Towards subwavelength optical detection using waveguides

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A novel approach to detect the signal from an optical disk based on the use of multimode optical waveguides is presented. The method is based on detecting the differences in the coupled light into high-order modes of the waveguide as this is scanned along a sequence of optical marks.

Introduction

In the last years, the demand for optical data storage systems with high information density has grown considerably. A further increase in information density is hampered by the diffraction limit. In this paper we investigate a new approach to detect information from an optical disk. This method does not use a lens but a multimode waveguide[1]. In our approach, the waveguide is tilted with respect to the disk surface and is scanned along the surface. The coupling coefficient into different high-order modes of the waveguide is calculated as a function of its position on the disk. The marks on the disk are represented by an array of sources separated by a distance lower or equal than the Rayleigh limit. The Rayleigh limit can be seen as the minimum distance between two point sources that still can be resolved by a diffraction-limited system. Here, we analyze first the differences in the coupling into the waveguide for one or two point sources, and, secondly, we consider all binary combinations of five sources for various distances between the sources.

Theory

In our theoretical approach we consider a multimode waveguide which scans along an array of point sources as seen in Fig. 1. The coupling coefficient for mode m varies as the position coordinate d of the waveguide with respect to the sources changes.

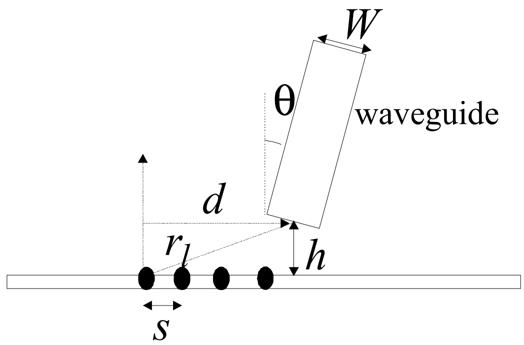

Figure 1: Outline of the model for detection of an array of point sources (thick dots) using a multimode waveguide of width W which is scanned at a height h from the point sources. The position of the waveguide with respect to the sources is given by d where d=0 coincides with the first source on the left. The waveguide is tilted by an angle θ with respect to the source plane.

In our model the waveguide has a core of width W and a cladding extending to infinity. Here we consider only the TE guided modes and follow the treatment of Ref.[2] to calculate the field distribution of the modes. We also assume that the waveguide has high contrast, i.e., that the index of refraction of the core n_{co} is much higher than the index of refraction of the cladding n_{cl}. Using these approximations, we arrive at the well known expressions for the transverse distribution of the electric field of the m-th mode inside the core:[2]

$$E_{x,m}(y) = A\cos\kappa_m y \quad m\ is\ even$$
$$E_{x,m}(y) = A\sin\kappa_m y \quad m\ is\ odd, \qquad (1)$$

where $\kappa_m = (m+1)\pi/W$, m= 0,1,2...M, and M= total number of modes. In order to find the power of the light coupled in the waveguide in the mode m, one calculates the coupling coefficient a_m. The absolute value of a_m gives the power. The coupling coefficient is given by[3]

$$a_m(d) = \int_{-W/2}^{W/2} E_s(\boldsymbol{r},d)E_m(y)dy\,, \qquad (2)$$

where $E_s(\boldsymbol{r})$ is the field from the point sources at the end face of the waveguide, $E_m(y)$ is the transverse field distribution of the mode m in the waveguide, and d is the scanning position of the waveguide with respect to the point sources (see Fig. 1). The total field due to the point sources $E_s(\boldsymbol{r})$ is given by the superposition of the field due to each separate source $E_{0s}(\boldsymbol{r})$, i.e.,

$$E_s(\boldsymbol{r}) = \sum_{l=0}^{n} E_{0s}(\boldsymbol{r}_l)\,, \text{ where } \quad E_{0s}(\boldsymbol{r}) = \frac{1}{\boldsymbol{r}_l}\exp(-j\boldsymbol{k}.\boldsymbol{r}_l)\,, \quad (3)$$

where $|\boldsymbol{r}_l|^2 = (h - y\sin\theta)^2 + (y\cos\theta + d - l\,.\,s)^2$ and n is the number of sources.

Results of the simulations

The optical scanning device was simulated with a MatLab program. In the program the scanning height, the tilt angle of the waveguide with respect to the sources and the width of the waveguide can be chosen as input parameters in order to calculate the absolute value of the mode coupling coefficients (a_m), as described in the previous section. The number of light sources n can be chosen as well as the source dimension (extended source instead of point source).

In the first simulation, we compare the coupling coefficient of the first-order mode as a function of the position d of the waveguide with respect to the sources for two cases: one and two point sources. In the latter case the distance between the two sources is 0.5 λ. In Fig. 2a the waveguide is not tilted while in Fig. 2b, a tilt of θ= 20˚ was imposed. By comparing Figs. 2a and 2b one can see that the field coupled to the waveguide with no tilt (Fig. 2a) is almost the same for the cases of one or two point sources, while by tilting the waveguide (Fig. 2b) the coupled field strength shows an asymmetric behaviour on scanning, resulting in better distinction between one or two sources. In order to quantify how distinct the coupling of one or two point sources into the waveguide is as a function of the distance between the sources, we define a visibility function given by

$$V = \left| \frac{I_{\max A} - I_{\min A}}{I_{\max A} + I_{\min A}} - \frac{I_{\max B} - I_{\min B}}{I_{\max B} + I_{\max B}} \right|, \qquad (4)$$

where I_{maxA} , I_{minA} are the maximum and minimum of the coupling coefficient $|a_1(d)|$ for the case of two sources and I_{maxB}, I_{minB} are the local maximum and minimum of the coupling coefficient $|a_1(d)|$ for the case of one source. By inspection of Fig. 2, one can see that there is one minimum (d=0) and two maxima. Since the second maximum (d > 0) yields better distinction, we have used it to calculate the visibility factor V given by Eq.(4). In Fig. 3 we show the visibility factor for different tilt angles of the waveguide from 0º to 20º in steps of 5º. The distance between the two sources varied from 0.65 λ to 0.05 λ. In Fig. 3 the increment in visibility can be seen when the waveguide is tilted. One can observe that, for a given tilt angle of the waveguide, the difference between one or two point sources can be distinguished up to 0.1 λ. This result is very encouraging if one compares it with the Rayleigh limit (~ 0.5 λ).

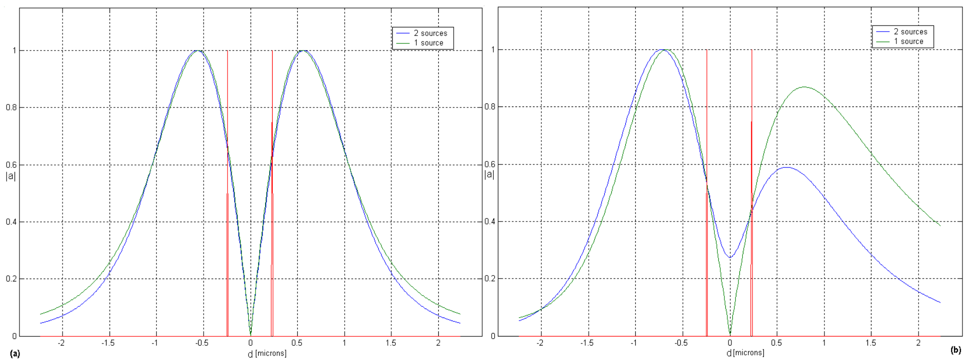

Figure 2: (a) the absolute value of the field of first-order mode is drawn for one source (zero at d=0) and two sources with a distance of 0.5 λ between them and a tilt of 0°. In (b) the absolute value of the field in the same mode is drawn for one source (zero at d=0) and for two sources also separated by a distance of 0.5 λ but now with a tilted waveguide of 20°. The width of the waveguide is 2 λ,, n_{co}= 3, scan height = 1 µm, wavelength = 0,9 µ m. The curves originating from one and two point sources have been normalized.

Finally, we expand our analysis to simulate the response curves due to multiple sources (or marks) on the CD-surface. When more sources are present we should consider all possible binary configurations. If a source is "off" it represents a logic "0" and when a source is "on" it represents a logic "1". In the case of five sources we have a total of 2^5 different source patterns. When we look at the coupling coefficients of the different patterns it is also possible to determine an overlap matrix. With no normalization of the curves the difference between the response functions due to patterns *A* and *B* is defined as

$$D(A,B) = \sqrt{\int_L \left| f(A) - f(B) \right|^2}\,, \qquad (5)$$

where *f(A)* and *f(B)* are the complex coupling coefficients of patterns *A* and *B*, respectively. Here *D(A,B)*=0 means that there are no differences between the functions. Using this equation we calculated the overlap matrices for the waveguide with a tilt of 20º for various distances between the five sources. This yields a 32x32 overlap matrix.

In order to know how close we can arrange the sources and still distinguish different sequences, we have calculated the overlap matrix for various distances between the sources and set threshold levels of 10%, 25% and 40% of the maximum value. In this way we could quantify the distinction between the various patterns for a given distance between the sources. The result shows that if the distance between the sources ≥ 0.15 λ the function *D(A,B)* is always bigger or equal than 10% of the maximum value, i.e., one can distinguish all patterns within 10%.

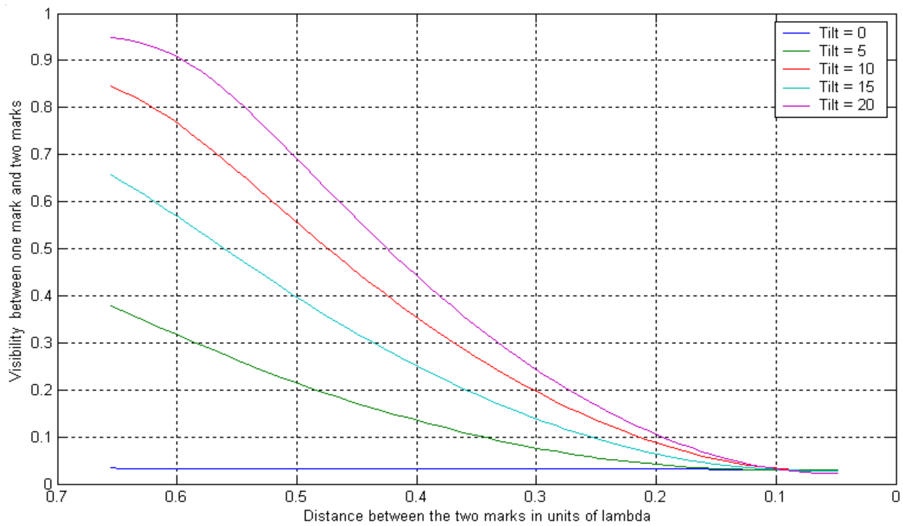

Figure 3: Visibility between one mark and two marks for the coupling to the first-order mode of the waveguide.. The different ascending curves are for different tilts of the waveguide varying from 0° (lower curve) to 20° (higher curve). Calculation parameters: $W = 2\lambda$, $n_{co} = 3$, scan height = 1 µm, λ = 0,9 µm.

Conclusions

We analyzed a new method to improve the distinction between various binary combinations of point sources separated by subwavelength distances by means of detection using a waveguide. The simulations show that if the waveguide scans above a sequence of isolated point sources, distinction between the coupling coefficient due to all binary combinations is greater or equal to 10% for distances between the sources up to 0.15 λ. These numbers are based on the detection of the complex coupling coefficients, i.e., the amplitude and phase of the field coupled to the waveguide. This detection system could have applications in optical recording, where the binary information would be written on the disk in a form of clusters of *n* pits (such as the *n* sources calculated above). The waveguide would detect all *n* pits at the same time, and via processing of information, the resulting pattern would be matched to one of the possible patterns for a given number of *n* pits. It is important to note that the method is based on the simultaneous detection of a cluster of pits and not individual pits such as in the present optical disk systems. This means that a buffer area between the clusters should be introduced in order to avoid cross-talk between the clusters. The distance between the clusters will depend on the dimensions and parameters of the waveguide and on the scanning height. Based on the fact that a considerably shortening of the distance between the pits seems to be feasible, we conclude that even with the presence of the buffer area this method has potential to increase the total information density on the disk.

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