. 2D intensity profiles of the experimentally synthesized (a) radially polarized beam and (b) HG_{10} beam. In (b), the transmission axis of the polarizer was set along the horizontal direction. The images were acquired using a beam profiling camera, which was placed before the microscope objective.

2.2. Phase-shaping scheme

Our phase shaping scheme, which uses a SLM in the excitation path, is illustrated in Fig. 3. As shown, the resulting HG_{10} beam was initially directed towards a SLM (Hamamatsu X10468- 07,

phase-only, reflective, pixel resolution of 792×600 , fill factor of 98%). Here, the SLM window was artificially divided into two subwindows, and the input HG_{10} beam was made to impinge symmetrically on these subwindows. This scheme allowed us to apply an additional and uniform phase delay into each lobe of the impinging HG_{10} beam. While maintaining an added phase delay of zero on one lobe of the HG_{10} beam, appropriate phase delays ranging from 0 to 2π were then applied on the other lobe. In this manner, the relative phase difference of the lobes can be precisely controlled. Note that the finite bit depth of the SLM limits the amount of phase levels between 0 and 2π . For this demonstration, we selected additional phase delays that correspond to 0, $2\pi/3$, $\pi/2$, $3\pi/2$ and 2π , respectively. Previously, we have used this phase shaping scheme to control all-optically the SHG efficiency from a single GaAs nanowire at the transversal focal plane [28] and to extract the global phase calibration curve of the SLM [37].

Fig. 3. Spatial phase- shaping scheme that was performed right before the excitation beam enters the microscope objective. The input polarization of the linearly polarized HG_{10} beam is aligned to the orientation of the SLM. In practice, the incident angle is less than 10° .

2.3. Sample

Our SHG far-field probe is based on an individual vertically-aligned zinc-blende GaAs nanowire [28]. These nanowires were grown using selective-area metallo-organic vapour phase epitaxy on GaAs (111)B substrates resulting in an array of nanowires. Previously, we discovered that the SHG from this particular type of nanowire is primarily driven by the longitudinal electric fields at the beam focus [28,30,31]. In this study, the typical length and diameter of the GaAs nanowires were about 2.6 μm and 55 nm. We carefully chose nanowires that are well separated in order to avoid possible coupling between neighboring structures. Whenever applicable, we always measured the SHG from the same nanowire in the array.

2.4. Calculation of focal fields

Under tight focusing conditions, the vectorial nature of the optical electric field needs to be considered. To calculate the 3D spatial distribution of vectorial electromagnetic fields at the focal region of lenses, the angular spectrum approach was used [38]. This formalism was implemented using Fourier Transform [39,40]. The following formulae were used to calculate the respective electric field components:

$$E_x(z) = FT[\exp(ik \cos \theta \times z) \times (E_{0x}(\sin^2 \varphi + \cos^2 \varphi \times \cos \theta) - E_{0y} \sin \varphi \cos \varphi (1 - \cos \theta))/\sqrt{\cos \theta}] \quad (1)$$

$$E_y(z) = FT[\exp(ik \cos \theta \times z) \times (E_{0y}(\sin^2 \varphi \cos \theta + \cos^2 \varphi) + E_{0x} \sin \varphi \cos \varphi (\cos \theta - 1))/\sqrt{\cos \theta}] \quad (2)$$

$$E_z(z) = FT[\exp(ik \cos \theta \times z) \times (E_{0x} \cos \varphi + E_{0y} \sin \varphi) \times \sin \theta / \sqrt{\cos(\theta)}] \quad (3)$$

Here, FT stands for the Fourier Transform operator, E_{0x} and E_{0y} correspond to the x and y input electric fields of E_0 (total input field) before focusing, φ is the azimuthal angle, and θ is related to the NA. The form for E_{0x} and E_{0y} can be found on page 61 of Ref. [36]. Phase masks in the form $\exp(i \times \text{delay} \times \text{mask}_{\text{window}}) \times E_{0x}$ were then applied to the HG₁₀ mode. The $\text{mask}_{\text{window}}$ is a 2D matrix of 1 or 0 values corresponding to where the delay is applied on the SLM. The focal field calculations were implemented using MATLAB and its 2D fast Fourier Transform function (*fft2*). In these simulations, the experimental conditions were reproduced. The pixel resolution of the calculated images is 27 nm in x , y , and z directions and only the intensities of the longitudinal electric field component are represented. For the spatially phase-shaped HG₁₀ beams, corresponding phase masks with uniform phase values were added on one of the lobes. Similar to the experimental demonstration, additional phase delays that correspond to 0, $2\pi/3$, $\pi/2$, $3\pi/2$ and 2π were used.

3. Results and Discussion

3.1. 3D longitudinal electric fields of tightly focused HG₁₀ beam

The second-harmonic response of our vertically-aligned GaAs nanowire is primarily driven by the longitudinal electric field component of the input electric field. By scanning an individual nanowire at the focal volume of interest, it is possible to obtain information about the 3D spatial distribution of longitudinal electric fields that drive the SHG of the nanowire. Therefore, we acquired the SHG signals point-by-point in three dimensions by considering two or three perpendicular planes (e.g., along xy , xz or yz directions) in relation to the 3D position of the nanowire.

The experimental 3D SHG maps of the nanowire illuminated by a focused HG₁₀ beam are shown in Fig. 4a. In the xy -plane, the longitudinal electric fields of the HG₁₀ beam exhibit a three-lobed intensity pattern. This consists of a middle lobe, which exhibits the strongest intensity, and two lobes that are situated symmetrically with respect to the middle lobe. Since the input HG₁₀ beam is linearly polarized along y , the lobes are oriented along this direction. These results are consistent with previous findings that utilized a SHG from a plasmonic scattering tip [19] or a semiconductor nanowire [28] for probing the 2D spatial distribution of longitudinal electric fields of a tightly focused HG₁₀ beam.

Our technique was also able to reveal the experimental spatial distribution of longitudinal electric fields of a HG₁₀ beam in the perpendicular yz or xz planes for the first time. In the yz -plane, the three-lobed distribution of the HG₁₀ beam can be seen as the scanning direction matches the orientation of the lobes. Correspondingly, the xz -plane only contains one lobe in agreement with the scanning direction. Both scans revealed an extension along the propagation direction, which is a consequential feature of 3D focusing.

Next, we calculated the longitudinal electric fields of a tightly focused HG₁₀ beam using vectorial theory (Fig. 4b). To simulate similar focusing conditions as in the experiment, we set the input wavelength to 1060 nm, NA to 0.8, environment to air and input polarization (before focusing) to y . As seen, the calculated 3D spatial distributions of the longitudinal electric fields of the HG₁₀ beam exhibit a three-lobed intensity distribution. Although we did not include the effect of nonlinear (SHG) signal generation from the nanowire as excited by a vector beam in our calculations, the general features of the focal fields (e.g., location of maximum signal intensities) still qualitatively resemble the experimental SHG maps. The experimental intensity distributions,

however, were found to be slightly more confined in three dimensions than that for the corresponding calculations due the confinement effects in coherent nonlinear optical signal generation [41].

Fig. 4. (a) Experimental 3D SHG maps taken using a single GaAs nanowire that is illuminated by a tightly focused y -polarized HG_{10} beam. The SHG maps were acquired in the xy , yz and xz planes. The maximum SHG signal intensity from the nanowire is about 45000 counts/50 ms under a 1 mW HG_{10} beam. This maximum SHG signal intensity is about 17 times higher than the background SHG signal from the substrate. For clarity, the SHG map of a single nanowire is marked. (b) Numerically calculated 3D spatial distributions of the longitudinal electric fields of a tightly focused HG_{10} beam. The simulation parameters were set so they resemble the actual experiment conditions.

3.2. 3D longitudinal electric fields of a tightly focused spatially phase-shaped HG_{10} beam

Next we performed the phase-shaping scheme above, and illuminated the nanowire using the spatially phase-shaped HG_{10} from the SLM. In this series of experiments, the relative phase delays of the two lobes were set to 0 , $2\pi/3$, $\pi/2$, $3\pi/2$ and 2π . This was done by applying those additional phase delays on one lobe of the HG_{10} beam while maintaining a fixed 0 phase delay on its other lobe. By scanning the nanowire at the focal volume, we expect to visualize the resulting longitudinal electric field distribution of the shaped HG_{10} beam in three dimensions.

Shown in Fig. 5a are SHG maps of the nanowire in the xy -plane when the nanowire is illuminated by the shaped beam. As seen, the SHG maps of the nanowires are strongly affected by the spatial distribution of the resulting longitudinal electric fields of the shaped beam. Without the additional phase delay, the SHG map exhibits a three-lobed intensity distribution similar to results in Fig. 4a. As the relative phase delay is increased from 0 to π , the recorded SHG maps displayed a change from a three-lobed to a two-lobed intensity distribution. This suggests a notable change in the spatial distribution of the longitudinal electric fields and hence coupling efficiency of light at the focus. At the relative phase delay of π , the SHG map from the nanowire resembles the longitudinal electric field distribution of a tightly focused linearly (y) polarized light [38]. In this case, the longitudinal electric field distribution corresponds to two lobes and situated off-axis or about 500 nm from the center. Note that at the center of a linearly polarized beam, there is no longitudinal electric field that could induce SHG from the nanowire. As the relative phase delay is increased from π to 2π , the three-lobed intensity distribution is eventually recovered. This is expected as the relative phase delay of 2π should make no difference to the beam. The results are consistent with our previous findings using 2D mapping at the transversal plane. Similarly, these experimental results were reproduced qualitatively in our calculations using vectorial focusing (Fig. 5b). We attribute mainly the small difference to the quality of the HG₁₀ beam before the SLM (Fig. 2).

Next, we used the same nanowire to probe the longitudinal electric fields of the phase-shaped beams in the yz -plane. As shown in Fig. 6a, the intensity distributions of the longitudinal electric fields of the phase-shaped HG₁₀ beams significantly change as the relative phase delay between the lobes is increased. These findings are consistent with the results in Fig. 5a, where there is a drastic change from a three-lobed to a two-lobed and back to a three-lobed intensity distribution as the relative phase delay is changed from 0 to π to 2π . Similarly, these experimental results are qualitatively reproduced in our calculations (Fig. 6b).

Our work provided direct evidence that the spatial distribution of longitudinal electric fields that arise from the strong focusing of a complex or arbitrarily phased-shaped beam can be tailored and mapped reliably in three dimensions. The technique goes beyond the capabilities of conventional techniques for directly mapping the longitudinal electric fields in three dimensions. For example, we foresee that the experimental mapping technique could be useful in decrypting the information that is encoded in 3D longitudinal electric fields [39,40] or in directly probing

the spatial distribution of an arbitrarily tailored longitudinal electric field distribution [42]. Such capabilities are expected to further advance the applicability of tightly focused vector beams and to promote new ways to manipulate light-matter interactions in general.

Our technique is based on the direct detection and mapping of SHG intensities from a single nonlinear scatterer (e.g., nanowire) that is excited by longitudinal electric fields. Therefore, the technique is still limited in detecting the actual orientation of the longitudinal electric field as exhibited by complex polarizations or even simple ones such as for the case of focused linearly polarized light. However, the SHG fields from the sample are intrinsically linked with the incident electric fields, i.e., the SHG and fundamental fields have deterministic phase relationships. In fact, this property has been exploited previously in interferometric SHG microscopy in order to detect the in-plane orientations of harmonophores [43,44]. With the help of a proper reference SHG field, detecting the relative orientation of the longitudinal electric fields at the focal volume could be achieved.

Fig. 5. (a) Experimental 3D SHG maps taken using a single GaAs nanowire that is illuminated by a tightly focused spatially phase-shaped y -polarized HG_{10} beam. For clarity, the SHG map of a single nanowire is marked. The SHG maps were acquired in the xy plane. The relative phase delay between the lobes are shown. (b) Numerically calculated 3D spatial distributions of the longitudinal electric fields of a

tightly focused spatially phase-shaped HG₁₀ beam. The simulation parameters were set so they resemble the actual experiment conditions.

Fig. 6. (a) Experimental 3D SHG maps taken using a single GaAs nanowire that is illuminated by a tightly focused spatially phase-shaped y -polarized HG₁₀ beam. The SHG maps were acquired in the yz plane. The relative phase delay between the lobes are shown. (b) Numerically calculated 3D spatial distributions of the longitudinal electric fields of a tightly focused spatially phase-shaped HG₁₀ beam. The simulation parameters were set so they resemble the actual experiment conditions.

4. Conclusions

To conclude, we demonstrated the tailoring of longitudinal electric fields in the focal volume of tightly focused spatially phase-shaped high-order laser beams, and successfully verified their

spatial distribution in three dimensions. We created a tailorable longitudinal electric field distribution by precisely controlling the relative phase delay between the two lobes of a HG₁₀ beam using a spatial light modulator. 3D point-scanning microscopy based on the SHG from a single nanowire was used to evaluate the 3D spatial distribution of the generated longitudinal electric fields. This approach could be useful in harnessing and probing longitudinal electric fields with arbitrary spatial intensity distributions in the 3D focal volume.

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References

- [1] J.E. Curtis, D.G. Grier, Structure of optical vortices, *Phys. Rev. Lett.* 90 (2003) 133901.
- [2] M. Padgett, R. Di Leonardo, Holographic optical tweezers and their relevance to lab on chip devices, *Lab Chip.* 11 (2011) 1196–1205.
- [3] G. Gauthier, I. Lenton, N. McKay Parry, M. Baker, M.J. Davis, H. Rubinsztein-Dunlop, T.W. Neely, Direct imaging of a digital-micromirror device for configurable microscopic optical potentials, *Optica.* 3 (2016) 1136–1143.
- [4] C. Sun, N. Fang, D.M. Wu, X. Zhang, Projection micro-stereolithography using digital micro-mirror dynamic mask, *Sensors Actuators A.* 121 (2005) 113–120.
- [5] G. Bautista, M.J. Romero, G. Tapang, V.R. Daria, Parallel two-photon photopolymerization of microgear patterns, *Opt. Commun.* 282 (2009) 3746–3750.
- [6] M.J. Booth, Adaptive optical microscopy: the ongoing quest for a perfect image, *Light Sci. Appl.* 3 (2014) e165.
- [7] B.R. Boruah, M.A.A. Neil, Laser scanning confocal microscope with programmable amplitude, phase, and polarization of the illumination beam, *Rev. Sci. Instrum.* 80 (2009) 013705.
- [8] C. Maurer, A. Jesacher, S. Bernet, M. Ritsch-Marte, What spatial light modulators can do for optical microscopy, *Laser Photonics Rev.* 5 (2011) 81–101.
- [9] Q.S. Hanley, P.J. Verveer, M.J. Gemkow, D. Arndt-Jovin, T.M. Jovin, An optical sectioning programmable array microscope implemented with a digital micromirror

- device, *J. Microsc.* 196 (1999) 317–331.
- [10] M. Liang, R.L. Stehr, A.W. Krause, Confocal pattern period in multiple-aperture confocal imaging systems with coherent illumination, *Opt. Lett.* 22 (1997) 751–753.
 - [11] C. Maurer, A. Jesacher, S. Fürhapter, S. Bernet, M. Ritsch-Marte, Tailoring of arbitrary optical vector beams, *New J. Phys.* 9 (2007) 78.
 - [12] O. Masihzadeh, P. Schlup, R.A. Bartels, Control and measurement of spatially inhomogeneous polarization distributions in third-harmonic generation microscopy, *Opt. Lett.* 34 (2009) 1090–1092.
 - [13] K.J. Mitchell, S. Turtaev, M.J. Padgett, T. Čížmár, D.B. Phillips, High-speed spatial control of the intensity, phase and polarisation of vector beams using a digital micro-mirror device, *Opt. Express.* 24 (2016) 29269–29282.
 - [14] C.J. Sheppard, S. Saghaei, Transverse-electric and transverse-magnetic beam modes beyond the paraxial approximation, *Opt. Lett.* 24 (1999) 1543–1545.
 - [15] R. Dorn, S. Quabis, G. Leuchs, Sharper Focus for a Radially Polarized Light Beam, *Phys. Rev. Lett.* 91 (2003) 233901. doi:10.1103/PhysRevLett.91.233901.
 - [16] K.S. Youngworth, T. Brown, Focusing of high numerical aperture cylindrical-vector beams, *Opt. Express.* 7 (2000) 77–87.
 - [17] Q. Zhan, Cylindrical vector beams: from mathematical concepts to applications, *Adv. Opt. Photonics.* 1 (2009) 1–57.
 - [18] G. Bautista, M. Kauranen, Vector-Field Nonlinear Microscopy of Nanostructures, *ACS Photonics.* 3 (2016) 1351–1370.
 - [19] A. Bouhelier, M. Beversluis, A. Hartschuh, L. Novotny, Near-Field Second-Harmonic Generation Induced by Local Field Enhancement, *Phys. Rev. Lett.* 90 (2003) 013903.
 - [20] A. Bouhelier, M.R. Beversluis, L. Novotny, Near-field scattering of longitudinal fields, *Appl. Phys. Lett.* 82 (2003) 4596–4598.
 - [21] N. Hayazawa, Y. Saito, S. Kawata, Detection and characterization of longitudinal field for tip-enhanced Raman spectroscopy, *Appl. Phys. Lett.* 85 (2004) 6239–6241.
 - [22] Y. Gilbert, R. Bachelot, P. Royer, A. Bouhelier, G.P. Wiederrecht, L. Novotny, Longitudinal anisotropy of the photoinduced molecular migration in azobenzene polymer films, *Opt. Lett.* 31 (2006) 613–615.
 - [23] T. Grosjean, D. Courjon, Photopolymers as vectorial sensors of the electric field, *Opt.*

- Express. 14 (2006) 2203–2210.
- [24] H. Ishitobi, I. Nakamura, T. Kobayashi, N. Hayazawa, Z. Sekkat, S. Kawata, Y. Inouye, Nanomovement of Azo Polymers Induced by Longitudinal Fields, *ACS Photonics*. 1 (2014) 190–197.
 - [25] C. Ecoffey, T. Grosjean, Far-field mapping of the longitudinal magnetic and electric optical fields, *Opt. Lett.* 38 (2013) 4974–4977.
 - [26] T. Bauer, S. Orlov, U. Peschel, P. Banzer, G. Leuchs, Nanointerferometric amplitude and phase reconstruction of tightly focused vector beams, *Nat. Photonics*. 8 (2013) 23–27.
 - [27] T. Bauer, P. Banzer, E. Karimi, S. Orlov, A. Rubano, L. Marrucci, E. Santamato, R.W. Boyd, G. Leuchs, Observation of optical polarization Möbius strips, *Science*. 347 (2015) 964–966.
 - [28] L. Turquet, J.-P. Kakko, X. Zang, L. Naskali, L. Karvonen, H. Jiang, T. Huhtio, E. Kauppinen, H. Lipsanen, M. Kauranen, G. Bautista, Tailorable second-harmonic generation from an individual nanowire using spatially phase-shaped beams, *Laser Photonics Rev.* 11 (2017) 1600175.
 - [29] G. Bautista, M.J. Huttunen, J. Mäkitalo, J.M. Kontio, J. Simonen, M. Kauranen, Second-harmonic generation imaging of metal nano-objects with cylindrical vector beams, *Nano Lett.* 12 (2012) 3207–3212.
 - [30] G. Bautista, J. Mäkitalo, Y. Chen, V. Dhaka, M. Grasso, L. Karvonen, H. Jiang, M.J. Huttunen, T. Huhtio, H. Lipsanen, M. Kauranen, Second-Harmonic Generation Imaging of Semiconductor Nanowires with Focused Vector Beams, *Nano Lett.* 15 (2015) 1564–1569.
 - [31] G. Bautista, J.-P. Kakko, V. Dhaka, X. Zang, L. Karvonen, H. Jiang, E. Kauppinen, H. Lipsanen, M. Kauranen, Nonlinear microscopy using cylindrical vector beams: Applications to three-dimensional imaging of nanostructures, *Opt. Express*. 25 (2017) 12463–12468.
 - [32] G. Bautista, C. Dreser, X. Zang, D.P. Kern, M. Kauranen, M. Fleischer, Collective Effects in Second-Harmonic Generation from Plasmonic Oligomers, *Nano Lett.* 18 (2018) 2571–2580.
 - [33] L. Turquet, X. Zang, J.-P. Kakko, H. Lipsanen, G. Bautista, M. Kauranen, Demonstration of longitudinally polarized optical needles, *Opt. Express*. 26 (2018) 27572–27584.

- [34] R. Camacho-Morales, G. Bautista, X. Zang, L. Xu, L. Turquet, A. Miroshnichenko, H.H. Tan, A. Lamprianidis, M. Rahmani, C. Jagadish, D.N. Neshev, M. Kauranen, Resonant harmonic generation in AlGaAs nanoantennas probed by cylindrical vector beams, *Nanoscale*. 11 (2019) 1745–1753.
- [35] C. Dreser, D.A. Gollmer, G. Bautista, X. Zang, D.P. Kern, M. Kauranen, M. Fleischer, Plasmonic mode conversion in individual tilted 3D nanostructures, *Nanoscale*. 11 (2019) 5429–5440.
- [36] L. Novotny, B. Hecht, *Principles of Nano-Optics*, Cambridge University Press, New York, 2006.
- [37] L. Turquet, M. Kauranen, G. Bautista, Phase Calibration of Liquid-Crystal-Based Spatial Light Modulators Using the Spatial Structure of Focused Optical Fields, *Phys. Rev. Appl.* 11 (2019) 044050.
- [38] B. Richards, E. Wolf, Electromagnetic diffraction in optical systems. II. Structure of the image field in an aplanatic system, *Proc. R. Soc. London Ser. A*. 253 (1959) 358–379.
- [39] A. Carnicer, I. Juvells, B. Javidi, R. Martínez-Herrero, Optical encryption in the longitudinal domain of focused fields, *Opt. Express*. 24 (2016) 6793–6801.
- [40] A. Carnicer, I. Juvells, B. Javidi, R. Martínez-Herrero, Optical encryption in the axial domain using beams with arbitrary polarization, *Opt. Lasers Eng.* 89 (2016) 145–149.
- [41] W.R. Zipfel, R.M. Williams, W.W. Webb, Nonlinear magic: multiphoton microscopy in the biosciences., *Nat. Biotechnol.* 21 (2003) 1369–1377.
- [42] F. Maucher, S. Skupin, S.A. Gardiner, I.G. Hughes, An intuitive approach to structuring the three electric field components of light, *New J. Phys.* 21 (2019) 13032.
- [43] S. Yazdanfar, L. Laiho, P. So, Interferometric second harmonic generation microscopy, *Opt. Express*. 12 (2004) 2739–2745.
- [44] S. Bancelin, C. Couture, K. Légaré, M. Pinsard, M. Rivard, C. Brown, F. Légaré, Fast interferometric second harmonic generation microscopy, *Biomed. Opt. Express*. 7 (2016) 399–408.

Declaration of Interest Statement*Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: