Optics Communications 285 (2012) 4312–4316

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Speckle decorrelation influence on measurements quality in vortex metrology

Luciano Angel-Toro[a,*], Daniel Sierra-Sosa[a,b], Myrian Tebaldi[b], Néstor Bolognini[b,c]

[a] *Grupo de Óptica Aplicada, Departamento de Ciencias Básicas, Universidad EAFIT, Medellín, Colombia*
[b] *Centro de Investigaciones Ópticas, CIOp (CONICET, CIC) and OPTIMO (Dpto. Ciencias Básicas, Facultad Ingeniería, UNLP), P.O. Box 3, (1987), M.B. Gonnet, Argentina*
[c] *Facultad de Ciencias Exactas, UNLP, La Plata, Argentina*

ARTICLE INFO

Article history:
Received 16 December 2011
Accepted 3 July 2012
Available online 20 July 2012

Keywords:
Speckle
Vortex metrology
Decorrelation
Reisz transform
Optical processing
Fourier optics

ABSTRACT

We study speckle decorrelation effects in connection with conventional vortex metrology techniques. Our proposal is based on processing speckled images recorded by using two different experimental set-ups. In both schemes two laterally displaced patterns are generated: one scheme allows for obtaining undecorrelated speckle distributions and the other for decorrelated ones. Vortex networks associated with speckle patterns are analyzed by employing the usual tools developed for vortex metrology. For each recorded image, a 2D pseudo-phase map is generated on the basis of the Reisz transform. Then the vortices are located, and parameterized in terms of their topological charge, eccentricity, vorticity and angles between the zero crossing lines from the real and the imaginary parts of the analytical signal. After tracking the homologous vortices onto the maps, the histograms corresponding to the coordinate displacements are analyzed. We show that histograms interpretation is prone to failure due to its high sensitivity to decorrelation. Experimental evidences are presented to support the restrictions imposed by decorrelation of actual speckles due to uniform in-plane displacements.

1. Introduction

In speckle photography, a quantitative analysis of relative displacements between two [1,2] or several [3–5] speckled intensity distributions can be achieved by comparing images corresponding to the initial and final states of a diffuser, i.e. the states before and after a rigid movement or a local deformation of a diffusing surface. In this technique, the recorded intensity distributions are superimposed, and by using the Fourier optics methods, suitable systems of fringes can be obtained, whose periods and orientations allow for determining the magnitude and the direction of relative displacement onto the diffuser plane. When analyzing uniform in-plane displacements, the relevant information can be accessed by processing Young's fringes obtained by Fourier transforming the multiplexed images that where superimposed in the specklegram. However, for the analysis of local displacement fields, a spatial filtering procedure should be implemented onto the Fourier transform plane to produce isothetic (equal displacement) fringes. In both cases, the analysis procedure can be performed by analog or digital processing techniques.

Vortex metrology also allows for determining the relative displacements between two speckle or speckle-like distributions onto a surface. However, the relative displacements occurring between the exposures are analyzed by implementing different digital operations [6–9]. In particular, two random intensity distributions, corresponding to two different states of a plane surface under study, are recorded. Then, these distributions are individually processed to obtain, from each, a related analytical complex signal, via a digital version of an integral operator, like the Hilbert, Reisz or Laguerre–Gauss linear transforms. This allows for generating the real and imaginary components of that signal, and also for representing an associated 2D pseudo-phase map, in which the singularities (vortices) can be localized and parameterized by using different computational tools. Specifically, the precise sub-pixel positions identification of vortices and the characterization of their respective topological charge and core structures are achieved by processing the information from vicinities (neighbor pixels) of the respective singularities. Then, the relative displacements between images are determined on the basis of the analysis of histograms, depicting the measured distances between the different pairs of homologous vortices along two perpendicular coordinate axes. The coupled homologous vortices are those that have the same topological charge and best fit the respective values for the core structures, which are defined by their values of eccentricity, vorticity and angles between the zero crossing lines from the real and the imaginary parts of the analytical signal.

---

[*] Corresponding author.
E-mail address: langel@eafit.edu.co (L. Angel-Toro).

0030-4018/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2012.07.021

In applications where speckle-like patterns are used as markers on a surface, the effects associated with speckle decorrelation are not of concern, except for the flow of markers in and out of the observation region. However, the limitations imposed by speckle decorrelation are in general difficult to manage in the context of vortex metrology.

In this work, we investigate the effect of the actual speckle decorrelation when using the conventional tools of vortex metrology for uniform in-plane displacement analysis. We use speckle distributions generated by means of a plane diffuser, which is laterally displaced between two successive image recording steps. The generation of the analytical signals corresponding to the speckle distributions has been done by digitally implementing the Reisz transform. For the precise determination of the loci of vortices onto the pseudo-phase maps, we first employ an adaptation of the residue location method from phase unwrapping techniques, which allows for the identification of pixel vicinities containing singularities [10]. Then, to calculate the sub-pixel positions of vortices, we use the conventional procedure based on the analysis of the crossing through zero of the real and imaginary components of the analytical signal, in the vicinities of the singularities [7]. The tracking of the homologous vortices is done by matching the information on the topological charge and the core structures of vortices.

In Section 2, the effects associated with speckle decorrelation in the field of vortex metrology are outlined. Section 3 is devoted to present and analyze two representative experiments, supporting the influence of decorrelation on the quality of histograms and the certainty of measurements for in-plane displacements, when using the conventional tools for analysis in vortex metrology.

2. Effect of decorrelation on histograms

The decorrelation associated with in-plane displacements can be described in terms of a combination of three different effects [7] that we briefly discuss. First, as the displacement increases, the illuminated area onto the diffuser slightly changes, and consequently, a rather different set of radiators is associated with waves interfering at the observation plane. As a consequence, the shape of speckles begins to change.

In applications like speckle photography, this effect could not have a significant influence on the fringes quality and measurements. Nevertheless, in the context of vortex metrology, changes in speckles should not be disregarded because they are in general associated with quite significant changes in the core structure of the phase singularities. The distortions of the phase singularities core structures increase the difficulty of finding the correct counterparts, to calculate the respective coordinate differences.

As objective speckle fields decorrelate, the phase vortices onto the corresponding 2D phase-maps migrate to nearby positions [11]. The correct pairing of sources migrating is fairly unambiguous for slightly decorrelated speckle patterns, but is not so obvious at larger decorrelations. Similar random movements of vortices in connection with speckle decorrelation were also observed in subjective speckle fields, both for in [12] and out of plane [13] vortices displacements.

Second, the changes in vortex networks, due to decorrelation, also include the creation and annihilation of pairs of vortices with opposite topological charge, for which there are no counterparts we can find when tracking the homologous vortices.

Third, the flow of the phase singularities across the boundary of the observation region also causes decorrelation, i.e. the diffuser displacement implies that some of the vortices move into or out of this area across the boundary. Then, it also makes impossible finding their counterparts in the other pseudo-phase map.

Although all these three effects are of concern, changes in the shape of speckles, and consequently in the core structures of vortices, are those that probably have the most negative influence in the outputs of algorithms conventionally implemented for analysis in vortex metrology. Indeed, we show that, as the decorrelation increases, the reliability of results in general diminishes, because of the difficulty for obtaining high quality histograms under more restrictive circumstances. For illustration purposes, experimental results are presented and discussed.

3. Recording experimental arrangements and histograms analysis

The experimental arrangements to produce both undecorrelated and decorrelated speckles are schematized in Fig. 1. A collimated beam from a He–Ne laser (633 nm) is employed as the illuminating source. In Fig. 1a, the beam directly impinges onto an opaque mask with a circular aperture, attached to a diffuser located immediately behind the mask. Then, objective speckles are formed on the observation plane a distance z apart from the diffuser. On that plane a CCD camera is placed for recording. Because in this arrangement the mask and the diffuser are moved jointly, the same set of radiators generates the speckles before and after displacement and no decorrelation occurs. In Fig. 1b, an image of the mask is formed onto the diffuser, which is moved while the illumination beam remains fixed. Then, in this case the speckles decorrelate.

In both arrangements, a piezoelectric analog/digital actuator (30 nm steps) is used to produce the in-plane displacements. A 5 mm diameter light-spot is projected onto the diffuser, and the distance between the diffuser and the observation plane is settled to $z=50$ cm. Then, the average transversal speckles size is about 77 μm.

In each arrangement, we record two speckled images corresponding to the states before and after the diffuser displacement, whose direction coincides with the laboratory coordinate horizontal x-axis. The displacement magnitude in between exposures is $\Delta x=30$ μm, which represents a 2 pixels distance in the image. Note that this distance is less than half of the average transversal speckle size. Afterwards, each recorded image is processed by using the Reisz transform to produce a related 2D pseudo-phase map containing the vortices. To localize them, a modified version of the Goldstein residues location method was employed, followed by the conventional procedure based on the zero crossing analysis for the real and the imaginary components of the analytical signal. Then, the tracking of homologous vortices is carried out through the evaluation of the topological charge and the corresponding core structure properties, i.e. the vorticity, eccentricity and zero crossing angles. Finally, the relative coordinate displacement between images is performed through the homologous vortices matching onto the respective pseudo-phase maps, and the corresponding histograms generation and analysis.

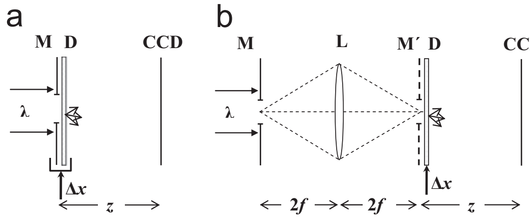

Fig. 1. Experimental arrangements for recording speckled images before and after an in-plane displacement, for (a) undecorrelated and (b) decorrelated patterns, where λ: wavelength, D: diffuser, M: mask, M’: image of M, L: lens of focal distance f, CCD: camera, and Δx: in-plane displacement.

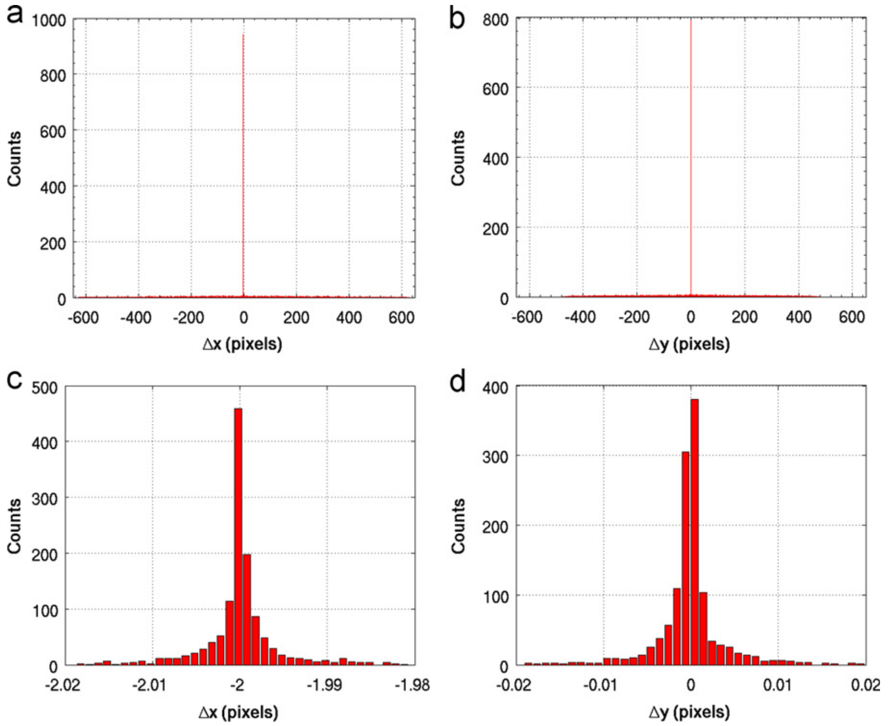

Fig. 2. Histograms for displacements of phase singularities along the x and y coordinate axes, when no decorrelation is involved. Changes in vortices positions are related with a 30 μm in-plane displacement along the x axis (1 pixel corresponds to 15 μm in the recorded images). In (a) and (b) the results of the first interrogation for coordinate differences between homologous vortices are presented. In (c) and (d) a refined identification of displacements is shown.

In Fig. 2 we present the results of a representative experiment in which no decorrelation effects are of concern, except for that related with the singularities flow across the boundaries of the recording area, which is unavoidable. For recording, the set-up in Fig. 1a is employed. Note that these results are quite similar to that reported in [6–8], where speckle-like not decorrelated patterns were employed to measure the in-plane displacements. In Fig. 2b and c, the histograms represent the distributions of the coordinate relative displacements between different vortex pairs, after a first step of vortices movement interrogation, which is done on the basis of pairing those vortices with equal topological charge and similar core structure parameters. Although there is no a-priori information that in principle we can assume, neither on the direction nor on the magnitude of displacement, this step makes possible obtaining an approximate coordinate displacements estimation, and also it allows for restricting the interrogation area in the second step of the homologous vortex tracking. Then, to refine the evaluation of displacements, a new pairing of homologous vortices is conducted, but in this case we use together the information on the approximate coordinate differences of vortices which are candidates to be paired. This information is inferred from the location and width of the highest column in the histograms depicted in Fig. 2a and b. Here, each column represents a coordinate displacement interval of 0.05 pixels, and the taller column reaches 941 and 792 counts along the x and y axes, respectively. Their central peaks are centered at $\Delta x = -2.0137$ pixels and $\Delta y = 0.0238$ pixels, so the interrogation area in the second step is settled (in pixels) as $|\Delta x + 2.0137| \leq 0.0250$ and $|\Delta y - 0.238| \leq 0.0250$. The calculations are made on the basis of 1500 and 1492 vortices that are localized onto the pseudo-phase maps associated with the initial and final states of the diffuser, respectively.

The results for the second interrogation step are presented in Fig. 2c and d, for the x and y coordinate displacements, respectively. Note the change in the horizontal scales in comparison with Fig. 2a and b. After refining the histograms, 1250 pairs of homologous vortices are found, and the displacements we measured are $\langle \Delta x \rangle = -2.0000$ pixels and $\langle \Delta y \rangle = 0.0001$ pixels, their variances being $\sigma_x^2 = 1.6747 \times 10^{-5}$ pixels^2 and $\sigma_y^2 = 1.3014 \times 10^{-5}$ pixels^2, respectively. Although each column in the respective histograms represents an interval of 0.001 pixel, the computation of displacements and their variances is done by using the information on the precise locations of vortices.

These results confirm the capacity of the method for accurately measuring the lateral displacements of vortices when no decorrelation is of concern.

On the other hand, in Fig. 3 the results for an experiment where speckle decorrelation causes a significant uncertainty in measurements are presented. In this case images are recorded by using the set-up in Fig. 1b. Following the same procedure we outlined above, in Fig. 3a and b, the histograms are generated on the basis of a first interrogation of the relative coordinate displacements for homologous vortex pairs, as in Fig. 2a and b. In this case the computation is done by using the information on the properties and the loci of 1537 and 1486 vortices associated with the pseudo-phase maps, for the original speckles before and after displacement, respectively. In Fig. 3a and b, each column is 1.2 pixels wide, and their taller columns reach 493 and 649 counts for the Δx and Δy displacements, respectively. These columns are found to be centered at $\Delta x = -2.0986$ pixels and $\Delta y = 0.0041$ pixels. Observe that, although these histograms remain useful for identifying the approximate displacement coordinates, it is apparent that in both histograms quite noisy side lobes are of concern because of decorrelation. Besides, when experiments to improve the histograms quality are conducted, which is done by imposing more restrictive criteria for tracking the pairs of homologous vortices, a natural limit is found because of a dramatic reduction of the number of such pairs, which in turns reduces the discrimination capacity of maxima in the histograms.

To improve the histograms, we proceed as before, by implementing the same strategies for processing and presenting the

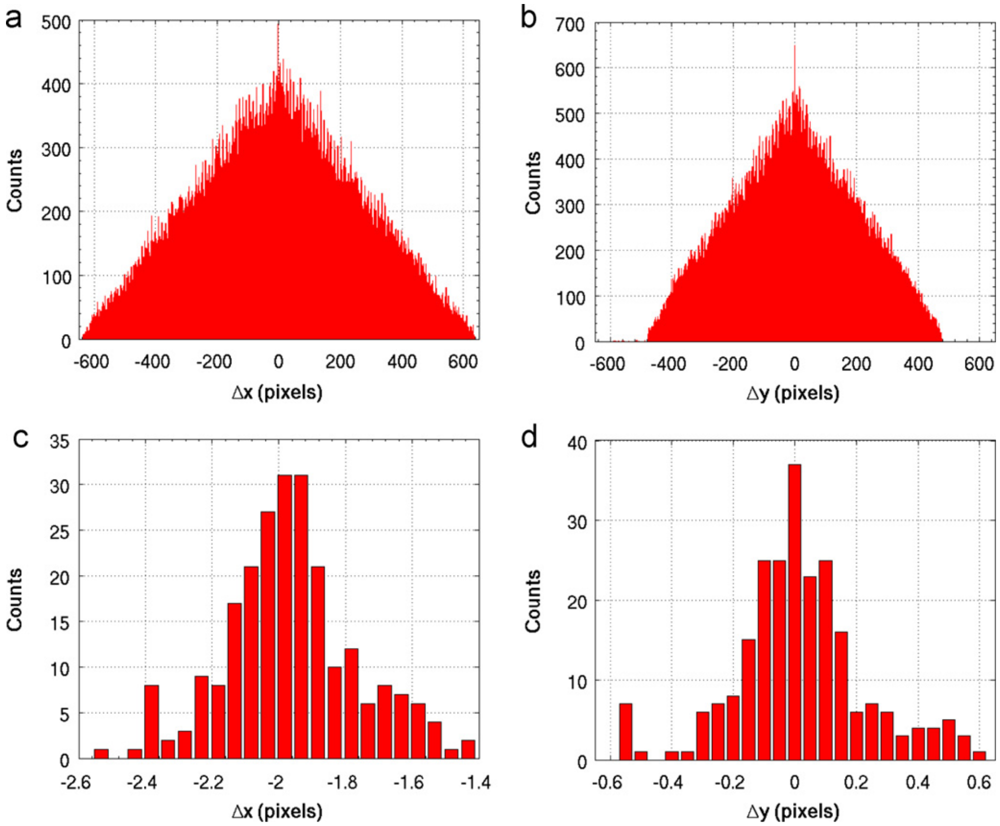

Fig. 3. Histograms for relative displacements of phase singularities along the x and y coordinate axes, when decorrelation is involved. Changes in vortices locations are associated with a 30 μm in-plane displacement along the x axis (1 pixel corresponds to 15 μm in the recorded images). In (a) and (b) the results of the first interrogation for coordinate differences between homologous vortices are presented. In (c) and (d) a refined identification of displacements is shown.

Table 1
Comparison between experimental results obtained on the basis of undecorrelated and decorrelated speckle patterns.

	Undecorrelated patterns	**Decorreleted patterns**
Coupled homologous vortices (%)	84.1	14.9
$\langle \Delta x \rangle$ **(pixels)**	-2.0000	-1.9653
$\langle \Delta y \rangle$ **(pixels)**	0.0001	0.0058
σ_x^2 **(pixels^2)**	1.6747×10^{-5}	0.0333
σ_y^2 **(pixels^2)**	1.3014×10^{-5}	0.0387

information described in connection with Fig. 2c and d. The corresponding refined histograms are presented in Fig. 3c and d. In this case, each column in the histograms represents a 0.05 pixels interval, and only 222 pairs of homologous vortices are found. By taking into account the precise locations of vortices onto the pseudo-phase maps, the average of coordinate displacements are $\langle \Delta x \rangle = -1.9653$ pixels and $\langle \Delta y \rangle = 0.0058$ pixels, and the respective variances are $\sigma_x^2 = 0.0333$ pixels^2 and $\sigma_y^2 = 0.0387$ pixels^2.

In Table 1, the average coordinate displacements and the respective variances, for both undecorrelated and decorrelated speckled images, are summarized. Also the respective percentages of paired homologous vortices, in relation with the total number expected cases, are presented. Taking into account the values of expected average coordinate displacements, which are $\langle \Delta x \rangle = -2.0000$ pixels and $\langle \Delta y \rangle = 0.0000$ pixels, respectively, it is apparent that a higher precision is achieved in the case of undecorrelated patterns, and also in this case smaller values of the respective variances are obtained. On the other hand, due to decorrelation, a significant reduction in paired homologous vortices and noisy lobes in the histograms are of concern.

Related effects were observed in connection with vortex analysis in dynamic speckle images [14], when studying the effect of in-plane displacements. There, it was established that there is a compromise among the number of detected vortices to obtain good statistics, the proportion of allowed misidentified vortices, and the displacement threshold. In fact, the refined histograms have less pairs of homologous vortices associated with their central peaks and they represent wider distributions than those for undecorrelated speckle patterns. As a result, a significant reduction of the certainty of measurements is of concern, which typically reaches several orders of magnitude as in the case that we presented.

4. Conclusions

In this work, we have investigated the influence of speckle distributions decorrelation in the context of vortex metrology, applied to the study of uniform in-plane displacements. Two experimental arrangements were implemented for recording the speckled images, before and after displacement, for both undecorrelated and decorrelated speckles. After recording, the processing of images was carried out as usual, by means of basic tools for vortex metrology that were implemented. However, a comparison of the experimental results allows for observing the different effects on measurements that can be associated with speckle decorrelation.

Changes in the shape of speckles are associated with vortices migration to nearby positions and changes in the vortex core structures. We showed that these effects have a negative influence in the outputs of algorithms conventionally implemented for analysis in vortex metrology, specifically, when used for measuring the uniform in-plane displacement of a diffusing surface.

The quality of our results for undecorrelated speckles is comparable to those previously reported for similar measurements using speckle-like patterns, in which structural changes of markers are not involved. Indeed, in this work we presented experimental evidences to support that, under the restrictions imposed by decorrelation of actual speckles, the reliability of results in general diminishes. This is because of the difficulty to obtain high quality histograms, which in turn is related with a reduction in the number of homologous vortices that can be tracked during the process, and the noisy lobes of histograms. It stands for a higher probability of misidentified homologous vortices.

After a second interrogation procedure for pairing the homologous vortices, by using the information on the approximate coordinate displacements, the refined histograms obtained have less pairs of homologous vortices associated with the highest peak, and stand for wider distributions when compared with those histograms for undecorrelated speckle or speckle-like patterns. As a result, a significant reduction of the certainty of measurements occurs.

We used the Reisz transform for generating the pseudo-phase maps from the speckled intensity distributions; however, other integral transforms could be used. In particular, the Laguerre–Gauss transform, to control the spatial frequencies and the density of vortices onto the 2D phase maps.

Research on the influence of speckle decorrelation in vortex metrology but for measuring different magnitudes is currently being conducted.

Acknowledgements

Luciano Angel-Toro acknowledges Universidad EAFIT (Colombia) and financial support under TWAS-UNESCO Associateship Scheme at Centres of Excellence in the South for visiting the Centro de Investigaciones Opticas (CIOp) at La Plata-Argentina in 2011. This research was performed under Grants CONICET No. 112-200801-00863 (Argentina), ANCYT PICT 1167 (Argentina), and Facultad de Ingeniería, Universidad Nacional de La Plata No. 11/I125 (Argentina).

References

[1] R.P. Khetan, F.P. Chiang, Applied Optics 15 (1976) 2205.
[2] F.P. Chiang, R.P. Khetan, Applied Optics 18 (1979) 2175.
[3] L. Angel-Toro, M. Tebaldi, N. Bolognini, M. Trivi, Journal of the Optical Society of America A 17 (2000) 107.
[4] L. Angel-Toro, M. Tebaldi, N. Bolognini, Optics Communications 274 (2007) 23.
[5] L. Angel, M. Tebaldi, N. Bolognini, Applied Optics 46 (2007) 2676.
[6] Wei Wang, Nobuo Ishii, Steen G. Hanson, Yoko Miyamoto, Mitsuo Takeda, Optics Communications 248 (2005) 59.
[7] Wei Wang, Tomoaki Yokozeki, Reika Ishijima, Atsushi Wada, Yoko Miyamoto, Mitsuo Takeda, Steen G. Hanson, Optics Express 14 (2006) 120.
[8] Wei Wang, Tomoaki Yokozeki, Reika Ishijima, Mitsuo Takeda, Optics Express 14 (2006) 10195.
[9] Wei Wang, Steen G. Hanson, Mitsuo Takeda, in: G.H. Kaufmann (Ed.), Advances in Speckle Metrology and Related Techniques, Wiley-VCH, 2011, p. 207. (Chapter 5).
[10] Dennis C. Ghiglia, Mark D. Pritt, Two-Dimensional Phase Unwrapping: Theory, Algorithm, and Software, John Wiley & Sons, 1998.
[11] J.M. Huntley, J.R. Buckland, Journal of the Optical Society of America A 12 (1995) 1990.
[12] C. Falldorf, W. Osten, F. Elandaloussi, E. Kolenovich, W. Jüptner, Proceedings of SPIE 4398 (2001) 238.
[13] E. Kolenovic, W. Osten, W. Jüptner, Proceedings of SPIE 3744 (1999) 174.
[14] Gonzalo H. Sendra, Héctor J. Rabal, Ricardo Arizaga, Marcelo Trivi, Journal of the Optical Society of America A 26 (2009) 2634.