Optical vortex phase determination for nanoscale imaging

B Sokolenko1,2*, N Shostka1, O Karakchieva1, D Poletaev2, V Voytitsky3, S Halilov2, A Prisyazhniuk2, A Ilyasova2, E Kolosenko2

1Department of Science and Research, V.I. Vernadsky Crimean Federal University. Simferopol, 295007, Crimea
2Institute of Physics and Technology, V.I. Vernadsky Crimean Federal University. Simferopol, 295007, Crimea
3Taurida Academy, V.I. Vernadsky Crimean Federal University. Simferopol, 295007, Crimea

E-mail: simplex@crimea.edu

Abstract. In this research we develop a principle of optical vortex phase analysis and its application to surface imaging with high accuracy measurements in nanoscale range. Two-coordinate scanning of the sample allow to retrieve an information about shape and roughness for optically transparent and reflecting surfaces exceeding optical diffraction limit. The interference between singular beam and reference wave, in general, carrying optical vortex with single or doubled topological charge allow to extract the data about phase delay caused by surface features or refraction. This method is also applicable for non-destructive testing of biological structures and live cells in real-time regime. Automatic processing of vortex interferograms allow to achieve a vertical and longitudinal resolution down to 1.75 nm and 7 nm respectively for visible light sources.

1. Introduction
Precise determination of surface roughness and relief is essential task for the manufacturing of optical and mechanical components with high degree of quality and smoothness in engineering, metrology research and materials science applications [1]. For this purposes a great number of instruments and measuring principles were developed last two decades. In general, they are divided into contact and non-contact [2] methods of interaction with the test sample. The first principle uses stylus probe detector and based only on mechanical interaction with an object. This method is inapplicable to the wide range of practical tasks because the scratched surface may be damaged or received parameters are not adequate. Especially it touches such cases as biological systems imaging, polymer structures analysis or metrology of thin film layers.

In contrast, optical methods of profilometry and surface analysis has a lot of advantages, among them: non-contact and non-destructive interaction with test sample [3], relatively high resolution [4], accuracy and flexible control [5-7]. The principle of optical profilometry based on interferometric measurements of optical field, consisting of amplitude and phase information received from the surface being studied [8, 9]. Phase images may be considered as two-dimensional phase distribution or as optical path difference of interfering beams. The relation between geometrical heights \( h(x, y) \) of surface profile of optically homogeneous reflecting objects to the phase \( \phi(x, y) \) of reflected wave may be expressed by simple equation [1]:

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
where $\lambda$ is the wavelength of interfering light beams.

For imaging of optically inhomogeneous transparent threads, we can assume the dependence of optical path difference is proportional to local projection of refractivity index $n(x, y, z)$ on the beam direction:

$$h(x, y) = \frac{\lambda\varphi(x, y)}{4\pi}.$$  \hspace{1cm} (1)

In this technique, the main task is in choice of phase recovering procedure to define phase difference between interfering wave fronts by the values of registered intensity. Temporal modulation, or phase shifting interferometry [10], records sequential interferograms by changing the phase of a reference beam with respect to a sample beam. For this purposes it uses no less than a three interferograms for each point of imaging object [8, 9]. Numerous papers considered methods with using of multi interferograms sequence to extract the phase and surface relief [11]. A profilometer of this type, provides relatively high measurement accuracy of the order of 1 nm, is known, for example, in [12].

The method of multi-step interferograms provides high accuracy of measurements for stationary interference fields, quick data acquisition and large amount of image pixels. The main disadvantage of multi-step methods associated with determination of local phase values in terms of intensity $I(x, y)$, measured during different time intervals. Therefore, fluctuations of light source intensity and frequency as well as vibrations and mechanical instability of interferometric setup impose accuracy limits, especially in dynamic processes and biological applications [13].

The main issues of phase microscopy and imaging are caused by interpretation of collected information from the sample. Phase retrieval algorithm is a practically important, thereby, the modern optical branches, especially singular optics, become an effective instrument in salvation the problem of creation multifunctional microscopes and profilers which use numerical methods in image and data analysis. In numerous manuscripts which describe the methods of surface reconstruction from primary interference distributions, authors used the Fourier [14] and Hilbert transform [13, 15] for phase extraction. Recently, spatial phase-shifting algorithm and derivate method have been developed to enhance the speed of field retrieval without using computationally intensive calculations [16, 17].

Another branch of methods is non-interferometric acquisition can also be used. Non-interferometric analyzers recorded a series of intensity images measured at different axial positions, from which a quantitative phase image is reconstructed with interactive phase retrieval process, which is based on the optical transfer function of intensity equation [18, 19].

Currently the most popular methods include the measurement of light modulation envelope and phase estimation or use its combination. The phase of the electromagnetic wave is determined by using interferometer with considering of refractive index of the material in case of transparent object under investigation. Phase estimation method is the most suitable data processing method in 3D optical microscopy and profilometers with using of both smooth plane waves and beams with phase singularities carrying helical wavefront.

A practical application of singular beams in the vortex scanning optical imaging allows to study, for example, surface geometry and optical density of the sample by analysis of singular phase transformation [20] and depends of the features of incident beam and aperture of optical systems [21].

In manuscripts [22-24] authors demonstrated a new solution for visualization and characterization of nanometer structures called Optical Vortex Scanning Microscope where the sample is scanned by moving vortex. This study demonstrates the response of the optical vortex imbedded in focused Gaussian beam to the shift from the critical plane inside the object arm of interferometer. Scanning procedure enables to cover all area of surface and plot a vortex trajectory, which has a characteristic way of movement and depends on thickness of the probe. Further research of Optical Vortex Scanning Microscope conducted with developing of analytical models and phase retrieval algorithms [25, 26].
In the recent research [27] authors describe both theoretical and experimental results of imaging system using movable optical vortex, where the image of the probe was combined with the structured singular beam. Nevertheless, the phase distribution after the object may be recovered with quite good accuracy, thus using of optical vortices in imaging and microscopy opens new perspectives for development of relief retrieval algorithms and new optical instruments design. By analyzing of captured interference patterns in form of vortex spiral or retrievable light structures, we can extract an information about phase shift between superposed beams and, as result, about surface roughness state and relief or sample thickness [28] and the task for optimization of such procedures on practice is the purpose of given research.

2. Phase retrieval from interference pattern of coherent waves

Interference of two smooth optical beams, converging at some angle, is often used in modern optical sensors of physical values. Interference pattern of reference and subject wave superposition in Mach-Zehnder or in Michelson interferometer is quite sensitive element and applied to sensors construction with using of fibers, crystals and acousto-optic devices. In certain methods, the physical value is determined by intensity changing within the limited screen area. The disadvantage of this technique is in nonlinear dependence of intensity on the phase difference between beams and allow determining phase difference with low accuracy up to \( \pi \) or using approximately linear area of dependence between intensity and phases in narrow range of phase differences (up to \( \pm \pi/2 \)). It causes on low accuracy of measured value.

Development of a new branch of optics called singular optics [29] allow to create various devices and systems as optical vortex tweezers, beam reducers and sensors, which use singular beams [30-33]. Therefore, it becomes actual to consider the possibility of using singular beams in detectors of physical values, especially in surface roughness measurement and thickness sensing and microscopy [34, 35].

During the interference of singular beam carrying axial optical vortex with the reference Gaussian beam and in case of coaxial spreading with different radii of wavefront curvature, we can observe spiral interference pattern, which rotational angle is determined by phase difference between the beams. This dependence has linear nature, thus it is possible to measure physical value by rotation of interference spiral pattern. At the same time, accuracy of phase determination increases substantially.

In fact, we may use two types of measuring schemes: when singular beam is a probe beam and when vortex imbedded into a reference beam. In both cases, interference patterns are same, but direction of spiral rotation will be inverted.

Therefore, we can conclude that both sensor schemes may be used to determine physical value by the phase interference spiral. The design and alignment of the second sensor scheme is simpler than the first one, but has limitation for our purposes of surface imaging, which will be discussed further.

Let us consider intensity distribution of interference pattern of smooth Gaussian and singular beams. It is defined by the following equation:

\[
I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\Phi_1 - \Phi_2),
\]

where \( I_1, I_2 \) are the intensities of Gaussian beam and singular beam respectively. \( \Phi_1, \Phi_2 \) are phases. During co-axial propagation, if beam radii of curvature are much different, an interference pattern is formed on the screen in form of spiral. The position of lightest curve is determined by the value of phase difference:

\[
\Phi_1 - \Phi_2 = 2m\pi, \quad (m = 0,1,2K)
\]

(for dark curve the phase difference is \( \Phi_1 - \Phi_2 = (2m + 1)\pi \)). The phase of a Gaussian beam is defined as:
\[ \Phi_1 = k z + \arctan \left( \frac{z}{z_{0g}} \right) + \frac{kr^2}{R_s(z)} + \varphi_{og}, \]  
(5)

where \( R_s(z) = z \left( 1 + \frac{z_{0g}^2}{z^2} \right) \) is the radius of wavefront curvature of Gaussian beam, \( z_{0g} = \frac{k \omega_{0g}^2}{2} \) is the Rayleigh length, \( \omega_{0g} \) is the Gaussian beam waist, \( \varphi_{og} \) denotes initial beam phase. Optical vortex phase is determined by equation:

\[ \Phi_2 = k z + (l + 1) \arctan \left( \frac{z}{z_{0v}} \right) + \frac{kr^2}{R_s(z)} + \varphi_{ov} - l \phi, \]  
(6)

where \( R_s(z) = z \left( 1 + \frac{z_{0v}^2}{z^2} \right) \) is the radius of wavefront curvature of vortex beam, \( z_{0v} = \frac{k \omega_{0v}^2}{2} \) is the Rayleigh length for the singular beam, \( \omega_v, \varphi_{ov} \) are vortex beam waist and initial beam phase respectively, \( l \) is the number of intertwined helices of wavefront or azimuthal index, \( r \) denote polar screen coordinates and \( z \) is the distance to the screen. Phase difference from equations (3) and (4) can be find as follows:

\[ \Phi_1 - \Phi_2 = \arctan \left( \frac{z}{z_{0g}} \right) -(l + 1) \arctan \left( \frac{z}{z_{0v}} \right) + kr^2 \left( \frac{1}{R_s(z)} - \frac{1}{R_s(z)} \right) + \varphi_{v} + l \phi. \]  
(7)

Because on the screen plane \( z = const \), phase difference can be expressed at the form:

\[ \Delta \Phi = \Phi_1 - \Phi_2 = -ar^2 + b' + l \phi, \]  
(8)

where \( a = k \left( \frac{1}{R_s(z)} - \frac{1}{R_s(z)} \right), \quad b' = \arctan \left( \frac{z}{z_{0g}} \right) -(l + 1) \arctan \left( \frac{z}{z_{0v}} \right) + \varphi_{v}. \)

The curve of equal phase on the spiral can be expressed as given in the following equation: 
\( l \phi = ar^2 + b_0, \) \( (b_0 = \Phi_2 - \Phi_1 + b'). \) The simplest case for spiral analysis rises when topological charge of optical vortex \( l = 1. \) Thus, spiral equation can be expressed as follows:

\[ \phi = ar^2 + b_0, \]  
(9)

Let us consider the influence of geometrical path difference to the phase difference between singular beam and reference arm. Note that vortex phase in probe beam is changing linearly during the variation of path. Total phase shift which is observable due to angular rotation of interference spiral can be calculated from simple equation:

\[ \Delta \Phi = \frac{4\pi}{\lambda} n(d_1 - d_2) = \frac{4\pi}{\lambda} n h, \]  
(10)

where \( d_1 - d_2 = h \) is a difference between currently observable and neighboring heights of sample surface, which is reflecting the probe beam and \( n \), in general case, is the refractivity index of the medium [1, 36]. Therefore, the recorded spiral can be considered as rotational curve (line of constant phase) turned on the angle \( \Delta \Phi \) and equation of phase spiral can be expressed as given below:

\[ \phi = ar^2 + b_0 + \Delta \Phi, \]  
(11)

or \( \phi = ar^2 + b. \)
There are several ways to determine the phase difference change of interfering beams [14, 22-25]. We restrict ourselves on finding of intensity minima along spiral phase curve in interference pattern of two waves. In this method, intensity is summed along curvature of equal phase $\phi = \text{const}$ (see Eq. 8) as show in Figure 1(c, d). Advantage of this technique is to reduce the noise threshold but still it has strict requirement to accuracy of finding spiral central point. The center of interference spiral according to the equations (6) and (7) coincides with the center of optical vortex accompanied with intensity minima on the beam axis. It can be easily identified by scanning of vortex beam along $x$ and $y$ axis and determination of average intensity minima. As a result, we can find coordinates of spiral center $(x_c, y_c)$ and error of their calculation $\Delta x_c$ and $\Delta y_c$ and, finally, roughness state, relief or sample thickness.

### 3. Singular beams in phase profilometry measurements

In this research we consider analytically an interference of singular beams with the wavelength $\lambda$ carrying optical vortices of topological charge $l$. One of the important features of the singular beams is the screw dislocation of wavefront expressed from (8) as beam phase spatial dependence in the form [37]:

$$\Phi(\varphi, z) = kz + l\varphi,$$

where $z$ is the propagation direction, $\varphi$ is the azimuthal angle at the beam cross section and $k$ denotes wavenumber in a free space. In simplified form, optical vortex with topological charge $l$ may be expressed in terms of Laguerre-Gaussian mode $LG_l^0$ with zero radial index.

Let us consider first the propagation of the paraxial $LG_l^0$ beam along the $z$-axis. The transverse profile $E_x$ of the beam have a wavenumber $k = nk_0$, where $k_0 = \frac{2\pi}{\lambda}$ is a wavenumber in a free space and $n = \sqrt{\varepsilon}$ – refractivity index of medium (for convenience it can be assumed $n = 1$). In the paraxial approximation, we can treat the linearly polarised electromagnetic field component as $E = \tilde{E}_x(r, \varphi, z)\exp(-ikz)$ where $\tilde{E}_x(r, \varphi, z)$ is the slowly varying complex amplitude which satisfies the paraxial wave equation [38]:

$$\nabla_z^2 E_x(r, \varphi, z) + 2ik \frac{\partial E_x(r, \varphi, z)}{\partial z} = 0,$$

where transverse Laplacian $\nabla_z^2 = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \varphi^2}$, $(r, \varphi)$ – is the cylindrical coordinates and radius is $r = \sqrt{x^2 + y^2}$. A particular solution to the paraxial wave equation (13) for the Laguerre-Gaussian vortex beam can be written as follows [39, 40]:

$$E_x = \frac{\alpha_0}{w} \left( r \right)^M \left( \frac{r^2}{w^2} \right) \exp \left( -\frac{r^2}{w^2} \right) \exp \left( -\frac{ikr^2}{2z(1 + z_R^2/z^2)} \right) \times$$

$$\times \exp(-il\varphi) \exp \left( i(2m + l - 1) \arctan \left( \frac{z}{z_R} \right) \right) \exp(-ikz),$$

where $\alpha_0$ is the beam waist at the plane in $z = 0$, $z_R = \frac{k\alpha_0^2}{2}$ denotes Rayleigh length of the beam and current beam radius is expressed as $w = \alpha_0 \sqrt{1 + (z/z_R)^2}$. Topological charge of vortex beam is...
introduced as $l = \pm 1, \pm 2, \ldots$. The vortex position, by definition, is described by the equation $\text{Re} \hat{E}(x, y, z) = \text{Im} \hat{E}(x, y, z) = 0$. In equation (12) we suppose azimuthal angle is $\varphi = \arg(x + iy)$.

Numerical calculation of intensity distribution for Gaussian envelope (corresponding to $l = 0$ in equation (14) and intensity of whole vortex beam with $l = 1$ and typical axial minima are shown on figure 1 (a, b). The interference and phase patterns in figure 1 (c, d) depicts vortex phase as a helix.

Figure 1. Theoretically calculated intensity distribution $(\text{Re}E(r, \varphi))^2$ of Gaussian beam (a) when $m = 0$ and vortex beam (b) with topological charge $l = +1$ and its interference (c) and phase $\text{Im}E(r, \varphi)$ (d) profile. Other beam parameters are next: $\omega_s = 180\, \text{mcm}$, $n = 1.00$, $z = 1\, \text{m}$, $\lambda = 632.8\, \text{nm}$. Pictures are plotted in Cartesian coordinates.

Singular beam phase is extremely sensitive to changes of optical path between superposed waves. When the optical path of two beams travelling, for example, in arms of interferometer, are equal, it means that waves have the same waist radius and curvature of wavefront. But small variations of optical or geometrical path, which are the same in our case, provokes well-known relative phase shift whether is observable via interference spiral behaviour. Let us consider a case when singular beam propagates through the free space between mirrors of non-equable Mach-Zehnder interferometer and interfere with Gaussian beam. In the object arm we may slightly change the optical path $\Delta = 0 \div \lambda$, where $\lambda$ is the wavelength. The resultant phase for different $\Delta$ is depicted in figure 2.

Figure 2. Theoretical analysis of singular beam phase $\text{Im}E(r, \varphi, z + \Delta)$ of $LG^1_0$ beam with topological charge $l = +1$ for different optical path $z + \Delta$. Other beam parameters are next: $\omega_s = 180\, \text{mcm}$, $n = 1.00$, $z = 1\, \text{m}$, $\lambda = 632.8\, \text{nm}$.

Thus, optical path difference manifests itself in phase spiral rotation. The handedness of turn depends of vortex charge sign, in case $l = +1$ it acts on clockwise twist of helical wavefront when $\Delta$ increases. Decreasing of path difference on value $\Delta$ causes anticlockwise rotation of vortex phase relatively to the reference beam.
This method [28] makes possible to match phase image or interference pattern with real parameters as local thickness of thin nanometer film or geometrical path difference caused by surface relief. Observable on practice interference fringes or spiral need further image processing [23-25] for phase retrieval, where wide range of algorithms allow to extract $\varphi$ of the beam with high accuracy [14].

The simplest way for rapid and computationally non intensive analysis is using of direct data from image sensors and cameras with minimal adjustment and transformations. For this purpose we propose to employ superposition of high sensitive probe beam carrying optical vortex with the reference one, but also containing singularity with opposite sign [38]. Phase perturbations caused by geometrical path difference between the beams will noticeably reflect on intensity of resulting image. To understand this, let us consider interference of singular beams described by equation (14) with opposite topological charges $l = \pm 1$ and $l = \pm 2$. The numerical simulation of this process is shown in figure 3.

![Figure 3](image_url)

**Figure 3.** Numerical model of superposition of two optical vortices with opposite signs. Intensity distribution $(\text{Re}E(r,\varphi))^2$ of singular beam (first column) when $l = \pm 1$ in first row and $l = \pm 2$ in the second row. Phase portraits $\text{Im}E(r,\varphi)$ of vortices with opposite signs are shown in second and third rows respectively. An interference of both vortex beams is depicted in fourth column for each topological charge. Other beam parameters are the next: $\omega = 180$ mcm, $n = 1.00$, $z = 1m$, $\lambda = 632.8$ nm. Pictures are plotted in Cartesian coordinates.

Applying the same methodology and reasoning as in case of vortex phase rotation in dependence of different geometrical path difference, we can show dynamics of superposed singular beams with opposite topological charges when one of them experienced a phase shift. This process in sequential form is shown in figure 4.
Figure 4. Evolution of superposed vortex beams intensities with topological charge $l = \pm 1$ (first row) and $l = \pm 2$ (first row) for different optical path $z + \Delta$. Other beam parameters are next: $\omega_0 = 180\, mcm$, $n = 1.00$, $z = 1m$, $\lambda = 632.8\, nm$.

Making one full turn, intensity pattern coincides with itself at geometrical path difference equal to wavelength $\lambda$. Note, that whole picture coincides only ones for topological charges $l = \pm 1$ and twice for $l = \pm 2$. Thus, the symmetry of the pattern caused by topological charges of interfering singular beams. Further increasing of topological charge induces multiplication of high intensity spots around of image centre and are not essential for our application and we restrict ourselves only on superposition of single charged optical vortices for two reasons: at first, interference pattern of single charged vortices has well defined intensity minimum and only one symmetrical axis thus it may be automatically defined with high accuracy. Secondly, the beam spot in this case has much less radius and allow to make beam focusing more easy due to structural stability of optical vortices with $l = \pm 1$. Therefore this method can be used as addition to direct vortex phase analysis as quick draft regime of profile measurement. On estimated evaluation, phase rotation measurement allow to achieve vertical resolution down to $1.75\, nm$ for He-Ne laser source with $\lambda = 632.8\, nm$ and less than $1\, nm$ for blue light laser. Rough measurements with resolution $\approx 4\, nm$ can be performed by processing of interference pattern formed by two coherent optical vortices with opposite signs.

Practical optical vortices appear as rings of light with dark area on the beam axis. A well-known diffraction limit for Gaussian beams was established as relation of wavelength $\lambda$ to the aperture of optical system by simple equation for spot diameter: $d = 1.22 \frac{\lambda}{fD}$, where $f$ is the focal distance of lens and $D$ is its aperture diameter. To evaluate radius of the beam carrying optical vortex with topological charge $l$ we use the next relation [41]:

$$R_0 = a \frac{\lambda f}{\pi D} \left(1 + \frac{l}{l_0}\right),$$  \hspace{1cm} (15)

Where $a = 2.585$, $l_0 = 9.80$. As result, for practical using we may restrict only central part of the beam carrying single charged vortex which diameter is smaller than diffraction limit. We have measured analytically and experimentally confirmed the relation between beam diameter and the diameter of dark area which is in 2.79 times smaller as shown in figure 5.
Figure 5. Schematically depicted tightly focused vortex beam intensity (a) with topological charge \( l = +1 \) and its transverse spreading in the free space (b). Other beam parameters are next: \( \omega_0 = 180 \, \text{mcm}, \, n = 1.00, \, z = 1\, \text{m}, \, \lambda = 632.8 \, \text{nm} \).

The sharp interference curves with a characteristic "spiral", corresponding to optical vortices can be imaged by the camera and assayed. Total phase shift which is observable due to angular rotation of interference spiral can be calculated from simple equation (10) as a geometrical path difference between observable and neighboring levels of reflecting sample surface.Focused beam spot of 1 mcm on the sample surface perform the longitudinal resolution down to 7 nm.

4. Conclusion
We have analytically considered evaluation of optical phase features and sensitivity to geometrical path changes and have shown that the distinguishable spiral phase rotation occurs at \( \lambda/300 \), where \( \lambda \) – is a wavelength. Proposed technique may be applied to optically transparent and reflecting surfaces exceed optical diffraction limit. Moreover, this method applicable for non-destructive testing of live cells and biological tissues in real-time regime. Automatic processing of vortex spiral interferograms allow to achieve a vertical resolution down to 1.75 nm. The experimental evaluation of measurement accuracy and finding of optimal phase retrieval procedure is a task of future investigations.

Acknowledgments
This work was partially supported by the V.I. Vernadsky Crimean Federal University Development Program for 2015 – 2024 via grant support for young researches.

5. References
[1] Paul J Caber 1993 Applied Optics 32
[2] Schmit J, Reed J, Novak E, Gimzewski J K 2008 Journal of Optics A: Pure and Applied Optics 10
[3] Zhenrong Z, Jing Z, Peifu G 2010 Optica Applicata 40
[4] Lukin E S, Anufrieva E V, Popova N A, Morozov B A 2009 Functional Ceramics 1
[5] Best G, Amberger R, Baddeley D, Dithmar S, Heintzmann R, Cremer C 2011 Micron 42
[6] Hsieh H, Chen Y, Jian Z, Wu W, Su1 D 2009 J.of Pys. Measurement Science and Technology 20
[7] Kitagawa K, Electron J 2012 Imaging 21
[8] Tian C, Liu S 2016 Optics Express 24
[9] Xing S, Guo H 2017 Applied Optics 56
[10] Pham Q D, Hayasaki Y 2015 Applied Optics 54
[11] Tychinsky V P 1989 Opt. Commun 74
[12] Sasaki O, Okazaki H 1986 Applied Optics 25
[13] Lee K, Kim K, Jung J, Heo J, Cho S, Lee S, Chang G, Jo Y, Park H, Park Y 2013 Sensors (Basel)
[14] Takeda T M, Ina H, Kobayashi S 1982 J. Opt. Soc. Am. 72
[15] Ikeda T, Popescu G, Dasari R R, Feld M S 2005 Opt. Lett. 30
[16] Debnath S K, Park Y 2011 Opt. Lett. 36
[17] Bhaduri B, Popescu G 2012 Opt. Lett. 37
[18] Waller L, Kou S S, Sheppard C J, Barbastathis G 2010 Opt. Express 18
[19] Kou S S, Waller L, Barbastathis G, Marquette P, Depeursinge C, Sheppard C J 2011 Opt. Lett. 36
[20] Wang W, Yokozeki T, Ishijima R, Takeda M, Hanson S G, 2006 Opt. Express 14
[21] Popiolek-Masajada A, Sokolenko B, Augustyniak I, Masajada J, Khoroshun A and Bacia M 2014 Optics and Lasers in Engineering 55
[22] Masajada J, Leniec M, Jankowska E, Thienpont H, Ottovaere H, Gomez V 2008 Opt. Express 16
[23] Masajada J, Leniec M, Augustyniak I 2011 J. Opt. 13
[24] Augustyniak I, Popiolek-Masajada A, Masajada J, Drobczynski S 2012 Appl. Opt. 51
[25] Plociniczak L, Popiołek-Masajada A, Szatkowski M, Wojnowski D 2016 Opt. Las. Technol. 81
[26] Plociniczak L, Popiołek-Masajada A, Masajada J, Szatkowski M, 2016 Appl. Opt. 55
[27] Popiołek-Masajada A, Masajada J, Kurzynowski P, Photonics 4
[28] Sokolenko B, Poletaev D 2017 Proc. SPIE 10350, Nanoimaging and Nanospectroscopy V
[29] Curtis J E, Grier D G 2003 Phys. Rev. Lett. 90
[30] Curtis J E, Koss B A, Grier D G 2002 Opt. Comm. 207
[31] Friese M E J, Rubinsztein-Dunlop H, Gold J, Hagberg P, Hanstorp D 2001 Appl. Phys. Lett. 78
[32] Paterson L, MacDonald M P, Arlt J, Sibbett W, Bryant P E, Dholakia K 2001 Science 292
[33] Fadeyeva T A, Rubass A F, Sokolenko B V, Volyar A V 2009 J. Opt. A: Pure Appl. Opt. 11
[34] Bowe B W, Toal V 1998 Optical Engineering Vol. 37, Issue 6
[35] Szatkowski M, Popiołek-Masajada A, Masajada J 2014 Proc. SPIE 9194
[36] Wyant J C, Creath K 1992 International Journal of Machine Tools and Manufacture Volume 32
[37] Bekshaev A, Karamoch A 2009 arXiv preprint arXiv:0906.2619
[38] Vickers J, Burch M, Vyas R, Singh S 2008 J. of the Opt. Soc. of America A. 25, Issue 3
[39] Allen L, Beijersbergen M W, Spreeuw R J C, Woerdman J P 1992 Phys. Rev. A 45
[40] Buchhave P, Tidemand-Lichtenberg P 2008 Opt. Exp. 16, Issue 22
[41] Curtis J E, Grier D G 2003 Optics Letters 28, Issue 11