A numerical model for super resolution effect in optical discs.

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ABSTRACT

A simplified computational model for super resolution effect in optical discs is proposed and simulations are compared with experimental results, providing basic understanding of this phenomenon. Simulations show that resolution beyond the diffraction limit is achieved and signal destruction occurs at some frequencies when the super resolution layer is activated.

Keywords: Super resolution, nonlinear layer, readout model, signal destruction

1. INTRODUCTION

The resolution in Optical Data Storage (ODS) was pushed further with the recent Blu-Ray technology. By focusing a 405nm laser with a high numerical aperture lens (NA=0.85), the Blu-Ray system can resolve data marks as small as 138nm. To increase the current Blu-Ray's capacity one could either reduce the wavelength used to ultra-violet (UV) or increase the numerical aperture. On the first case, it is hard to find suitable materials in the ultra-violet (UV) regime. For NA > 1 a solid immersion lens (SIL) has to be used, which results in a substantive increase in complexity of the optical disc system. For these reasons an alternative techniques has to be considered for the next ODS generation. Another possible way for the next generation is to use a nonlinear effect to overcome the diffraction limit. This was first reported by Bouwhuis¹ for optical data storage application and is named Super-Resolution (SR). In this paper, he suggests that if a nonlinear material is used as a layer in an optical disc, then all diffracted orders would be wider than usual, in such way that it would be possible to have overlap among higher orders within the zeroth order even after the cut-off frequency, breaking the diffraction limit. More recently, a similar technique was demonstrated by Tominaga² by using a thin Sb film as nonlinear layer. He was able to observe modulated signal beyond the diffraction limit and the technique was called Super Resolution Near Field (SRens), becoming a very promising technique for the next generation of ODS.

The figures 1(a), 1(b) and 1(c) show the idea behind the super resolution effect. The SR layer has a refractive index which changes with the laser intensity. If the incident laser intensity is above a certain threshold, then the refractive index of the material abruptly changes, creating a small area with different optical properties. In this way, the laser spot can be smaller than $\lambda/2NA$. As an example of such materials, one can see in the figure 1(a) the refractive index values for a AgInSbTe (AIST) layer below and after a threshold. Figure 1(b) shows the formed beam in the layer stack and the figure and 1(c) shows the overlap of the -1st and +1st expanded orders within the zeroth order, illustrating the SR principle.

In order to understand the super resolution effect, a computational model is required. A complete computer program based on rigorous vectorial diffraction model is expected to perform calculations of four distinct parts: first, the incident field has to be focused by the lens onto the layer stack. Then the field transmitted throughout all the layers must be calculated taking into account the non-linearity of the super resolution layer as a function of the laser power. After that, a vectorial diffraction theory has to be applied to calculate the diffracted field after

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Figure 1. A schematic view of super resolution effect on optical discs. 1(a) The refractive index values before and after the threshold limit for an AgInSbTe(AIST) based layer. 1(b) An aperture is created in the super resolution layer if the laser intensity is above the threshold. In this way, a spot smaller than $\lambda/2NA$ can be obtained. 1(c) the effect of a nonlinear layer in Fourier space all orders become wider than usual (the inner circle) and eventually fall within the zeroth order resulting in a modulated signal beyond the cutoff frequency.

the interaction with the data structure. Finally, the diffracted field must be propagated back to the objective lens where the readout signal is calculated. The whole procedure suggests that a rigorous vectorial diffraction model would require extremely high computational resources and a long processing time. In the present work, we propose a simplified computational model to describe the SR effect. The model is based on the experimental data given on table 1 and uses scalar diffraction theory to estimate the readout signal behavior, according to Hopkins³ and Milster⁴ models. To verify and validate the results, rigorous vectorial calculation is shown for the field immediately after the layer stack a comparison with some experimental results is also done. The present approach, although not rigorous, can be used to get qualitative description of the problem and the main results can be further investigated in a rigorous way.

2. NUMERICAL APPROACH

2.1 Geometry of the system

The geometry for a readout program based on scalar theory is shown in figure 2. We keep the classical transmission set-up for simplicity. The input field distribution in the objective lens $f(x, y)$ is focused onto the disc surface, which can be calculated by taking the Fourier transform of the input field ($U(u, v) = \mathcal{F}[f(x, y)]$). After interaction with the disc structure ($A(u, v) = R(u, v) * U(u, v)$), the field is propagated to the collector lens by means of an inverse Fourier transform ($g(x, y) = \mathcal{F}[A(u, v)]$). The diffracted field distribution is finally integrated over the pupil lens area giving the readout signal ($I_f = \iint |g(x, y)|^2 dx dy$).

Figure 2. Light path for readout system using scalar diffraction theory. The input field is focused by a lens onto the disc surface and diffracted back to the collector lens after interacting with the disc data. The readout signal is calculated by integrating the field distribution over the collector lens.

2.2 Making a correct Fourier transform

Fourier transforms can be easily calculated by the Fast Fourier Transform (FFT) algorithm. However, phase information can be lost during the process if the algorithm is not correctly applied. To make the correct transformation, one need to discretize the function $F(u) = \int_{-\infty}^{+\infty} f(x)e^{(-2\pi i u x)} dx$ in a sample grid and then compare the result with the FFT definition. Using the software package Matlabtm, the FFT algorithm in one dimension is defined as

$$F(u(k)) = \sum_{j=1}^N f(x(j))e^{[-\frac{2\pi i}{N}(j-1)(k-1)]} \quad (1)$$

where $j = 1 : N$, $k = 1 : N$ and N is the total number of points. Usually, we choose $f(x)$ within $x \in [-x_{max}, x_{max}]$ dividing the whole interval in N points. In this case, $\Delta x = \frac{2x_{max}}{N-1}$ is the smallest resolution in the grid and therefore we have $x(j) = -x_{max} + (j+1)\Delta x$. The same holds for the variable u : $u \in [-u_{max}, u_{max}]$, and $u(k) = -u_{max} + (k-1)\Delta u$, where $\Delta u = \frac{2u_{max}}{N-1}$. Substituting $x(j)$ and $u(k)$ in the discretized function, we reach, after some manipulations

$$F(u(k)) = e^{2\pi i u(k)x_{max}} \sum_{j=1}^N \{f(x(j))e^{2\pi i [x(j)+x_{max}]u_{max}}\} e^{-2\pi i [\Delta x \Delta u (j-1)(k-1)]} \Delta x \quad (2)$$

We recognize the FFT definition (equation 1) on the second exponential term after the summation if we set $\Delta x \Delta u = \frac{1}{N}$ and define $f'(x(j)) = f(x(j))e^{2\pi i [x(j)+x_{max}]u_{max}}$. Thus, equation 2 can be written as

$$F(u(k)) = \text{phase} \sum_{j=1}^N f'(x(j))e^{\frac{-2\pi i}{N}[(j-1)(k-1)]} \Delta x \quad (3)$$

The conclusion is that, to perform a correct FFT calculation, one has to use the modified function $f'(x(j))$ and add manually the extra phase term. Another alternative is to use the built in function called `fftshift` together with FFT on the primitive function $f(x(j))$. But the extra phase still has to be added. To summarize, a correct Fourier transformation will be

$$F(u(k)) = \text{phase} * \text{fftshift}(\text{FFT}_{\text{Matlab}}) * \Delta x \quad (4)$$

2.3 Adding super resolution effect

It is well known that the refractive index of the SR material shows two values depending on the laser intensity being above or below a given threshold (figure 1(a)). Based on this fact, we simulated the SR effect in the following way: first, a routine searches in the focused field where the intensity is below and above this threshold (its value is defined in arbitrary units, for simplicity) and then, the layer effect is taken into account by means of $\exp(ikzn)$, where k is the wave vector, z the layer thickness and n the refractive index that can take values either below or above the threshold (see table 1). The result is the modified beams shown in the figures 3(a), 3(c) and 3(b).

Figure 3. Focused spot beams. 3(a) is the focused beam intensity distribution for $\lambda = 405nm$ and $NA=0.85$ in air, without any layers. 3(b) and 3(c) are the focused beam when an AIST or InSb layer is present, respectively. The table 1 gives the refractive index and the layer thickness used in our simulations. The calculated field distribution will be propagated forward after interacting with the disc.

This approach only takes into account the changes in the refractive index in the layer, neglecting any possible scattering after the aperture. In this way, this can be seen as a first approximation for the super resolution effect.

Table 1. Refractive index of AIST and InSb materials used as a layer in our simulations.

Material	Refractive index below threshold	Refractive index after threshold	Thickness
AgInSbTe (AIST)	$2.66+3.3i$	$2.87+2.94i$	25nm
InSb	$3+2.73i$	$2.1+3.4i$	20nm

2.4 Vectorial Calculation on Focal Region

A rigorous approach for the focused beam in the vicinities of the focal region can be found by solving the following diffraction integral.⁵

$$\vec{E}(\vec{r}) = -\frac{i}{2\pi} \iint_{\Omega} \frac{\vec{a}(k_x, k_y)}{k_z} (x) e^{i\vec{k} \cdot \vec{r}} dk_x dk_y \quad (5)$$

where the integration domain Ω is the exit pupil of the system, $\vec{k}$ is the propagating vector and $\vec{a}(k_x, k_y)$ is the vector amplitude of the electrical field. An extension of this theory, which provides the field distribution after a multilayer structure was used to calculate rigorously the field distribution in the focal plane, for the layer depicted in figure 4.⁶

Figure 5(a) shows the total field distribution for a focused beam when $NA=0.85$ and $\lambda = 405nm$ and no layers are present. Figures 5(b), 5(c) and 5(d) show the components of a circularly polarized electric field incident on

Figure 4. Layer stack used in our simulations. A 25nm AIST (or 20nm InSb) layer sandwiched between two 50nm dielectric layers (ZnS:SiO₂, n=2.2) on top of a substrate layer (n=1.5).

Figure 5. Focused fields distribution. The figure 5(a) is the focused field distribution for NA=0.85 and $\lambda = 405nm$ when no layers are present as result of the equation 5. Figures 5(b), 5(c) and 5(d) shows the z, y and x components of a circularly polarized electric field incident on the layer stack of the figure 4 by applying the calculation method described in.⁶

the layer stack of the figure 4. The simulation of the SR effect in the vectorial case is performed in a different way than in the scalar case. First, the calculation is carried out using the material refractive index below the threshold and after that, a new calculation is carried out using the refractive index value after the threshold. The two results are combined according to the intensity profile of the beam, i.e., the position corresponding to the low intensity sets the below threshold profile, while the high intensity position sets the above threshold profile. Figures 6(a) and 6(b) show the normalized field intensity profile after the super resolution layer. Comparison with scalar results shows that the field profile has a similar shape in both cases, suggesting that both approaches are similar. In this way, a rigorous calculation of the scattered field by the pits structure could use this result as

input file, in a first approximation.

(a) AIST profile

(b) InSb profile

Figure 6. Field intensity profiles for AIST and InSb. The layer stack used is the same as in figure 4. The refractive indexes and thickness for InSb and AIST are given in the table 1. The parameters for the system were $NA=0.85$ and $\lambda = 405nm$. The scalar and vectorial field distribution shows a similarity concerning its shape.

3. SIMULATION OF THE READOUT SIGNAL

After the super resolution layer, the light is diffracted according to the Hopkins model.³ We checked the peak-to-peak signal as a function of the mark length, for a periodic structure. The results are plotted in figure 7(a) and 7(b) for InSb- and AIST-based layer stack. As expected, resolution beyond the diffraction limit (i.e. $< 120nm$) is obtained for both types of layer stack, although the enhancement for AIST is rather weak. As the mark length increases, the resolution for the InSb type disc decreases before taking off again (figure 7a). This is not observed for the AIST type media. Its resolution after SR onset is slightly better up to a certain length. For marks large enough, the two regimes coincide. One should notice that the frequency, at which occurs the signal destruction, depends on the laser intensity, i.e. the power threshold for the SR onset. One should notice that this

has already been observed experimentally if one agrees to switch the results from InSb- and AIST- based media.⁷ This might be due to our model which deals with transmitted light, whereas the reflected light is measured. It is interesting to check the effect of SR layer in the diffracted orders by looking at the Fourier plane. It can be readily verified that the diffracted orders forwarded on the pupil plane, when the super resolution layer is activated, are wider than the diffracted orders when the SR layer is deactivated (figures 7(c) and 7(d)). Based on that, we can conclude that the readout beyond the diffraction limit is possible if those expanded orders overlap with the zeroth order, which is consequent upon the onset of the SR layer.

Figure 7. 7(a) and 7(b) Readout signal beyond the diffraction limit for a Blu-Ray based system ($\lambda = 405\text{nm}$ and $NA = 0.85$). The solid black curve was calculated at low intensity (no SR effect) and the others at different intensities, above the threshold. For the InSb plot (figure 7(a)), at 100nm, the best resolution occurs just after the threshold is reached (1.1u.a curve), decreasing as the intensity increases. However, this same curve gives the worse modulation at 150nm. 7(c) and 7(d): The diffracted orders in the Fourier plane for a case of without and with InSb SR layer, respectively. It is possible to visualize the broadening of each diffracted order, responsible for the signal modulation beyond the diffraction limit.

To get a better understanding of the read-out mechanism of the InSb type disc, the calculation was extended to the case of three isolated marks with variable length (figure 8(a)). The result at 150nm is reported figure 8(b). At low laser power, i.e. below the SR threshold, the pits are clearly seen with a decrease of reflectivity due to the diffraction. As soon as the SR sets on, the signal is barely modulated, as expected from the figure 7(a). For higher energies, the pits are seen again. Most of the surface exposed to the laser spot is then in the SR state. Thus, the transmitted light is more homogeneous allowing the proper diffractive read-out of the pits. At 120nm, the marks are not visible at low power (figure 8(d)). The SR is needed for the detection. However, only two out of three pits are seen. This was also experimentally observed.⁷ When the laser power increases further, the

modulation vanishes again. The same behavior is found with the 100nm marks: no modulation below the SR threshold and only two pits out of three are visible after SR onset. But at higher power, instead of a degraded modulation, a signal inversion occurs and the three marks are clearly present. Experiments couldn't confirm this fact, presumably because at too high power the disc degrades very quickly.

Figure 8. 8(a) Pit structure. 8(b), 8(c) and 8(d) Readout signal of the three data marks of 150nm, 120nm and 100nm, respectively. 8(b) At SR low power regime (threshold is defined as 1 a.u.), the 150nm marks readout signal was barely modulated, as expected from the figure 7(a). For higher energies, the pits are seen again. 8(d) At 120nm, the marks are not visible at low power. In the SR regime (1.3 a.u.), only two out of three pits are seen. This was also experimentally observed.⁷ When the laser power increases further, the modulation vanishes again, and the readout signal becomes similar as when the SR layer is not activated. The same behavior occurs at 100nm 8(d). These results suggests that a laser intensity that is suitable for reading marks at some frequency may not resolve a different frequency.

4. CONCLUSIONS

A simple extension of a scalar readout program was proposed in order to investigate the basics aspects of super resolution effect. Although not rigorous, the model gives results which are qualitatively in agreement with experimental facts. It predicts the signal destruction at specific frequencies and signal inversion for different intensities. The main advantage of such approach is that it is very fast, once FFT algorithm is used. This

method could be used to check more global results, followed by vectorial calculations to fully describe the problem.

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