Near-field Projection Optical Microscope (NPOM): A New Approach to Nanoscale Super-Resolved Imaging

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Abstract

A new super-resolution method, entitled Near-field Projection Optical Microscope (NPOM), is presented for near-field measurements and imaging. This novel imaging concept enables to reconstruct nanoscale measured objects without the need to scan them on the surface, as usually done in existing analysis methods such as NSOM (near-field scanning optical microscope). The main advantage of the proposed concept, besides lack of mechanical scanning mechanism, is in the fact that the full field of regard/view is obtained simultaneously and not point by point like in scanning configuration and in addition, by using compressed sensing, the number of projected patterns that decompose the spatial information of the inspected object, can be smaller than the obtainable points of spatial resolution. In this paper, in addition to the mathematical formalism, series of complementary numerical tests were performed, using challenging objects and patterns to prove the accuracy of the reconstruction capabilities. As expected, the accuracy will increase with the number of projected patterns.

Introduction

As explained above, NPOM is a new method dedicated to near-field microscopy, and sharing super-resolution capability, but without the need to scan the surface. Instead of physical scanning, the method uses special patterns and gets a reading in the sensor for each pattern (equation 1). From the reading in the sensor for each pattern and pattern function, it is possible to reconstruct the object (equation 2). It is possible to numerically demonstrate (in addition to above analytical development), that the original object is well reconstructed. If the method's resolution is independent of the size of the sensor, it is dependent on the quality and the quantity of the patterns. Fig. 1 presents schematics of the setup.

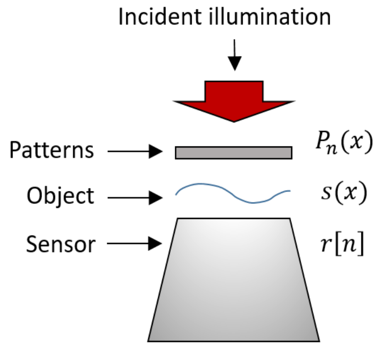

Fig. 1. NPOM setup's components.

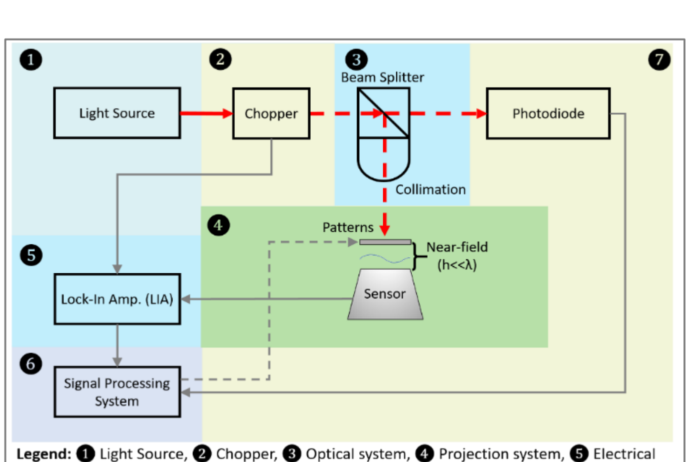

Fig. 2. Experimental design.

1D Visualization Results

We start the visualization process while using first *sin* and *cos* patterns. The reason why there is a specific usage of these functions is because we need to support the reconstruction of both even functions (*cos*) and odd functions (*sin*).

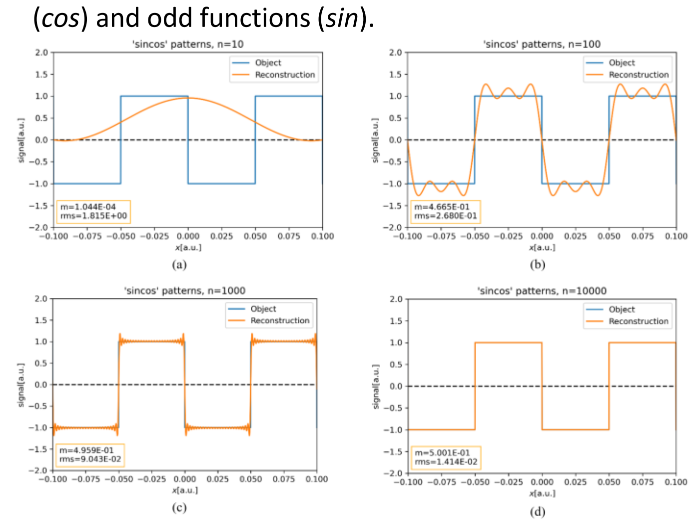

Fig. 3. Reconstructed images for several representative numbers of patterns. (a) n = 10; (b) n = 100; (c) n= 1000; (d) n = 10000.

2D Visualization Results

The next legitimate question would be: "Can we get an accurate reconstruction while using 2D *random* patterns"? The answer is positive, but this time, the test became more challenging, since *random* patterns were chosen. One can discover the original shapes of the object (insert in Fig. 5), becomes more clear and accurate. While Fig. 5(a) and 5(b) are still far from the full reconstruction, and only few series of signs are identifies, in Fig. 5(c) and 5(d), one can already read the caption "USAF-1951" of the US Army resolution test chart. The projection method of the NPOM is clearly demonstrated, while the success criteria parameter is the number of iterations: The higher the number of iterations, the accurate the obtained picture.

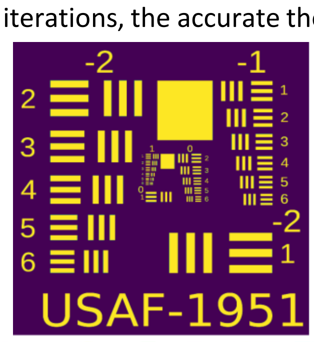

Fig. 4. US Air Force resolution test chart.

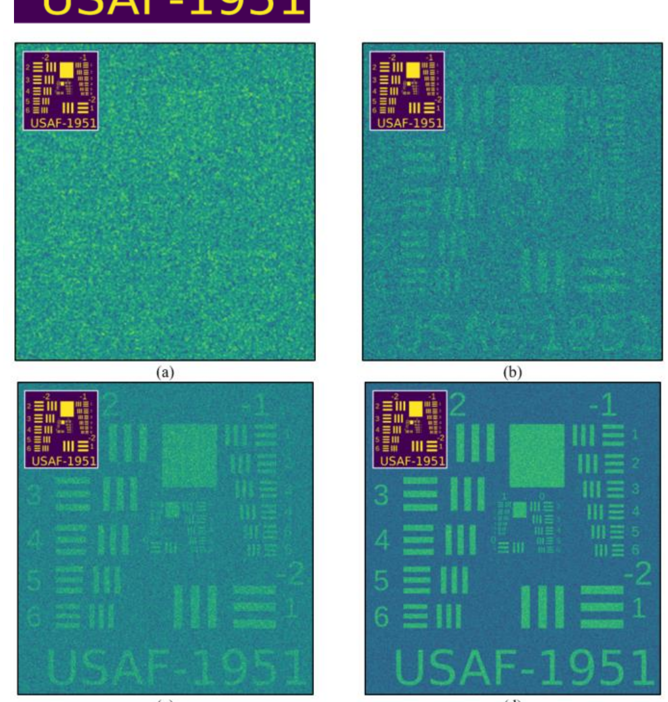

Fig. 5. Usage of *random* patterns with Moving-Average-Filter (MAF). (a) n = 1000; (b) n =10000; (c) n = 100000; (d) n = 1000000.

Mathematical Reduced Formalism

We will denote by $P_n(x)$ the set of projected patterns. They can be *random* patterns acting as an orthogonal base used for compressed sensing decomposition. We assume we have N such patterns (the number of the functions in the decomposition base). We will denote by s(x) the object that is to be imaged. The readout value we get per projected pattern of $P_n(x)$ is:

$$r[n] = \int s(x) P_n(x) dx \quad (1)$$

In case that compressed sensing is to be applied, then the restoration problem with sparsity constraints is formularized as follows:

$$rect(x\nu_0) \sum_n exp\left(-2\pi i n \nu_0 (x - x')\right) = \delta(x - x') \quad (2)$$

Therefore, we will obtain the desired reconstruction

Preliminary Conclusions

We presented a new method to analyze the near-field without the need of physical scanning. The method consists from patterns projection and not scanning of the nanometric probe. The main advantage of the proposed concept besides lack of mechanical scanning mechanism, is in the fact that the full field of regard/view is obtained simultaneously and not point by point like in scanning configuration and in addition, by using compressed sensing, the number of projected patterns that decompose the spatial information of the inspected object, can be smaller than the obtainable points of spatial resolution. Mathematical formalism and complementary numerical visualization were presented in order to demonstrate the accuracy of the method. Looking at these combined analytical and numerical analyses, one may reach the following preliminary conclusions:

1. In spite the fact that *sin* and *cos* patterns are more difficult for fabrication, they definitely provide better results.
2. On the contrary, *random* patterns may be easier for fabrication, however a big quantity is required as well as the usage of other tools, in order to get acceptable reconstruction.
3. The resolution of the method is limited by:
   a. The pattern resolution itself. Dense enough patterns will enable super-resolution. However, it remains limited by the distance between atoms/molecules in the material.
   b. The number of patterns. For good enough acceptable accuracy, one could observe that using sin and con patterns required few hundreds in order to distinguish an object, sharing tenth of the pattern itself.
4. The patterns accuracy should be known in advance, so anyway, it seems we may need using microscope for the patterns themselves.

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