TIME-FREQUENCY ANALYSIS OF NEAR-FIELD OPTICAL DATA FOR EXTRACTING LOCAL ATTRIBUTES

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ABSTRACT

Near-field microscopy has been developed to characterize optical properties of materials below the diffraction limit. It consists of scanning a probe, which can be of atomic dimensions, a few nanometers above a material surface, and detecting electromagnetic interaction. The resulting near-field optical images are conventionally analyzed by means of Fourier based methods although these data are nonstationary. This observation suggests that time-frequency analysis is potentially a powerful tool for extracting attributes such as local resolution of near-field optical microscopes. In this paper, we use bilinear time-frequency distributions and their optimized version by the AOK procedure to analyze experimental near-field optical and magneto-optical raw images. We show that this approach allows local characterization of optical resolution and separation of relevant optical information from artifacts caused by the scanning probe recording process.

1. INTRODUCTION

Scanning Near-Field Optical Microscopy (SNOM) has been developed to make optical images with spatial resolution exceeding the classical diffraction limit $\sim \lambda/2$ in optical microscopy, where λ is the wavelength of the incident radiation. The basic principle behind SNOM is electromagnetic interaction between the sample of interest and a probe scanned above the surface of this sample (Fig 1). The small dimension of the probe end, approximately 50 nanometers, and the small distance d between the tip and the sample, a few nanometers, may produce resolution far superior to that of an optical microscope. Resolution is mainly a function of illumination conditions, polarization, tip shape, tip and sample materials, and obviously of the distance d. Note that atomic force or share-force feedback is used to maintain d constant. Traditionally, resolution is qualitatively assessed by visual inspection of standard samples, and estimated using sharp edge 10%-90% criterion or Fourier based methods. There is evidence that these methods are not ideal for nonstationary data, and depend on some arbitrarily selected optical resolution criteria. In addition, they cannot be applied automatically since they require to discriminate relevant near-field information from artifacts that may be caused by the scanning probe. As a solution to this problem, it has been recommended to perform local characterization of relevant information in recorded data. For example, local resolution has been estimated using pseudo modulation transfer function in [1], and 1D wavelet analysis in [2, 3, 4]. These methods investigate spectral characteristics of each scanning line. For example, entropy has been used with tree analysis in [2], and energy of scanning lines has been considered in [3]. In [4], the first level of wavelet analysis has been used, without proposing any optical resolution criterion. A discussion on 1D and 2D signal processing methods in scanning probe microscopy can also be found in this paper. The authors show that 1D methods are suitable since piezo actuators can generate steps or tip rubbing between consecutive scanning lines.

Another potential approach for characterizing SNOM images is to represent them in the Time-Frequency (TF) domain. For practical reasons, candidate methods must be non-parametric. In addition, every signal component must be precisely located in the resulting representations, and the

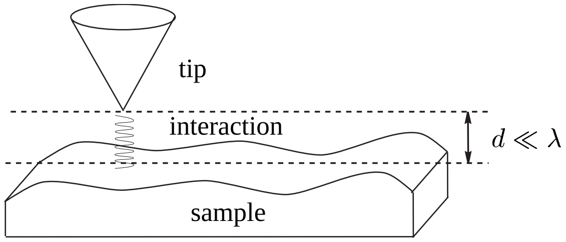


Fig. 1. Principle of scanning probe microscopy.

latter must satisfy the time and frequency shift covariance property. Cohen's class TF distributions satisfy these criteria [5, 6]. In this paper, we show the reliability, flexibility and efficiency of these tools to process near-field optical data compared with Fourier based methods [7] traditionally used in scanning probe microscopy. This paper is organized as follows. Cohen's class TF distributions and their optimized version by the Adaptive Optimal Kernel (AOK) procedure [8] are introduced in Section 2. In Section 3, this approach is applied to experimental data and results are compared with [7]. A new application which consists in separating relevant optical signal from artifacts inherent to the scanning probe technique is proposed in Section 4. Finally, some concluding remarks are presented in Section 5.

2. TIME-FREQUENCY ANALYSIS

2.1. Bilinear TF representations

Time-frequency analysis plays an important role in signal processing since it extends the usual spectral analysis by making it time-dependent. A lot of theoretical work has been achieved and many different classes of representations, parametric or not, have been proposed. Most of the non-parametric solutions of current interest belong to the Cohen class. The latter comprises all the bilinear distributions ρ_x that are covariant with respect to time and frequency shifts of the signal [5, 6]. This particular class is defined as

$$\rho_x(t, f; \Pi) = \iint W_x(u, v)\, \Pi(u - t, v - f)\, du dv. \quad (1)$$

Here, Π is a 2D-parameterizing kernel and W_x represents the Wigner distribution

$$W_x(t, f) = \int x\left(t + \frac{\tau}{2}\right)\, x^*\left(t - \frac{\tau}{2}\right)\, e^{-2j\pi f\tau}\, d\tau. \quad (2)$$

The Wigner distribution plays a central role in the Cohen class. Its usefulness partly derives from the fact it satisfies many desirable properties. In particular, it offers optimal joint time and frequency resolutions, which means that signal components are optimally concentrated in the TF domain. However, the readability of the Wigner distribution is dramatically affected by troublesome interference terms that are inherent to its bilinear structure. To overcome this drawback, distributions that are parameterized by low-pass kernels Π to exploit the convolutive form (1) have been proposed [5, 6]. However, while this smoothing procedure attenuates the interferences in W_x, it also spreads out the components of the signal x, called auto-components, in the TF domain.

2.2. Signal dependent TF representations

In the recent years, it has become evident that no single kernel can enhance significantly the readability of W_x for a large class of signals. Hence there has been increasing interest in signal-dependent TF representations in which the kernel Π varies with the signal [9]. Such representations perform much better than fixed-kernel one. However, these techniques provide a single kernel for the entire signal, forcing compromises in the kernel design for signals with multiple components. This can be improved by an adaptation of the kernel Π over time and frequency to match the local signal characteristics [8, 10, 11]:

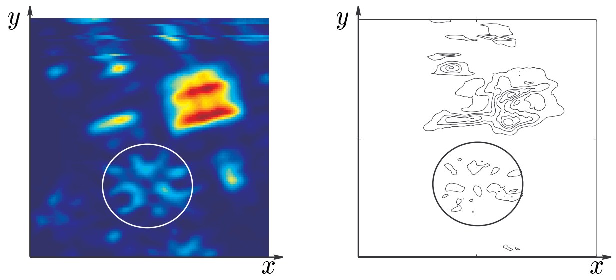
$$\rho_x(t, f; \Pi_x) = \iint W_x(u, v)\, \Pi_x(u, v; t, f)\, du dv. \quad (3)$$

In this direction, the AOK procedure [8] is a powerful tool for designing signal-dependent radially Gaussian kernels that adapt over time. This technique performs well for a large variety of signals and the resulting representations remain covariant with respect to time and frequency shifts. In addition, the implementation proposed by the authors allows on-line adaptation of the kernel, and supports running computation of TF representations optimized by the AOK procedure.

In this paper, we shall apply this TF distribution to experimental SNOM images, selecting one scanning line $y(x)$ at a time. Here x and y denote columns and rows of images, respectively. This kind of TF analysis provides 4D representations parameterized by $\{x, y, f_s, \rho_{y(x)}(x, f_s)\}$, where f_s denotes spatial frequency along every scanning line $y(x)$. For practical reasons, f_s can be fixed beforehand for representing such distributions, as shown in this paper.

3. CHARACTERIZATION OF LOCAL OPTICAL RESOLUTION OF SNOM IMAGES

We shall now apply the TF approach to a classical near-field optical image, and we shall compare the result with [7]. In that paper, the same data have been processed with a Fourier based method, selecting one scanning line at a time. The optical resolution, defined by a cutoff frequency estimated



(a) (b)

Fig. 2. Characterization of the optical resolution of a SNOM image. (a) SNOM image. (b) TF analysis ($f_s = 0.46875$).

over spline-fitted spectrums, was 153 ± 17 nm. Since every line is 7000 nm long and is sampled by 128 pixels, the corresponding normalized frequency approximately equals 0.36 ± 0.04. Note that this frequency is supposed to correspond to the limit between relevant optical information and noise, the latter having a high-frequency content.

Using TF analysis, any given frequency can be precisely localized in the SNOM image, even if it is greater than the cutoff frequency. Fig 2.(a) shows the near-field optical data considered both in this paper and in [7]. Fig 2.(b) presents a TF analysis of this image at the normalized frequency 0.46875, obtained with a bilinear distribution modified by the AOK procedure. This representation shows that relevant patterns with spatial frequency content higher than the cutoff frequency exist in some regions of the optical image, e.g., the structure indicated by the white ellipse. This means that the estimation procedure for determining the cutoff frequency failed, the hypothesis of high level of noise in high frequencies being incorrect in this case. TF approach is then a powerful tool to analyze SNOM images since it provides a local characterization of spatial frequencies that is useful in scanning probe microscopy.

4. SEPARATION OF OPTICAL INFORMATION FROM ARTIFACTS

A potential application of TF analysis is separating relevant optical information from artifacts caused by the SNOM imaging process [2]. In this section, we analyze a magneto-optical SNOM image of a magnetic material deposited on a transparent substrate.

Our system consists in a commercial Atomic Force Microscop (AFM) coupled with an inverted optical microscop. It records simultaneously SNOM images (magneto-optical data) and AFM images (topographical data) as follows. By diffracting near-field above the material surface, the commercial AFM silicon probe that we use also plays the role of near-field optical probe. This probe vibrates vertically near its resonance frequency in the non-contact AFM mode. The objective of the inverted optical microscop is illuminated by the collimated beam of a HeNe laser ($\lambda = 632.8$ nm). A polarizer ensures linear polarization of light. The laser beam is focused on the garnet-air-probe interface, passing through the transparent substrate. The near-field diffracted by the probe partly interferes with the light back-reflected by the layer interfaces and the probe cantilever. An analyzer is placed into the detection path, crossed with the polarizer orientation. With this configuration, described in more details in [13], our SNOM system is sensitive to walls between domains of opposite magnetization. However, it is also very sensitive to topographic features of the surface. This information is considered as an artifactual consequence of aforementioned interferences and is unwanted in magneto-optical images.

In this section, the sample of interest is an iron garnet layer of 7 microns thickness deposited on a transparent substrate. It is composed of micron-size stripes and bubbles with magnetic direction perpendicular to the layer plane. Figs 3.(a) and 3.(b) are 10 by 10 microns SNOM and AFM images of this sample, respectively. Comparing them, we note that the SNOM image contains both information on magnetic structures (the bubble $\mathcal{B}$ and the stripe $\mathcal{S}$) and topographic artifacts (e.g., the line and the dust located by the arrows). In certain cases, these two kinds of information may be correlated. In the present case, they should be discriminated with spatial frequency information since the size of topographic features is lower than 100 nm. With this aim in view, we have performed a TF analysis of the AFM image presented in Fig. 3.(a) using a distribution modified by the AOK procedure presented in Section 2. Choosing a relatively low normalized frequency, e.g. 0.0430 in Fig. 3.(c), the TF analysis shows only magnetic structures whereas topographic features have disappeared. On the contrary, only artifacts are visible when one consider larger normalized frequencies, e.g., 0.1992 in Fig. 3.(d). This result conforms with theory and demonstrates the ability of TF analysis to separate relevant optical signal from artifacts inherent to the scanning probe technique.

5. CONCLUDING REMARKS

Due to specificity of near-field optical data, the community of microscopists has indicated the need to define carefully the concept of optical resolution and to perform local characterization of spatial frequency information. In this paper, we have shown that TF representations are powerful tools to analyze SNOM images compared with Fourier based methods traditionally used in scanning probe microscopy. As an example, they allow to discriminate relevant near-field information from artifacts caused by the AFM feedback. Note that the latter is required for maintaining the distance between the probe and the sample of interest constant. To complete the work begun in this paper, our approach should be used to estimate optical resolution and should be generalized to other scanning probe microscopies, where objective quantification of information in experimental and theoretical images remains partly unsolved.

6. REFERENCES

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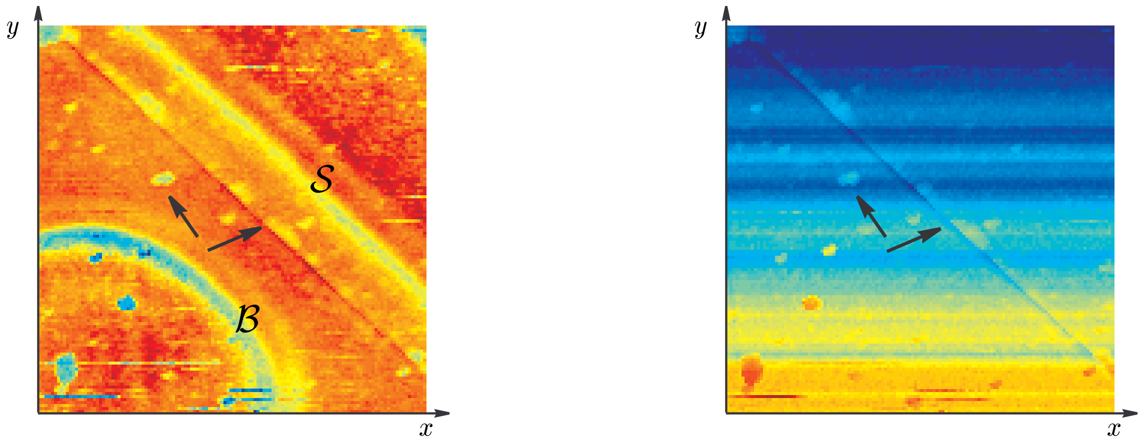
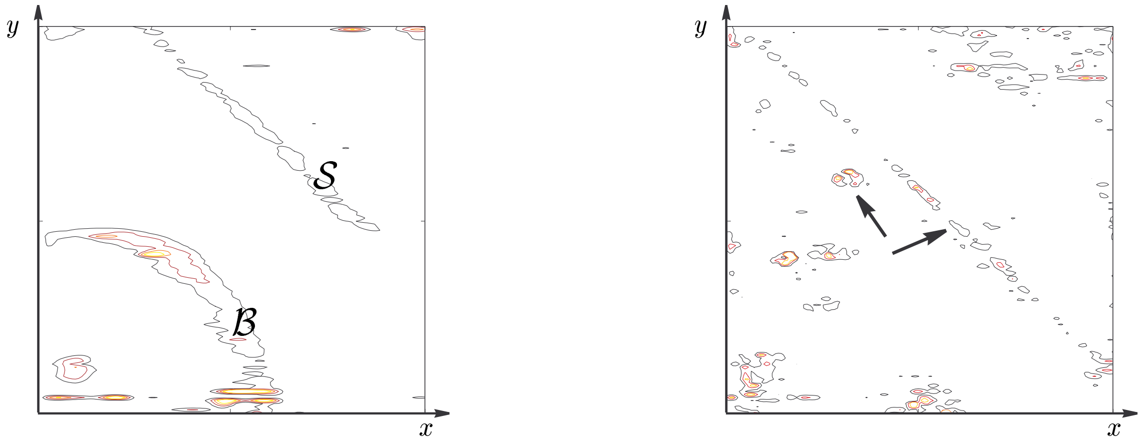


(a) SNOM image

(b) AFM image



(c) TF analysis of the SNOM image ($f_s = 0.043$)

(d) TF analysis of the SNOM image ($f_s = 0.1992$)

Fig. 3. Separation of relevant optical information from artifacts caused by the SNOM imaging process.

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