Spatial (super)resolution of nanometric objects: Periodic structure and 'Single' object

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ABSTRACT

The optical scanning microscopy resolution is limited by the numerical aperture NA of the objective and the wavelength of the light. However when an optical property of the object changes under the influence of the laser spot, detection of details smaller than the optical diffraction limit becomes possible. In optical disk the object can easily be provided with nonlinear optical materials enabling superresolution. We study in this paper the difference in behaviour between a periodic structure and a 'single' mark.

Key words: Superresolution, periodic structure, 'single' object, non linear material, ROM

1. INTRODUCTION

With the advent of high definition television and the ever increasing storage demands resulting from the Internet, higher capacity storage systems are an ongoing requirement. Optical storage has proven to be an excellent medium for such storage needs; however, increasing the capacity of optical recording in the far-field optical diffraction limit is restricted by the minimum resolvable spacing given by the resolution limit or Rayleigh's criterion $0.61\lambda_0$ /nsinθ where λ_0 is the wavelength of the light, θ the aperture of the objective and n the refractive index of the medium of the object space.

The drive towards higher storage densities in the far-field limit is thus reaching a significant technological and cost limit with the use of lasers in the UV range. To circumvent such issues, the use of optical near-field recording techniques has been an active area of research. Most techniques (metallic coated cone shaped fibers, metallic diffusing tips, Solid Immersion Lens, ….) require to control very precisely the distance between the near field source and the recording area. This requirement might be a brake on the removability and/or the handling of the disc.

Hence super-resolution [1,2,3,4] appears to be a promising technique which implies a "super-resolving" structure using only thin film technology and is a candidate to be a likely successor to the next generation of Blu-ray discs since it combines removal and backwards compatibility with earlier optical storage media.

In this paper we propose to analyse from a purely optical point of view how it becomes possible to read and resolve smaller marks than the resolution limit of the objective. We consider two extreme cases: the first case treats the behaviour of a periodic structure (with a period less than the resolution limit) and the second case deals with the case of the detection of a single mark (always with a dimension less than the resolution limit). This paper is the starting point to study the readout process -using the 'super-resolution effect'- of a mixed signal with different pit (space) lengths and to underline the difficult points and their consequence on the signal treatment analysis or on the current tacking servo-system method… .

2. CASE OF A PERIODIC STRUCTURE

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A limited object diffracts both propagating ($|k_{x\ lim}| \leq \omega/c$) and evanescent ($|k_{x\ lim}| > \omega/c$) waves. They correspond to radiative components of the field (which propagate and can consequently be captured after a long distance) and to non radiative components.

The Fourier transform allows to analyze the 'frequency content' of a signal and the resolution can most easily be judged with the aid of this frequency response function. In the case of an infinite periodic structure with a period 'a', we obtain in the Fourier plane a diagram with discrete orders which gives the characteristic spatial frequencies of the object, the spacing between the harmonics being 2π /a. The diffracted waves in the order 0, +1 and -1 correspond respectively to the spatial frequencies 0, 2π /a and -2π /a. The waves in the order 0 don't contain information about the spatial frequency content of the object; it is only the greater orders (…, -2, -1, +1, +2, …) related to the higher frequencies which yield information about the details of the object. From this remark, we can evaluate what is the minimum dimension 'a_{min}' for the period 'a' of the object to keep the diffracted orders +1 and -1 in the propagating region. We find $a_{min}=\lambda_0/n$ (Figure 1).

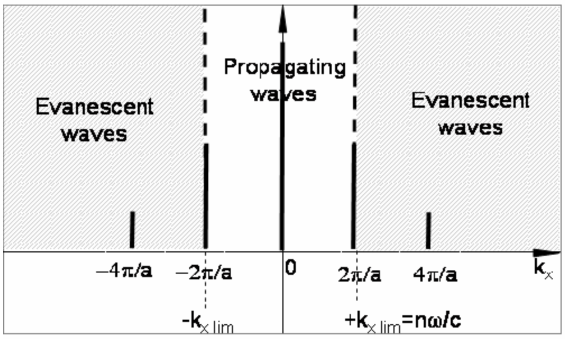

Figure 1: Condition on the period 'a' of the structure to have the first-order diffracted beams (+1 and -1) in the propagating region.

If the case of λ_0=405 nm and n=1.6 (index of the medium -polycarbonate- of the object at the blue wavelength), we find a_{min}=253 nm. With a numerical aperture of 0.85, a_{min} increases up to 297 nm. So it is clear that for a period of 160 nm for example the orders +1 and -1 don't propagate, they are outside the light cone. In this case only the fundamental frequency (k=0) is collected in the objective which is uniformly lighted, it is impossible to detect the periodic structure of the object.
We have experimentally observed this behaviour during readout using a 405 nm light on ROM media with 80 nm pit through single frequency signal (the period a=160 nm in this case. See Figure 2). As it can be seen on Figure 8, at low readout power it is impossible to detect these marks (CNR=0 dB).

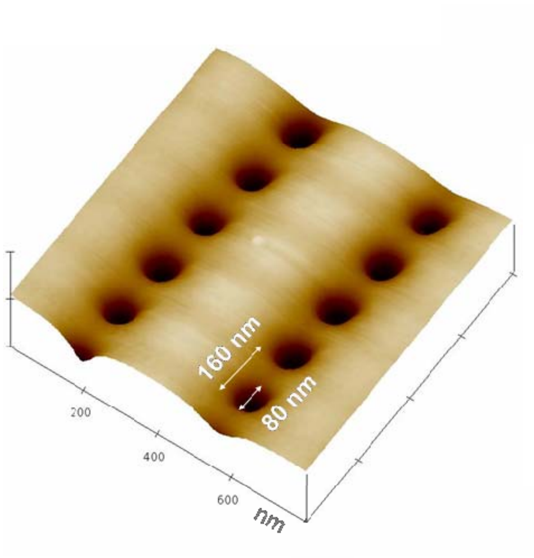

Figure 2: AFM image of the periodic structure. The dimension of the pits is 80 nm and the period a=160 nm.

In order to test the validity of the hypotheses proposed above we have made numerical experiments using the finite difference time domain method (FDTD). The simulated structure is shown Figure 3: the incident light (λ_0=405 nm) is directed on the structure through a lens of numerical aperture 0.85 (we can see the spatial distribution of the source above the periodic structure of the media). The focused spot size is 2.85 times greater than the pit size. The detector is shown at the top of the figure and allows to calculate the reflected power (integration of the Poynting vector).

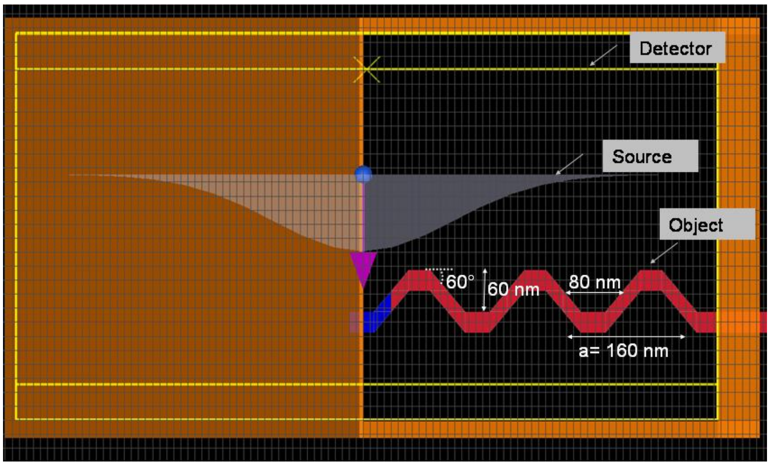

Figure 3: Geometry used in the FDTD simulation.

In agreement with the experimental results, we don't measure numerically any difference in reflectivity when the laser beam is centred on a pit or between two pits. The reflectivity contrast is null and the pits are not detected.

We can then wonder how to detect these small marks (embedded in a periodic structure). A way to create a reflection dependence of the marks is to break the periodicity of the structure. This can be done either by decreasing the spot size or by creating a local "defect" in the periodic structure. In the latter case, we can introduce such perturbation by using a non linear material whose optical properties varies locally and in a reversible way under the focused laser beam. Schematically (Figure 4) we consider in this case a single object (with a modified index) in a medium with an effective index (this medium is the periodic structure). So if we look at what happens in the Fourier plan, we have always the contribution of the periodic structure with the presence of the fundamental frequency but we add the contribution of the small modified area which contains higher spatial frequency information and more details of the object (Figure 5).

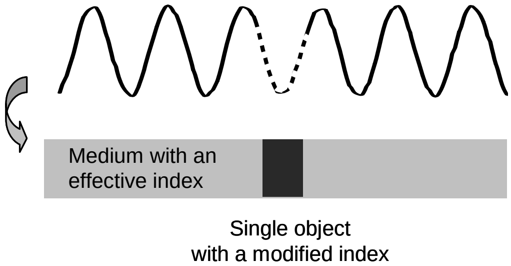

Figure 4: Schematic representation of a local optical change of the object embedded in the periodic structure. The equivalent optical structure may be described as a single object (with a modified index) within a homogeneous medium (with an effective index).

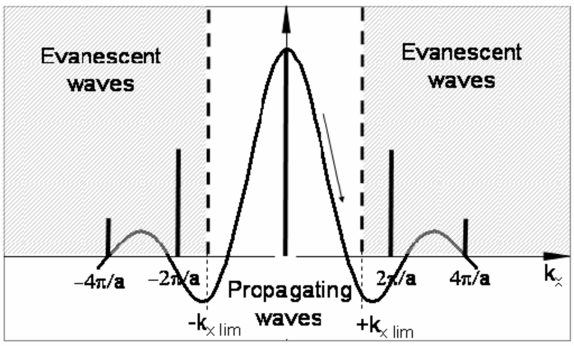

Figure 5: The structure described above (cf. Figure 4) allows to introduce higher spatial frequencies in the spectrum.

According to a previous paper more based on the physical processes underlying the nonlinearity in specific materials [5], we consider a material whose reflectivity increases with the readout power and through FDTD simulation we look at the influence of the local optical changes of the material on the reflection when the spot is centred on a pit or between two pits. We have evaluated the influence of the dimension of the modified area from 0 to 250 nm (Figure 6). We expect that the different geometries of the involved patterns (when the laser beam is centred on a pit or between two pits) will induce a difference in the reflectivity signal.

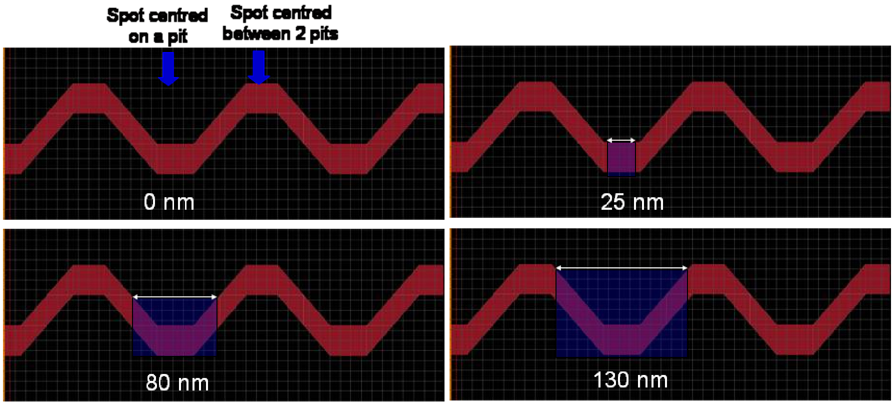

Figure 6: Size of the optically modified area from 0 (no change of the optical properties of the medium) to 130 nm.

We can see on Figure 7 that the optical contrast (defined as the difference in reflectivity when the spot is centred between two pits and when the spot is centred on a pit) varies and gets an optimum for 80 nm. In agreement with the above mentioned hypotheses we can see that it becomes possible to detect numerically these marks. Note that when the dimension of the optically modified area becomes too large (∞), the periodicity of the structure is restored and the marks are no more detected. Figure 8 shows our experimental results obtained on the ROM media with 80 nm pits (shown Figure 2) and covered with a film of the material mentioned above instead of the standard aluminium mirror. CNR of more than 40dB are measured at the optimal readout power and this signal is sufficiently high to observe a waveform by using an oscilloscope.

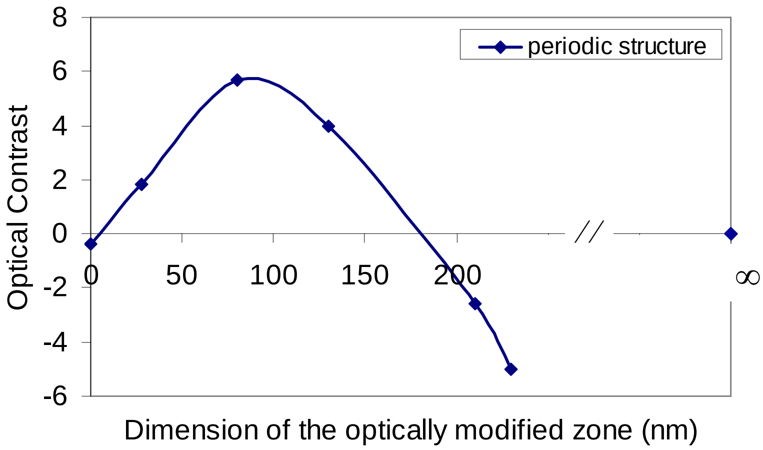

Figure 7: Calculated reflectivity contrast (contrast= reflectivity between 2 pits – reflectivity on pit) versus size of the optically modified zone.

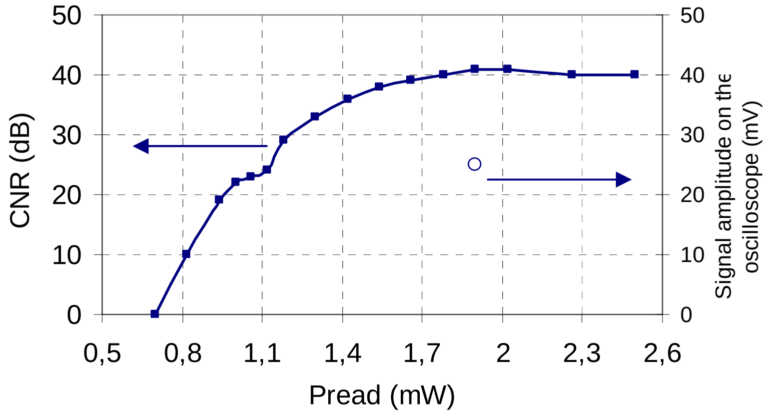

Figure 8: Measured CNR (and corresponding signal amplitude on the oscilloscope) versus readout power when reading the periodic structure shown Figure 2.

3. CASE OF A SINGLE MARK

In a real signal we can encounter patterns corresponding to single frequency signal as previously described but we can also have the opposite case where the mark is isolated (between two long spaces for example). We can then wonder if it is possible to detect this mark whose size is less than the resolution limit of the objective.
We see that this case is very similar to the one treated in the previous paragraph, we have to consider a single object (the pit) in a homogeneous medium (Figure 9).

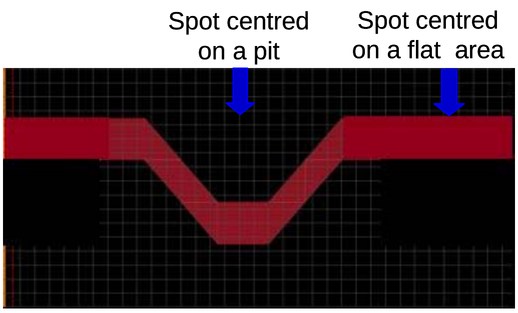

Figure 9: Schematic representation of a 'single' mark.

We have then numerically measured the contrast in reflectivity between the pit and a flat area as a function of the dimension of the locally modified area varying from 0 to 250 nm. A contrast appears even without changes of the optical properties of the material. We see that the contrast has an optimum for a modified area of 80 nm (Figure 10). So it appears clearly that it is possible to detect an isolated mark with a contrast close to the one obtained on a periodic structure. Moreover the optimal contrast is obtained in both cases for the same dimension of the modified area (80 nm in the case of our material) which means that the optimal readout power is the same for an isolated mark and for a mark embedded in a periodic structure.

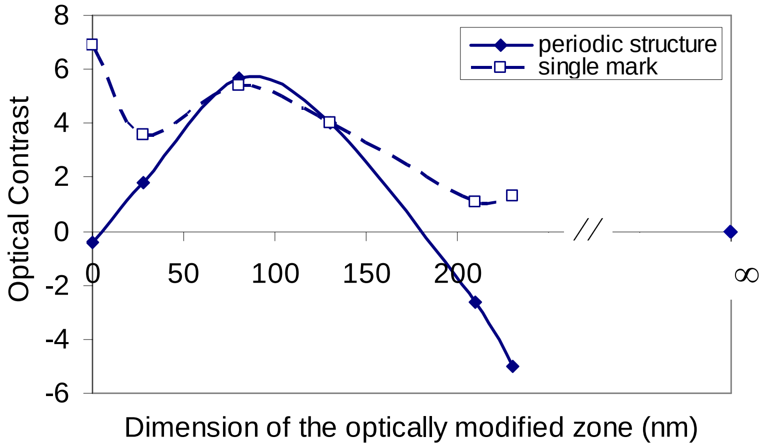

Figure 10: Comparison of calculated reflectivity contrast versus size of the optically modified zone in both cases: Dashed line: case of a 'single' object. Continuous line: case of a 'periodic structure' (cf. Figure 7).

4. CONCLUSION

In this work we have seen that the periodicity of a structure less than the resolution limit prevents the resolution of the object. It is necessary to break this periodicity with the use for example of a non linear material to introduce in the propagating area ($|k_x| \leq \omega/c$) (we use a far field detection mode) higher frequencies which yield information about the smaller details radiative components.

We have shown that it is possible to detect an isolated mark with the same optical contrast than a mark in periodic structure. The optimal readout power is the same for both structures. These two observations are encouraging results for the readout process of random patterns. However we have studied in this paper only two extreme cases. We have to look at now in more details what would happen in a pattern where there is mixed signal with various pit and space lengths. The development of the more adapted subsequent signal treatment is one of our main targets.

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