Measurement of decay lengths of evanescent waves: the lock-in nonlinear filtering

D Barchiesi, T Grosges and A Vial

Laboratoire de Nanotechnologie et d’Instrumentation Optique, Institut Charles Delaunay—CNRS FRE 2848, Université de Technologie de Troyes, 12 rue Marie Curie BP-2060, F-10010 Troyes Cedex, France
E-mail: thomas.grosges@utt.fr

New Journal of Physics 8 (2006) 263
Received 24 July 2006
Published 2 November 2006
Online at http://www.njp.org/
doi:10.1088/1367-2630/8/11/263

Abstract. We study the influence of the lock-in amplifier and probe vibration on the measurement of decay lengths of evanescent waves after reconstruction of the Scanning Near-field Optical Microscopy signal. Thanks to the reconstruction which gives a tomography-like 3D map of the detected signal, the vertical decay lengths can be measured directly, from only one lateral scan. A nonlinear fit is applied to recover the exponential decays in simulated signals and experimental data.

Contents

1. Introduction 2
2. The measurement of evanescent decays 2
   2.1. The lock-in demodulation ........................................ 2
   2.2. The direct measurement of a unique decay length ............ 3
   2.3. Principle of reconstruction ...................................... 4
   2.4. The lock-in filtering of one evanescent wave ............... 4
3. The decays of experimental data 6
4. Conclusion 9
References 10

1 Author to whom any correspondence should be addressed.
1. Introduction

The characterization and imaging of nanostructures and fields are becoming a domain of interest in several fields such as physics, chemistry, biology and data storage [1]–[4]. The Scanning Near-Field Optical Microscopes (SNOM) allow the detection of the optical field at a few nanometres above nanostructures. The SNOM techniques are based on the detection of an electromagnetic signal scattered by a subwavelength-sized probe scanning the investigated sample. Due to the nanometric size of the probe end, the nanostructure and the confinement of the light, the signal-to-noise obtained from such a configuration is low. In order to increase the signal-to-noise ratio and to decrease the useless spatially slow varying signals, a lock-in amplifier is often used with homodyne [5] or heterodyne [6, 7] detection techniques. The detection is locked in the vertical vibration of the probe and the amplifier gives the first Fourier harmonics of the detected signal. Due to the filtering character of the lock-in, a direct and general physical discussion on the contrast in near-field optics, based on a given harmonic, is obviously difficult [8]–[10]. A reconstruction of the ‘real’ optical signal from all the available harmonics is necessary to discuss the contrast of the data [11, 12]. Moreover, the reconstruction of such a signal gives a tomography-like map of the near-field along the vertical vibration of the probe. Therefore, from a unique xy-scan, an approximation of the exponential decays of evanescent waves can be computed and the decays can be deduced from an appropriate fit.

In this paper, we discuss the filtering effect of the homodyne detection mode and its influence on the measurement of the decay of evanescent waves. Experimental data are processed and it is shown that the signal detected above the nanostructures is a superposition of exponential decays.

2. The measurement of evanescent decays

2.1. The lock-in demodulation

The basic principle of the lock-in detection is the use of the periodic vibration of a metallic or dielectric probe, in the vicinity of an investigated sample, in order to record their diffraction patterns. Assuming an harmonic vibration of the probe, working in tapping mode, with amplitude $A$: $z(t) = A(1 + \cos(2\pi ft))$, $f$ being the frequency of the probe vibration, the recorded signals through the lock-in detection are the first Fourier series amplitudes and phases of the harmonics $H_n$ of the field diffracted by the probe. The harmonics $H_0, H_1, \ldots, H_N$ of the signal $S(x, y, z)$ are provided through the lock-in amplifier and can be written as a function of the probe position in the scanning xy-plane [11, 12]

$$H_n(x, y) = \frac{1}{\pi} \int_0^{2A} S[x, y, (z/A - 1)] \frac{T_n(z/A - 1)}{\sqrt{z(2A - z)}} \, dz,$$

where $T_n(z/A - 1) = \cos(n \arccos(z/A - 1))$ is the Chebyshev polynomial of the first kind ($z \in [0, 2A]$) [13]. The physical information on the near-field is present in all harmonics given by the lock-in. We investigate the filtering properties of the lock-in and a method to measure the characteristics of the near-field signal (i.e. the decay lengths).
2.2. The direct measurement of a unique decay length

The contrast of the high harmonics images strongly depends on the amplitude of vibration $A$ of the probe and the lock-in acts like a $z$-filter. This filtering effect and the contrast dependence are intrinsic to the lock-in detection, to the vertical vibration of the probe and to the probe properties [14].

As an example, we focus on the measurement of a pure evanescent decay length $D_p$. In the general case, the detected signal results from a superposition of evanescent waves but can reveal only one decay above a flat surface

$$S(x, y, z) = S(z) = \exp(-z/D_p).$$

(2)

The investigated signal is recorded through the lock-in and therefore takes into account the interaction between the probe and the sample. No a priori hypothesis is necessary to discuss this decay length.

To measure such a decay length, the classical method consists of recording approach curves [8, 10]. The drawback of this method is the time requirement to record the approach curves at each scanning step in the $xy$-plane. Another approach could consist of taking advantage of the filtering effect of the lock-in to measure $D_p$. We show in figure 1 the computation of the amplitude of the four first harmonics of the signal (see equation (2)) as a function of the relative decay length $D_p/A$. The probe is supposed to vibrate in tapping mode and therefore its vertical position varies in $[0, 2A]$. Each harmonic exhibits a maximum of its amplitude for a fixed ratio $D_p/A$. Therefore, by varying $A$ and detecting this maximum, the measurement of $D_p$ becomes possible. Table 1 helps to deduce $D_p$ from the maximum of the harmonic amplitudes. The drawbacks of this method are the detection of the maximum, which could be tedious and difficult due to the experimental noise, the time needed to vary $A$ with small steps and its accurate control. Moreover, $A$ depends on the mechanical properties of the probe and of the cantilever themselves. In order to avoid such difficulties, a reconstruction of the signal along the probe vibration direction can be used.
Table 1. Maximum of $H_i$ as a function of $D_p/A$ (figure 2).

| $H_i$ | $D_p/A$ |
|-------|---------|
| 1     | 1.298   |
| 2     | 0.441   |
| 3     | 0.213   |
| 4     | 0.122   |

2.3. Principle of reconstruction

In order to ensure the pertinence of the physical interpretation and to study the real contrast of the field, the ASNOM real signal must be at least partially reconstructed from the first Fourier harmonics [12]. This reconstruction is a tomography-like method which enables the computation of an approximation of the approach curve directly from the lock-in data [15]. The reconstructed ASNOM signal $R_N$ from $N$ recorded harmonics can be expressed as a function of the position of the probe $z$ and is given by:

$$ R_N(x, y, z) = H_0(x, y)T_0(z/A - 1) + 2 \sum_{n=1}^{N} H_n(x, y)T_n(z/A - 1). $$

(3)

The reconstruction accuracy increases with the number of recorded harmonics and it enables a $z$-tomography of the near-field for $z \in [0, 2A]$, without any approach curve. Nevertheless, the limitation of the number of detected harmonics $N$ and the amplitude of vibration $A$ induce a filtering of the detected signal that is characterized in the following subsection.

2.4. The lock-in filtering of one evanescent wave

The lock-in is used to remove the useless background and to increase the signal to noise ratio. Therefore the expected behaviour of the detection is high-pass filtering in terms of diffracted waves. The low diffracted orders (background) are partially removed from the signal and the relative magnitude of the evanescent waves depends on the amplitude of vibration of the probe [16]. Theoretically, an infinite number of harmonics is necessary to accurately measure any decay length. Experimentally, only a few number of harmonics are detected. Nevertheless, it is possible to compute an approximation of the decay length measurement $m(D_p)$. The filter associated to the measurement of one decay length $D_p$ can be expressed as:

$$ F = \frac{m(D_p)}{D_p}, $$

(4)

where the measured decay length $m(D_p)$ is computed from an exponential nonlinear mean square fit (Prony’s method [17]) of the reconstructed data. This exponential fit could reveal the existence of more than only one decay in the reconstructed signal. The signal is given in equation (2), the lock-in is modelled with equation (1) and the reconstruction is computed with equation (3).

Figure 2 shows the filter $F$ evolution as a function of the number of harmonics $N$ used in the reconstruction. The measurement of $D_p$ when the amplitude of vibration of the probe $A$...
Figure 2. Filter $F$ for various number of harmonics $N$ involved in the reconstruction: (a) as a function of $A/D_p$, (b) as a function of $D_p/A$.

Table 2. Limit of accurate measurement of $D_p$ after reconstruction with $N$ terms, for a given tolerance of 1, 5 and 10%.

| Tolerance (%) | $D_p/A >$ |
|----------------|-----------|
|                | $R_1$     | $R_2$     | $R_3$     | $R_4$     |
| 1              | 6.17      | 1.82      | 0.71      | 0.41      |
| 5              | 2.97      | 0.99      | 0.47      | 0.30      |
| 10             | 2.07      | 0.76      | 0.39      | 0.24      |

varying, is illustrated in figure 2(a). The measured decay length $m(D_p)$ is greater than the real $D_p$ ($m(D_p) > D_p$) for small $N$ and $A$ increasing. Figure 2(b) shows the filter effect for a given $A$. For $D_p$ lower than the amplitude of the probe vibration $A$, $m(D_p) > D_p$. $A$ being fixed, the greater $D_p$ is, the better is its measurement. Therefore, the probe vibration induces a cut-off frequency for the measurement of evanescent waves with small $D_p$ (high confinement). The amplitude of vibration $A$ limits the accurate measurement of small $D_p$. Table 2 shows the evolution of the limit of accuracy on the measurement of $D_p$ as a function of $N$. It becomes possible to deduce the lower limit of the measurement of $D_p$ with an accuracy of 1, 5 and 10% respectively. For example, for $N = 3$ and an amplitude of vibration $A = 18$ nm, $\min(D_p)$ is equal to 12.8, 8.5 and 7 nm with accuracy of 1, 5 and 10% respectively. The measurement of such a decay with the technique of approach curve would be more tedious [11]. Actually, the probe vibration is necessary to prevent tip crash on the sample. Therefore, the reconstruction must be also applied to the approach curve and this measurement is limited by the signal-to-noise ratio. In that case, the reconstruction of approach curves will enable the recovering of exponential decays with high accuracy but the experimental approach curve is more time consuming (especially if it is achieved at each scanning step) than the scan in tapping mode presented in this paper. In the following section, the presence of one or more evanescent decays is studied by considering the experimental signal obtained through a lock-in amplifier in the $xy$-scanning plane and its reconstruction.
3. The decays of experimental optical data

We consider the experimental optical images of latex nanoparticles obtained with ASNOM. That consists of illuminating by a p-polarized $\lambda_0 = 488$ nm argon laser beam, with an angle of incidence $\theta = 40^\circ$, focused on the surface of a sample made of 80–100 nm diameter latex particles deposited on a glass substrate [12]. The optical signals, produced by a vertical vibrating AFM commercial tetrahedral silicon probe (AC Series, Olympus) at frequency $f \simeq 300$ kHz and with amplitude $A = 18$ nm (this parameter is not restrictive), is recorded in the $xy$-scanning plane. The estimated shape of the end of the probe is spherical with radius lower than 10 nm. The tip angle is about 15–25°. The dc-term, corresponding to the zeroth order of the Fourier harmonics $H_0$ and the three first harmonics ($H_1, H_2$ and $H_3$) are used to compute the reconstruction $R_3$. The detection of higher harmonics is impossible in the present case due to the signal-to-noise ratio. If finer information is needed, an heterodyne detection should be used. Actually, this technique enables the detection of more than three harmonics as it is less sensitive to the noise. Moreover, the various harmonics are not acquired simultaneously with the lock-in amplifier (Model 5302 EG&G Instruments Corporation). Therefore, before reconstruction, a signal preprocessing using the maximum of correlation of AFM data is applied to the optical signal to compensate the possible lateral shifts. To measure the decay lengths we use the above mentioned exponential nonlinear mean square fit with a number of exponential terms that is optimized with regards to the rank of the Prony’s matrices [17]. In these computations, the fitting function of the reconstruction with three harmonics and $H_0$ at each scanning step $(x, y)$ (see equation 3) is given by

$$R_3(x, y, z) \approx \sum_{n=1}^{n=\text{rank}} c_n(x, y) \exp \left[ -\frac{z}{m(D_p(x, y))} \right] \exp \left[ j2\pi z/m(P(x, y)) \right], \quad (5)$$

with a rank equal to height. The coefficients of the fit are dependent on the lateral probe position $(x, y)$ during the scan. The reconstructed curves $R_3(x, y, z)$ are computed in five zones, above the nanoparticles (zones 1 and 2) and above the flat substrate (zone 3, 4 and 5), at the centre of the white squares showed in figure 3(a). Figure 3(b) shows the corresponding AFM image. The reconstructed curves and their fits are shown in figure 4. A first visual inspection of figure 4 reveals the quality of the fit. Actually, the root of mean square error (rms error) between the fit and the reconstructed data is lower than $10^{-5}$. The parameters of the fits such as the rms errors, the measured period of the cosine and sine oscillations $m(P)$, the measured decays lengths $m(D_p)$ and their amplitude $c_n$ obtained from the fit of the reconstructed signal in the zones showed in figure 3(a), are indicated in table 3. The precision of the determination of the numerical value depends only on the method of fit. Nevertheless, the significance of the values must be discussed. The values $m(P)$ are the period of cosine and sine functions that can be obtained by factoring the complex and complex conjugates coefficients $c_n$ of complex exponentials. The fit can provide negligible terms with tiny values of $c_n$. Some constant values with $z$ can be found in the table, where $m(P)$ is infinite. In this case, a constant background is found with additive exponential terms. The positive values of $m(D_p)$ are associated with the evanescent signal (see equation (5)). The negative ones correspond to increasing exponentials which contribute to the background.

Under the usual hypothesis of passive probe and field detection, a short evanescent decay is characteristic of the lateral size $m(D_s)$ of an illuminated nanometric object [18]. Its typical size $m(D_s)$ can be computed from the $z$-component of the diffracted wave vector in the medium of
Figure 3. Reconstructed signal $R_3(z = 0)$, with the dc term $H_0$ and three harmonics, and the corresponding AFM image.

Figure 4. Reconstructed signal $R_3(z)$, with the dc term $H_0$ and three harmonics (stars), and the corresponding fit (line) for $A = 18$ nm.

detection and is given by

$$w = 3 \left[ \frac{2\pi}{\lambda_0} \sqrt{1 - (\sin(\theta) + \Lambda_0/m(D_p))^2} \right] = \frac{1}{m(D_p)}, \quad (6)$$

where $\theta$ is the illumination angle and $\lambda_0$ the wavelength in vacuum. From this equation (6), the value of $m(D_s)$ can be deduced from the measured $m(D_p)$ by:

$$m(D_s) = \frac{\lambda_0}{\sqrt{1 + \left( \frac{\lambda_0}{2\pi m(D_p)} \right)^2 - \sin(\theta)}}. \quad (7)$$
Table 3. Computed parameters of the fitting function (see equation (5)) for the reconstructions at the centre of zones shown in figure 3. The evanescent decays correspond to positive values of \( m(D_p) \). The corresponding values of \( m(D_s) \) are also presented. The rms error of the fit is also indicated. Each column corresponds to the result of the fit with height terms (rank = 8). For exponential decreasing terms, a first approximation of the size \( m(D_s) \) of the involved diffracting structures computed from equation (7) is also indicated.

| Zone | \( \mathcal{R}(c_s) \) | \( \mathcal{N}(c_s) \) | \( m(P) \) | \( m(D_p) \) | \( m(D_s) \) | rms | Zone | \( \mathcal{R}(c_s) \) | \( \mathcal{N}(c_s) \) | \( m(P) \) | \( m(D_p) \) | \( m(D_s) \) | rms |
|------|----------------|----------------|-------------|-------------|-------------|-----|------|----------------|----------------|-------------|-------------|-------------|-----|
| 1    | -3.43e-9      | -3.43e-9      | 2.08e-4     | 2.08e-4     | 2.08e-4     | 1.62e-1 |      | -8.4e-14      | 7.64e-6      | 1.07e-2     | -1.26e-3    | 1.39e-3     | 1.39e-3 |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |
| 2    | -3.61e-8      | 3.61e-8       | -1.8e-20    | 2.0e-18     | -1.03e-5    | 2.28e-1  |      | 3.7e-25      | 5.6e-20      | 1.18e-4     | -7.6e-17    | 5.13e-7     | 5.13e-7 |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |
| 3    | -9.98e-6      | -9.98e-6      | -2.59e-4    | 1.07e-2     | -1.26e-3    | 1.26e-3  |      | 6.34e-6      | 6.34e-6      | -7.10e-4    | 9.54e-5     | 9.54e-5     | 9.54e-5 |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |
| 4    | 3.64          | -3.64         | 18.73       | -18.73      | 18.04       | 13.77   |      | 4.05         | 0.64         | -6.21       | 9.31        | 1.32        | 1.32   |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |
| 5    | 0.64          | 0.64          | -12.6       | 9.31        | 188.92      | 188.92  |      | 4.05         | 0.64         | -3.37       | -4.84       | 25.32       | 25.32  |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |
| 6    | -2.67         | -2.67         | -3.37       | -4.84       | 188.92      | 188.92  |      | 0.64         | 0.64         | -6.21       | 9.31        | 1.32        | 1.32   |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |
| 7    | -1.77e-9      | -1.77e-9      | -1.09e-4    | -1.09e-4    | 1.85e-2     | 1.85e-2  |      | 3.85e-6      | 3.85e-6      | 8.54e-5     | -8.07e-3    | 1.97e-1     | 1.97e-1 |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |
| 8    | 5.51          | 5.51          | 10.32       | -10.32      | 29.99       | -29.99  |      | -13.48       | -13.48       | -9.35       | -31         | 19.06       | 19.06  |
|      |                |                |             |             |             |       |      |                |                |             |             |             |      |

In the particular case of \( m(D_s) \ll \lambda_0 \) an approximation of equation (7) can be easily deduced: \( m(D_s) \approx 2\pi m(D_p) \) [18]. Table 3 shows the values of \( m(D_s) \) deduced from equation (7) and the measured values \( m(D_p) \) corresponding to evanescent decays, in each zone. Only the evanescent decays (characterized by positive values of \( m(D_p) \)) are associated to \( m(D_s) \). Therefore, no value
is indicated in table 3 if $m(D_p) < 0$. The zones 1 and 2 are above nanoparticles and the zones 3, 4 and 5 are above the glass substrate but correspond to different intensity patterns. Actually, zone 3 is above a dark fringe and therefore, no decay is expected above the sample. In contrast, zone 4 is above a bright fringe and zone 5 is above more complex interference pattern.

The examination of the results in table 3 (i.e. amplitudes $c_n$ and $m(D_p)$ values) leads to show that the usual hypothesis of a passive probe is erroneous. Indeed, under such an hypothesis of passive probe, in the dark-zone (i.e. zone 3, far from any particle) the major contribution would be due to a constant background and no evanescent wave would be revealed. We can remark that, in contrast to this hypothesis, the zone 3 is characterized by evanescent decays ($m(D_p) = 9.31, 1.32$ and $0.64 \text{ nm}$) times a cosine and sine oscillation of periods $18.04, 13.77$ and $3.64 \text{ nm}$, respectively. We can note that the value $m(D_p) = 1.32$ and $0.64 \text{ nm}$ are not significantly in agreement with the accuracy limit of measurement of $D_p$. This reveals a contribution due to the probe hidden in the global flat decreasing signal (see figure 4). Therefore, even in the dark fringes, where the signal is expected to be negligible, one evanescent decreases can be measured: $m(D_p) = 9.31 \text{ nm}$. This measured decay can only be associated to the presence of the probe under illumination. Moreover, under the hypothesis of passive probe, far from any particle, the differences between the dark zone (zone 3) and bright zones (zones 4 and 5) would come from a phase effect between the diffracted field and the background field. In contrast to this, the zones 4 and 5 reveal not only a phase effect but also evanescent decay lengths $m(D_p)$ equal to $25.32$ and $8.07 \text{ nm}$ ($8.07 \text{ nm}$ may be doubtful (table 2)) in zone 4 and $19.06 \text{ nm}$ in zone 5 (the value $3.58 \text{ nm}$ is out of the accuracy limit). The values $19.06$ and $25.32 \text{ nm}$ differ from more than $30\%$ and show that the exponential decay differs in the complex intensity pattern (zone 5) from the bright fringe (zone 4). The obvious trace of the probe can be observed in some zones of the sample. This fact may lead to the following conclusion: the image formation cannot be considered as a superposition of evanescent decays and the hypothesis of passive probe is not relevant.

Finally, the zones just above nanoparticles reveal evanescent decay lengths $m(D_p)$ equal to $38.09$ and $14.50 \text{ nm}$ in zone 1 and $29.24$ and $9.99 \text{ nm}$ in zone 2. Such decay lengths $m(D_p)$ cannot be directly related to the sizes of the nanoparticles and/or of the probe, as noted in table 3. This analysis of the parameters of fit clearly shows that a complete model of detection should be used to recover the physical (optical properties and geometry) parameters, including the detection [19].

4. Conclusion

We have studied the influence of the lock-in and the probe vibration on the measurement of the decay length of evanescent waves after reconstruction of the signal from the detected harmonics. We have applied a nonlinear method to fit the exponential decays in theoretically and experimentally reconstructed signals. The number of exponentials in the series has been chosen to get the best accuracy. This method could be applied to any near-field optical signal, recorded through homodyne or heterodyne lock-in detection. Thanks to the reconstruction, no approach curve is necessary and the decay lengths along the vertical direction can be measured directly, from only one lateral scan. In contrast to the usual hypothesis of passive probe and interferometric description of the electromagnetic field, this study reveals that the probe cannot be considered as passive and that the measured decay lengths cannot be directly related to the sizes of the nanostructures and of the probe. Therefore, the only way to interpret the decays is the resolution.
of the inverse problem taking into account the properties of the probes, the nanostructures, and
the substrate [20, 21].

References

[1] Zheng Z, Ming H, Sun X and Xie J 2005 Chin. Opt. Lett. 3 605–7
[2] Micheletto R, Denyer R, Scholl M, Nakajima K, Offenhauser A, Hara M and Knoll W 1999 Appl. Opt. 38
6648–52
[3] Liu Q, Kim J, Fukaya T and Tominaga J 2003 Opt. Express 11 2646–53
[4] Hillenbrand R, Taubner T and Keilmann F 2002 Nature 418 159–62
[5] Bachelot R, Gleyzes P and Boccara A C 1995 Opt. Lett. 20 1924–6
[6] Nesci A, Dandliker R and Herzig H 2001 Opt. Lett. 26 208–10
[7] Tortora P, Abashin M, Mrki T, Nakagawa W, Vaccaro L, Salt M, Herzig H, Levy U and Fainman Y 2005
Opt. Lett. 30 2885–7
[8] Inouye Y and Kawata S 1994 Opt. Lett. 19 159–61
[9] Wurtz G, Bachelot R and Royer P 1999 Eur. Phys. J. B 5 269–75
[10] Knoll B and Keilmann F 2000 Opt. Commun. 182 321–8
[11] Barchiesi D and Grosges T 2005 Opt. Express 13 6519–26
[12] Diziain S, Barchiesi D, Grosges T and Adam P M 2006 J. App. Phys. B 84 233–8
[13] Gradshteyn I S and Ryzhik I M 1994 Table of Integrals, Series and Products (London: Academic)
[14] Zenhausern F, Martin Y and Wickramsinghe H K 1995 Science 269 1083–5
[15] Barchiesi D 2006 Appl. Opt. 45 7597–601
[16] Walford J N, Porto J A, Carminati R, Greffet J-J, Adam P-M, Hudlet S, Bijeon J L, Stashkevitch A and
Royer P 2001 J. Appl. Phys. 89 5159–69
[17] Marple S L. 1987 Digital Spectral Analysis with Applications (Englewood Cliffs, NJ: Prentice-Hall)
[18] Van Labeke D and Barchiesi D 1992 J. Opt. Soc. Am. A 9 732–9
[19] Fikri R, Grosges T and Barchiesi D 2004 Opt. Commun. 232 15–23
[20] Macias D and Barchiesi D 2005 Opt. Lett. 30 2557–9
[21] Barchiesi D, Grimault A-S, Grosges T, Macias D and Vial A 2005 J. Korean Phys. Soc. 47 S166–S174

New Journal of Physics 8 (2006) 263 (http://www.njp.org/)