Wide field nanometric materials analysis by diffraction limited far field optical nanoscopy

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Abstract. In the development of nanomaterials and biomaterials, new characterization techniques are required that overcome the challenges presented by the increasing dimensional ratio between the different entities to be studied and the growing complexity introduced by the use of heterogeneous materials and technologies. Diffraction limited far field optical nanoscopy techniques are receiving growing interest because of their capacity to detect nm structures over very large fields and at high speed. In this paper we present a classification scheme of optical nanoscopy techniques and in particular highlight four categories of far field diffraction limited techniques based on increasing the contrast, measuring the phase, using deconvolution or using nano-markers. We thus demonstrate that by increasing the power of detectability, observability or measurability, a wealth of information concerning nanometric structures becomes available even though all the lateral details may not be resolved. These techniques conserve all the advantages of classical imaging such as real time or high speed measurement, large quantities of useful data, non-invasiveness, non-destructiveness and ease of use. Such a summary will be useful in stimulating the search for new solutions to certain difficult problems in nano-characterization of nanomaterials and biomaterials over wide fields.

1. Introduction
In considering one of the key enabling technologies of the last 50 years, microelectronics, it can be noted that research in this area has been marked from its conception by the growth in the gap between the size of the basic element and that of the finished system. If this ratio was a factor of 10 at the beginning of the 1960’s, it will approach $10^6$ in the next few years. For example, in today’s microprocessors, the gate length of a transistor is of the order of tens of nm while the overall size of the processor is more than 1 cm². In future components and systems based on nanotechnologies and biotechnologies, this ratio will continue to increase by several orders of magnitude. In addition, components and systems will grow in complexity since they will contain several different technologies as is already the case in microsystems (MEMS, MOEMS) and Systems on Chips (SOC). These two factors, the dimensional ratio problem and the complexity, present two significant challenges in the field of future nano-characterization to make these new technologies viable.

In the case of biomaterials, for example in layers of hydroxyapatite (the mineral part of bones and teeth), morphological, chemical, optical and mechanical information is necessary at several scales, from the nm level of the basic crystals to the mm level for the functional material [1]. In living organisms such as cells, the details of interest vary from the nm level for molecules, to 10 nm for larger proteins and up to several tens of nm for vesicles and this dynamically in solution.

In terms of high resolution characterization techniques, electron microscopy and near field microscopy provide certain solutions for imaging the basic elements at the nm level, but as with all
techniques, while being very good in certain applications their limitations make them unsuitable for others. For example, in electron microscopy, the electron beam and the vacuum or near-vacuum conditions can be destructive for many types of samples. In near field microscopy, point by point scanning limits the measurement bandwidth and the field of measurement and the physical presence of the tip leads to measurement biases and a restriction to surface or near surface characterization.

Far field optical microscopy has received renewed interest in recent years for several reasons, not the least being the innate high bandpass due to the parallel sampling of imaging that gives the capacity for real time analysis. The development of super-resolution techniques also makes it possible to go well beyond the limits of diffraction. Finally, there is the realization that far field imaging can in fact be used extensively for extracting important information from nano-structures and thus being able to solve certain scientific problems in the "nano-world". These different approaches mentioned, i.e. near field, far field and super-resolution, generally fall under the term of nanoscopy.

One thing that can be remarked when approaching this new field of nanoscopy is that there are so many different techniques that exist that it can be quite confusing for the materials specialist who is looking for an appropriate characterization technique. There are several different ways of classifying nanoscopy techniques. In figure 1 we propose one particular classification scheme that can help in better distinguishing one technique from another. It is neither exhaustive nor definitive, but merely useful. A first level of classification concerns the distance at which the optical information is obtained, in the far field, with an imaging objective, or in the near field with a physical probe placed in the nanometric vicinity of the surface such as SNOM (scanning near-field optical microscopy).

**Figure 1.** The four sub-divisions of diffraction limited far field techniques (marked in blue) in the context of a global classification scheme for nanoscopy techniques

Amongst the far field techniques, a second level of classification can be made concerning the lateral resolution attained. The lateral resolution is either limited by the effects of diffraction or, by the super resolution techniques used to go beyond diffraction limited imaging. Resolving lateral details below the wavelength of the light used while remaining in far field conditions, can be achieved by diffraction tomography (or DHM, digital holographic microscopy), SIM (structured illumination
microscopy), I5M, 4pi or STED (stimulated emission depletion). These techniques are of particular interest in the analysis of biological samples where a lateral resolution of 20 nm to 100 nm is required.

The second category of far field techniques concerns those that are diffraction limited, which can be sub-divided into four categories according to the method used to give the nanometric sensitivity:

1. Increasing the contrast by means of the illumination, the phase or the polarisation.
2. Measuring the phase by interferometry.
3. Using deconvolution in sub-pixel metrology techniques.
4. Using nano-markers such as fluorochromes or gold nano-particles.

It is this particular category of far field, diffraction limited techniques (marked in blue in figure 1) that is the subject of this paper. While being diffraction limited and unable to resolve all the lateral details, they can nonetheless be used to extract a number of different types of important information from nano-structures while conserving all the advantages of classical imaging [2]. For example, characterization can be performed over wide fields of hundreds of µm and even mm, at a very high rate, often allowing real time measurement and the production of a large quantity of data. The use of an optical probe is also non-invasive, non-destructive and non-toxic for living organisms.

It is worth underlining that even though the origins of several far field, diffraction limited techniques described date from over twenty years ago or even more, it is their “updating” using the combination of various physical principles and improved cameras and image processing techniques that make them so useful in nano-characterization. We pointed this out in several papers at the beginning of the 1990’s [2-4] but it is only in more recent years that the idea is becoming more popular. Both well-known and not so well-known techniques are worth another look at in the context of today’s nano- and biomaterials since they could provide some elegant solutions for certain problems in nano-characterization. Such a review could also stimulate the development of new instrumentation.

In the four sections that follow, we therefore present a summary of some of the results of far field, diffraction limited nanoscopy using contrast, phase measurement, deconvolution and nano-markers. We present some of the principles and some example results to demonstrate the type of information that can be obtained in nano-characterization.

2. Nanoscopy using high contrast for detection of nm structures

When the size of an object under a conventional optical microscope is slightly smaller than the Rayleigh limit, the intensity decreases rapidly to the point of the object becoming no longer visible. This can be described in terms of Rayleigh scattering, in which the object size \( d << \lambda \) and the intensity of the scattered light decreases as a function of \( d^{-6} \). But since scattering is uniform in all directions, one way of making nano-particles visible in the far field is simply to increase the contrast. For images containing small features that are present on a large uniform background, the contrast is given by the Weber contrast, \( C_W \):

\[
C_W = \frac{(I_{\text{Max}} - I_{\text{Min}})}{(I_{\text{Min}})}
\]

where \( I_{\text{Max}} \) is the maximum intensity (intensity of the features) and \( I_{\text{Min}} \) is the minimum intensity (background intensity). For an 8 bit image depth, \( C_W \) therefore varies from 1 to 255. In other types of images in which the structures have equivalent bright and dark features, the contrast is given by the Michelson contrast, \( C_M \), which varies between 0 and 1 and is defined by:

\[
C_M = \frac{(I_{\text{Max}} - I_{\text{Min}})}{(I_{\text{Max}} + I_{\text{Min}})}
\]

2.1. Dark field microscopy

In classical dark field microscopy [2, 3] the sample contrast comes from light scattered by the sample using a dark field illumination device by illuminating the sample with highly inclined light rays that are not collected by the objective lens and generally do not form part of the image. To illustrate the
effects of contrast on particle visibility, the results in figure 2 show dark field images of microprecipitates in crystals of GaAs using two different types of near IR illumination. In this case the microprecipitates are visible (figure 2(a)) because they have a size near to the resolution limit of about 1 µm. But the contrast of the particles is fairly low ($C_W = 1$ to $2$) since the background intensity is far from zero ($I_{\text{Min}} = 20$ to $80$ grey levels). While the direct illuminating light rays do not enter the objective lens, light diffused from scatterers above and below the observation plane does. Even with image processing, the contrast is not sufficient to observe nano-particles.

On the other hand, it should be pointed out that even with low contrast conditions, observation of µm sized microprecipitates can actually reveal important structural information about nano-structures. The image in figure 2(a) is in fact the addition of three images taken at different depths, which after image processing and colour coding give a 3D impression of the orientation of the distribution of the particles (figure 2(b)), which actually decorate a series of looped dislocations which are atomic in size. The reason the dislocation paths become observable is because not only they are decorated by “native-markers”, but they are also extended beyond the lateral resolution limit of the microscope. This example could therefore have been used in section 5 to illustrate the use of nano-markers.

A novel way of considerably reducing the background intensity in dark field microscopy is by using a thin beam of laser illumination at $90^\circ$ to the direction of observation in the laser scanning tomography (LST) technique. For example, by focusing a near IR ($\lambda = 1$ µm) laser beam on the cleaved face of a crystal of GaAs using LST, the cloud of 10 nm sized microprecipitates appearing after annealing, becomes clearly visible, as in figure 2(c) [3, 4]. In this case, the nanoparticles act like point sources that are visible individually if their density is less than $10^9$ to $10^{10}$ cm$^{-3}$ or as a continuous background level if their density is greater. While the technique works well in bulk materials, it is not suitable for analyzing defects in thin layers since it is limited to an observation plane that is more than 5 µm from the surface.

![Figure 2](image.png)

**Figure 2.** The use of near IR dark field microscopy for the observation of (a) looped dislocations decorated with microprecipitates in GaAs, (b) 3D observation of (a) after image processing (P. Montgomery 1990) and (c) cloud of 10 nm nano-particles (indicated by arrow) in GaAs using LST (1 x 1 mm) (M. Castagné & P. Gall-Borrut, CEM2, Univ. Montpellier II, 1990)

Other useful properties of Rayleigh scatterers are that they are sensitive to wavelength, the scattering intensity varying with $(1/\lambda)^4$ and they can be sensitive to the orientation of polarization of the illumination beam when assimilated to dipoles. The use of several illumination wavelengths [5] and the effects of polarization in more recent improvements of the LST technique allow the determination of the shape and nature of the different nanoparticles present. In fluorescence microscopy, the orientation of molecules in the far field has been observed due to the asymmetric polarization response of the Airy disc [6].

2.2. Preferential chemical etching and Nomarski (DIC)
A powerful although destructive technique for revealing nano-defects in the sub-surface of crystals is by the use of preferential chemical etching, which produces variations in roughness according to the
defects present. Nomarski microscopy (or DIC, differential interference microscopy,) can be used to improve the contrast of the edge details, making use of the high sensitivity of interferometry in a sheared image pair of the surface. The results in figure 3(a) show a DIC image of a surface of GaAs that has been etched to a depth of 0.6 µm [7]. What can be seen is a dislocation parallel to the surface that is decorated with micro-defects that is known as the Cottrel atmosphere. In this way, the etching reveals the presence of nanometric and even extended atomic sized defects that are amplified by DIC microscopy. The relief can also be quantified using phase stepping microscopy (see section 3.2).

![Figure 3](image)

**Figure 3.** Atomic sized dislocation paths made visible in GaAs by (a) Normarski after chemical etching (J. Weyher, 1990), (b) near IR phase contrast microscopy (P.C. Montgomery, CEM2, Univ. Montpellier II, 1990) and (c) near IR phase contrast microscopy with image integration (P.C. Montgomery, CEM2, Univ. Montpellier II, 1989)

2.3. Phase contrast microscopy

A non-destructive way of observing the same type of defects described previously is to increase the contrast of small variations in the refractive index within the crystal using near IR phase contrast microscopy (figure 3(b)) [7], revealing clearly the extended Cottrel atmosphere around the decorated dislocation. Measurement of the intensities shows a contrast $C_M = 0.1$. By using image integration to reduce camera noise, near IR phase contrast microscopy was used to produce the exceptional results in figure 3(c) in which despite the extremely low contrast $C_M = 0.01$, the observation of the dislocation path was possible. The extended atomic sized defect is made visible by the associated surrounding strain field in the tin doped GaAs crystal [8], the "pinning" effect of the dislocation path by microprecipitates being clearly visible.

![Figure 4](image)

**Figure 4.** A series of strobed images ($\delta t = 1$ s) using phase contrast microscopy of a giant vesicle showing shape fluctuations (V. Vitkova, Laboratory of Liquid Crystals, ISSP, BAS, Sofia, Bulgaria).
A more recent application of phase contrast microscopy in nano-characterization, is in the measurement of the elastic properties of lipid membranes through the study of thermal shape fluctuations of giant vesicles [9]. Although the thickness of the membranes of the unilamellar giant vesicles (10 µm radius) is less than 5 nm, because their refractive index is about 10% higher than that of the aqueous surroundings, the edge of the sphere becomes clearly visible. The thermal fluctuations are very complex, being the sum of many different vibration modes. To avoid blurring, the addition of stroboscopic illumination using a xenon flashlamp makes it possible to freeze the movement. The strobed images (4 µs pulse duration) in figure 4 taken at intervals of 1 s show clearly such fluctuations. Strobing from 0.1 to 1 MHz is possible. The system has been used to successfully estimate the friction between the monolayers comprising the bilayer of the membrane, as well as the bending elasticity modulus of the blocked exchange of molecules between the monolayers [9].

2.4. Surface Enhanced Ellipsometric Contrast microscopy (SEEC)
Another way of increasing the contrast is by using polarised light. The SEEC (surface enhanced ellipsometric contrast, commercially known as Sarfus) technique, uses dedicated substrates specially prepared with anti-reflection coatings that are designed for use in crossed polarised light to decrease the background intensity ($I_{\text{Min}}$) and thus increase the contrast by a factor of 10 to 100 [10]. The presence of nm layers or nanoparticles changes the state of the polarization, producing contrast and thus become visible. The results in figure 5 show an image from a video (figure 5(a)) of the crystallization of a 9 nm thick layer of polystyrene-b-polyethylene oxide (PS-b-PEO) diblock copolymers. In figure 5(b) can be seen bundles of DWNT (double walled carbon nanotubes) that are individually 9 nm in diameter. The technique is finding use in a growing number of applications in nano-characterization, such as for example in the study of nano-dots, nanowires, graphene, crystallites, thin films, polymers, membranes, polyelectrolytes, soft lithography, biochips and live cells.

![Figure 5](image)

Figure 5. The use of the SEEC technique to observe (a) the crystallization of a 9 nm layer of PS-PEO (G. Reiter, ICSI, Mulhouse, France) and bundles of DWNT carbon nanotubes (E. Flahaut, CIRIMAT, Toulouse, France) © Nanolane

3. Nanoscopy using phase for nm roughness measurement
The second family of far field diffraction limited nanoscopy techniques is that based on the measurement of the phase of the light reflected from a surface. Comparison of the wavefront of the light from the sample with that from a flat reference surface results in interference fringes and the conversion of the phase into intensity that allows the measurement of nm surface roughness and shape.

3.1. Interference Reflection Microscopy (IRM)
A simple interferometric setup exists for studying the behaviour of live cells on microscope slides in IRM (interference reflection microscopy, or RICM, reflection interference contrast microscopy).
Viewing through the glass substrate, interference is produced between the substrate surface and the cell membrane, producing fringes that can be quantified so as to measure the distance between the membrane and the substrate surface in adhesion studies. The high sensitivity of interferometry in the “fluctuation contrast” technique, also allows the detection of nm variations due to bunches of ligand-receptor links within the substratum [11].

3.2. Phase Stepping Microscopy (PSM)

By optimizing the optical configuration of the interferometer in a dedicated objective, the fringe contrast, $C_M$, which is also known as the fringe modulation or visibility in interferometry, can have quite a high value between neighbouring bright and dark fringes, corresponding to a height difference of $\lambda/4$, or roughly 170 nm in visible light. Thus even with an 8 bit image depth, measurement of intermediate intensities of fringes in combination with optimized phase stepping algorithms thus allows the measurement of nanometric or better surface roughness [2, 4, 14]. PSM (phase stepping microscopy), CSI (coherence scanning interferometry, also known as WLSI, white light scanning interferometry) are used for measuring a wide variety of surfaces such as semiconductors, metals, polymers, etc [1, 4]. Surfaces can be profiled in real time using 4D interference microscopy [12].

As mentioned in section 2.2, PSM is also used to quantify the surface roughness after preferential chemical etching, such as the hillocks and valleys on tin doped GaAs using a DSL (dilute Sirtl-like) solution in figure 6(a) [13] and on Hgl$_2$ using a KI solution in figure 6(b) [14] and to associate them to the different types of nano-defects in the crystals over very wide fields of hundreds of µm or several mm. The etching “amplifies” the presence of the nano-defects laterally and the high axial sensitivity of the PSM technique allows the roughness to be quantified and the defects to be catalogued.

**Figure 6.** The use of PSM for measuring, identifying and cataloguing the different types of defects in microelectronic crystals after preferential chemical etching in (a) Tin doped GaAs using a DSL solution (P. Montgomery, J. Weyher, CEM2, Université Montpellier II, Montpellier) and (b) Hgl$_2$ using a KI solution (InESS, Strasbourg)

Another example of the usefulness of PSM even though it is diffraction limited, is in the calibration of the laser fluence of an excimer laser ($\lambda = 308$ nm) for the annealing of 80 nm thick amorphous Si layers for flat panel displays [15]. To achieve this, a single measurement of the 3D roughness is made of a sample placed at the edge of the laser impact which has a “top hat” intensity profile and therefore has a linear variation of the laser fluence with distance along one of the axes (figure 7(a)). A profile of the roughness along this axis shows the variation in roughness as a function of the laser fluence (empty diamonds in figure 7(b)). The two zones to avoid are visible, zone B, in which the grain size is too small and the “SLG” (super lateral growth) region, in which the grain size is maximum but irregular. The optimal zone is at A, with a large and constant grain size and providing the optimal laser fluence required.
A comparison with the measurements made with AFM (black diamonds in figure 7(b)) shows that those made by PSM are smaller. This difference is due to the fact that the grains of poly-Si vary in lateral size from 0.1 µm to 1 µm, which is near to the lateral resolution limit of 0.4 µm of the microscope. But it can be noted that even though the roughness is undersampled by PSM, the general shape of the line profile across the SLG region is maintained. This application is a good demonstration of the use of PSM as a rapid technique over large areas in a type of combinatorial analysis. The optimal parameter (the laser fluence) is identified due to the variation of another parameter (the roughness), not between different samples but between different positions on a single sample that has been judiciously placed at the edge of the laser beam and has taken only a few seconds to measure.

![Figure 7. PSM used in combinatorial analysis to determine the optimal zone of laser fluence in the crystallization of poly-Si in flat screen processing (a) PSM roughness near the edge of the laser impact and (b) Comparison of the roughness measurements between PSM/AFM (InESS, Strasbourg).](image)

A more recent variation of the PSM technique, QLSI (quadriwave lateral shearing interferometry), allows the measurement of phase variations in a single image and therefore higher speed analysis. A high resolution wavefront sensor based on a 2D hole grating (modified Hartman mask) in front of the CCD is used in combination with FT analysis. The technique is particularly useful in the study of cell membrane dynamics and intracellular activities due to the high sensitivity that reveals very thin or small structures such as the lamellipodia surrounding cells [16].

4. Nanoscopy by deconvolution for nm positioning

In the case of simple structures consisting of small particles, straight edges or regular structures, a third family of far field nanoscopy techniques exists using deconvolution, based on the knowledge of the optical transfer function of the optical system for sub-pixel or sub-voxel metrology.

4.1. Edge and particle positioning

White light interferometry was used in early sub-pixel techniques for helping to better measure the positions of structural edges in integrated circuits, with a lateral measurement uncertainty in position of 10-20 nm [17]. In LST, analysing the 3D distribution of microprecipitates inside semiconductor crystals at a sub-micron scale can be carried out by measuring the intensity response of the particles as a function of either the Gaussian beam profile of the laser beam or the sinc² longitudinal PSF of the optical system, giving a measurement uncertainty of 0.1 µm along the optical axis [4].

4.2. Position referenced microscopy

A more recent version of sub-pixel metrology has been developed for the precise repositioning of live cells (figure 8(a) and (b)) using a carefully designed reference mask consisting of a pseudo-periodic pattern placed just below the sample (figure 8(c) and (d)) [18]. With a lateral measurement uncertainty of 20 nm, this technique allows the absolute reference positioning of live specimens (figure 8(d)) and enables for example the following of the evolution of the absorption of apoptotic bodies by fibroblasts (figure 8(b)) during long periods of tens of hours that are removed from a controlled environment for imaging on the microscope at regular intervals.
5. Nanoscopy using nano-markers for nm measurement of position or structure

The fourth and last group of techniques considered is by using nano-markers to study nano-structures. Apart from “native-markers” such as microprecipitates decorating dislocations in crystals, mentioned in section 2.1, the use of “foreign-markers” such as fluorochromes and gold nano-particles are finding extensive use in the study of nano-structures.

5.1. Total Internal Reflection Microscopy (TIRF)

While different fluorochromes are used to target many different types of nano-structures today in fluorescence imaging, the contrast can be enhanced further by reducing the background intensity ($I_{\text{Min}}$) using total internal reflection at an interface (figure 9(a)), or TIRF (total internal reflection microscopy) [19].

The evanescent field excites only the fluorophores that are attached to structures within a depth of about 100 nm. Detailed images within the region of the cell membrane (figure 9(b)) are thus accessible, opening up the possibilities of studying dynamic processes such as cell membrane adhesion, or the movement of nanometric vesicles. The study of individual molecules is possible with stochastic techniques such as PALM (photo-activated localization microscopy) and STORM (stochastic optical reconstruction microscopy).
5.2. Gold nanoparticles (AuNP)
Finally, in place of fluorophores, nano-particles of gold (AuNP) can also be used as useful markers, becoming point sources that are not resolved but are observable. They can thus be used in combination with two photon microscopy to map out the nanometric structure of collagen fibres using single 5 nm AuNP that are moved along the fibre [20].

6. Conclusions
In this paper we have underlined the growing interest in a certain class of far field optical nanoscopy techniques that are limited by diffraction but nonetheless allow the detection, observation or measurement of different types of information of structures at a nanometric scale. Different techniques exist to reveal such information, such as by increasing the contrast, by measuring the phase, by using deconvolution techniques, or by employing nano-markers such as fluorophores or gold nano-particles. By keeping a wide field, it is thus possible to observe the distribution of nano-defects inside crystals, to measure nanometric surface roughness, to study and measure nano-layers, to perform nanometric sub-pixel metrology and to reveal nanometric structures and dynamic functions in living cells.

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8. References
[1] Pecheva E, Montgomery P C, Montaner D and Pramatarova L 2007 Langmuir 23 3912
[2] Montgomery P 1990 Nanotechnology 1 54
[3] Fillard J P, Montgomery P C, Gall P, Castagne M and Bonnaffe J 1990 J. Cryst. Growth 103 109
[4] Fillard J P 1996 Near Field Optics and Nanoscopy (Singapore: World Scientific) p 197
[5] Ma M, Nango N, Ogawa T, Watanabe M and Eguchi M 2000 J. Crystal Growth 208 282
[6] Beversluis M R, Novotny L and Stranick S J 2006 Optics Express 14 7 2650
[7] Weyher J L and Montgomery P C 1990 J. Cryst. Growth 106 476
[8] Montgomery P C and Fillard J P 1989 Electron. Lett. 25 2 89
[9] Genova J, Zheligaskova A, Vitkova V and Mitov M D 2009 J. Optoelectronics & Advanced Materials 11 9 1222
[10] Aussere D and Valignat M P 2007 Optics Express 15 13 8329
[11] Atilgan E and Ovryn B 2011 Biomedical Optics Express 2 8 2417
[12] Montgomery P, Anstotz F, Montaner D, Pramatarova L and Pecheva E 2010 J. Phys. Conf. Ser. 253 012017
[13] Montgomery P C and Weyher J 2007 L’erosion nanoscopique Voir L’Invisible ed ECRIN, (Sophia-Antipolis : Omnisience) p 60
[14] Ponpon J P, Montgomery P C, Sieskind M and Amann M 2000 Appl. Surf. Sci. 165 233
[15] Benatmane A, Montgomery P C, Fogarassy E and Zahorsky D 2003 Appl. Surf. Sci. 208-209 189
[16] Bon P, Maucor G, Wattelier B and Monneret S 2009 Optics Express 17 15 13080
[17] Dockrey J W and Hendricks D 1989 Proc. Int. Conf. on Integrated Circuit Metrology, Inspection and Process Control III (San Diego, USA, 19 July 1989) (Proc. SPIE vol 1087) ed K M Monahan (Bellingham: SPIE) p 120
[18] Galeano J A, Sandoz P, Gaffe E, Launay S, Robert L, Jacquot M, Hirchaud F, Pretet J L and Mougin C 2011 Biomedical Optics Express 2 5 1307
[19] Chung E, Kim D and So P T C 2006 Optics Letters 31 7 945
[20] Chen B, Estrada L, C Hellriegel C and Gratton E 2011 Biomedical Optics Express 2 3 511