Performance Analysis of a multi-mode waveguide based optical disc readout system.

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In this paper we propose a method to improve the optical resolution for reading out optical discs, without making the spot size on the disc smaller than the diffraction limit. The idea is to reconstruct the bit pattern from the complete field profile (including amplitude and phase) of the light reflected from the disc. Phase and amplitude information are measured by picking up the wave front into different modes of a bimodal waveguide. Once picked up, these modes can be split by a photonic integrated circuit to be measured by separate detectors. By combining the information from the responses from the different modes, the bit error rate can be improved substantially.

210.0210 Optical data storage

110.0110 Imaging systems

100.5010 Pattern recognition and feature extraction

100.5070 Phase retrieval

Introduction

Optical data storage tries to cope with the strong need for exchangeable super high-density, high-data rate storage memories. Applications include large storage devices for back-up and miniaturized versions in mobile devices. In the search for higher information density, different approaches are being investigated to make read-out and writing of smaller marks possible.[1,2] It is well known that the smallest feature distinguishable in the far field is given by $\lambda/(2NA)$.[3] Therefore the most obvious way to increase resolution is decreasing the wavelength λ and increasing the numerical aperture (NA). However further improvement of these parameters is increasingly difficult. Therefore new techniques that can overcome the diffraction limit are being investigated. Examples include magneto-optical recording based on magnetic domain expansion[4] and near field read-out using aperture probes or solid immersion lenses (SILs).[5] Other approaches try to enhance the resolution in the far field, using phase masks placed in the pupil or image plane[6], or using interference microscopy to detect the phase of the optical field.[7]

In this paper a new way of reading out optical discs is presented. The idea is to use an integrated photonic chip with multimodal waveguide to pick up the optical field coming from the disc. Such a waveguide supports multiple optical modes and the relative amplitude by which these modes are excited will depend on both the amplitude and the phase profile of the field coming back from the disc. If we can split up the respective waveguide modes and detect the power in each of them separately, we may be able to reconstruct the data written on the disc with a higher resolution than in the case of a conventional system. The concept to increase the resolution in the far field is similar to other approaches using phase information such as interference microscopy.[7] The disc can be illuminated by a single mode or by a linear combination of multiple modes. A second rationale behind the approach of the scanning waveguide read-out system is the potential integration of all optical elements, including the laser and detectors on a single chip, thereby reducing the size of the pick-up head by an order of magnitude, eventually leading to a much more compact optical disc drive. Furthermore disc is illuminated with the same multimodal waveguide as used for the detection, which simplifies the design further and makes the alignment much less sensitive than for instance in a confocal microscope.

Overview of the scanning waveguide system

Description of the optical system

Fig. 1 shows a schematic picture of the scanning waveguide. The total system can be divided into two parts. The upper part comprises the photonic integrated circuit (PIC), which forms the gateway from laser source and detectors to the modes of the multimodal waveguide; the lower part describes the interaction between the modes of the multimodal waveguide and the disc at both ends of the imaging system. The PIC guides the input light from a laser source into the modes of the multimodal waveguide and guides the reflected modes back to the detectors. In general it should be designed to excite the desired linear combination of modes needed to illuminate the disc and to separate all modes reflected back from the disc to the different detectors. A PIC separating the zeroth and the first order mode has already been described in the literature[8,9]. The focus of the remainder of the current paper is on the lower part of Fig. 1: the propagation of the modes inside the waveguide towards the disc and the coupling of the reflected light from the disc into the backwards propagating modes of the waveguide. An imaging system images the light between the waveguide-air facet and the disc, and back. In this first approach similar optics as in a common DVD pick-up system could be used. The waveguide is placed in the far field, which means no special effort is needed to keep the pick-up head very close to the disc as in near field methods, it is neither needed to use immersion fluids as with a solid immersion lens[5]. In an alternative design, the waveguide moves directly over the disc with a small air gap in between. This means also evanescent waves are picked up, but at the cost of a more complicated mechanical design. As will be described in the next section, the second approach has only advantages for a very small gap between the waveguide and the disc. Therefore the main focus of this paper will be on the far-field approach.

To describe the optical properties of the waveguide scanning system, the detector response as a function of the patterns on the disc will be calculated in the next paragraphs. This response represents the power of the light picked up by each of the modes in the multimodal waveguide and will be derived by calculating the optical field along the optical light path from laser to detectors as shown on Fig. 2, which is an unfolded picture of the lower part of Fig. 1. The x-axis lies along the tracks and the waveguide facet, the y-axis is orthogonally to the waveguide chip, and the z-axis lies along the propagation direction. We used a scalar theory to calculate the optical fields ψ. This approximation is in principle only valid for small numerical apertures but does not change the final results.

Assume the multimodal waveguide has N guided eigenmodes. Since the disc is illuminated by a linear combinations of the modes, the field inside the waveguide at the air interface is given by

$$\psi_1\left(x_1, y_1, z = 0^-\right) = \sum_{i=1}^{N} \alpha^i m_{wg}^i\left(x_1, y_1\right). \tag{1}$$

Due to the linearity of the optical system it is sufficient to determine the excitation coefficients for each mode separately for calculating the response measured by the detectors. If we define

$m_{air}^{i}\left(x,y,z=0^{+}\right)$ as the field resulting from the transmission of $m_{wg}^{i}\left(x,y,z=0^{-}\right)$ through the waveguide-air interface, we find, for the field at the disc interface:

$$\psi_{2a}^{i}\left(x_2,y_2\right)=\int_{y_1}\int_{x_1} m_{air}^{i}\left(x_1,y_1\right)psf_{opt}\left(x_2-x_1/M\,,y_2-y_1/M\right)dx_1dy_1 \tag{2}$$

In this formula $psf_{opt}\left(x,y\right)$ represents the point spread function of the imaging system, or of the air gap, when propagating from the waveguide to the disc; M is the demagnification factor. [10] The disc reflectivity, which is modulated by the bit pattern, is approximated by a local function $bp\left(x,y\right)$ and the scanning position of the disc along the x-axis is x_s. The field ψ_{2b}^{i}, reflected from the disc, can then be calculated from the incident field ψ_{2a}^{i} by:

$$\psi_{2b}^{i}\left(x_2,x_s,y_2\right)=\psi_{2a}^{i}\left(x_2,y_2\right)bp\left(x_2-x_s,y_2\right) \tag{3}$$

The reflected field ψ_{2b}^{i} is imaged back onto the waveguide in the same way as for the illumination:

$$\psi_{3}^{i}\left(x_3,x_s,y_3\right)=\int_{y_2}\int_{x_2}\psi_{2b}\left(x_2,x_s,y_2\right)psf'_{opt}\left(x_3-M\,x_2,y_3-M\,y_2\right)dx_2dy_2 \tag{4}$$

$psf'_{opt}\left(x,y\right)$ now represents the point spread function for the imaging system when propagating from the disc to the waveguide[10] and is given by:

$$psf'_{opt}\left(x,y\right)=psf_{opt}\left(x/M\,,y/M\right) \tag{5}$$

At the air-waveguide interface, ψ_{3}^{i} excites the different modes in the multimodal waveguide. From the reciprocity theorem, it can be shown that the complex excitation coefficients $\chi^{i,j}\left(x_s\right)$

of the detected modes can be calculated by the overlap integral of the incident field and the different mode profiles outside the waveguide.

$$\chi^{i,j}(x_s) = \int_{y_3}\int_{x_3} \psi_3^i(x_3, x_s, y_3) m_{air}^j(x_3, y_3)\, dx_3 dy_3 \tag{6}$$

Combining equations (2–6) this results in:

$$\chi^{i,j}(x_s) = \iint\Bigg[\Bigg(\iint\Bigg\{\Bigg[\iint m_{air}^i(x_1, y_1)\cdot psf_{lens}(x_2 - x_1/M, y_2 - y_1/M) dx_1 dy_1\Bigg]$$

$$\times bp(x_2 - x_s, y_2)\Bigg\} psf'_{lens}(x_3 - M x_2, y_3 - M y_2)\, dx_2 dy_2\Bigg)$$

$$\times m_{air}^j(x_3, y_3)\Bigg] dx_3 dy_3 \tag{7}$$

By changing the integration order and replacing psf' using (5), equation (7) can be simplified to:

$$\chi^{i,j}(x_s) = \iint\Bigg[bp(x_2 - x_s, y_2)$$

$$\times \iint m_{air}^i(M x_1, M y_1) psf_{opt}(x_2 - x_1, y_2 - y_1) dx_1 dy_1$$

$$\times \iint m_{air}^j(M x_3, M y_3) psf_{opt}(x_2 - x_3, y_2 - y_3)\, dx_3 dy_3\Bigg] dx_2 dy_2 \tag{8}$$

Using the two dimensional convolution operator $\otimes$ and the definitions:

$$psf^{j}_{detect}(x,y) = psf_{opt}(x,y) \otimes m^{j}_{air}(Mx, My),$$

$$psf^{i}_{illum}(x,y) = psf_{opt}(x,y) \otimes m^{i}_{air}(Mx, My),$$

$$\text{and } psf^{i,j}_{tot}(x,y) = psf^{i}_{illum}(x,y)\, psf^{j}_{detect}(x,y) \tag{9}$$

equation (9) can be rewritten as:

$$\chi^{i,j}(x_s) = \int_y \int_x bp(x - x_s, y)\, psf^{i,j}_{tot}(x,y)\, dx dy = bp \otimes psf^{i,j}_{tot} \tag{10}$$

The response measured at the detector is proportional to the power in the excited modes and can be written as:

$$P_j(x_s) = \gamma \left| \sum_{i=1}^{N} \alpha^i \chi^{i,j} \right|^2 = \gamma \left| bp \otimes \sum_{i=1}^{N} \alpha^i\, psf^{i,j}_{tot} \right|^2 = \gamma \left| bp \otimes psf^{j}_{tot} \right|^2 \tag{11}$$

with $psf^{j}_{tot} = \sum_{i=1}^{N} \alpha^i\, psf^{i,j}_{tot}$, α^i the coefficients of the linear combination of the illumination modes as in equation (1) and γ a proportionality coefficient dependent on the detector characteristics. The effective point spread function psf^{j}_{tot} is a measure for the effective resolution of the signals captured at each detector and depends heavily on the characteristics of the imaging system as well as on the effective profile of the different waveguide modes. An alternative formula to describe the resolution of an optical system is the modulation transfer function (MTF), defined as the amplitude of the Fourier transform of the point spread function: $MTF_j(f_x, f_y) = \left| \mathcal{F}(psf^{j}_{tot}(x,y)) \right|$. $MTF_j(f_x, f_y)$ is a good measure for how well the spatial frequencies on a disc can be resolved at the detector side and $MTF_j(0,0)$, is a measure for the overall light throughput when no modulation is present.

It is interesting to have a close look at a system using only the zeroth order mode for illumination ($\alpha_0=1,\ \alpha_i=0$). In this case there is a close analogy between the response P_0 and the response of a confocal microscope. While a confocal microscope has a pinhole at the illumination and detector side, the field profile of the zeroth order mode $m_{air}^{0}\left(M\,x,M\,y\right)$ forms the effective aperture in the scanning waveguide system. A higher magnification implies a narrower effective aperture. For high magnifications and/or small waveguides, the zeroth order mode can roughly be seen as the equivalent of the pinhole in a confocal microscope. The additional losses in the optical path of the scanning waveguide system over that in a confocal microscope are limited to the losses at the waveguide-air interface. At this interface part of the light may be reflected due to the difference in refractive index. This can however be avoided by a suitable anti-reflection coating. Similarly there is an analogy between the response P_1 and a push-pull signal from a split photodiode (with the split between the two detector halves orthogonally to the track).[11] The relationship is however not as straightforward as for the response P_0. Fig. 3 shows the first order waveguide mode is approximately proportional to the first derivative of the zeroth order waveguide mode: $m_{air}^{1}\left(M\,x,M\,y\right)\approx\eta\frac{d}{dx}m_{air}^{0}\left(M\,x,M\,y\right)$ with η a proportionality coefficient. From equation (9) and (10) one easily finds:

$$\chi^{0,1}\left(x_s\right)\approx\frac{\eta}{2}\frac{d}{dx_s}\chi^{0,0}\left(x_s\right). \qquad (12)$$

If one writes $\chi^{0,0}\left(x_s\right)$ as $A\left(x_s\right)exp\left(j\varphi\left(x_s\right)\right)$, with A and φ the amplitude and phase of $\chi^{0,0}$ respectively, equation (11) gives:

$$P_0(x_s) = \gamma |A(x_s)|^2 \text{ and } P_1(x_s) \approx \frac{\gamma\eta^2}{4} \left| \frac{dA(x_s)}{dx_s} + A(x_s)\frac{d\varphi(x_s)}{dx_s} \right|^2 \tag{13}$$

Equation (13) shows that the response P_0 is only related to the amplitude A of the reflected field, while P_1 is also a function of the phase φ. This means the responses P_0 and P_1 contain partially independent information from the bit pattern on the disk. At first sight one could compare the first order signal P_1 with the push-pull signal (with split between the detector halves perpendicular to the track) .[11] Both approaches boost the higher frequencies, by taking a kind of differential response. The big difference is that the waveguide detection is a coherent method, which means the right and left part of the complex reflected field are subtracted from each other, while in the push-pull signal the intensity is subtracted. A full comparison between the two methods is beyond the scope of this paper, but the most striking difference can be shown for the example of a pure amplitude grating: The push-pull signal subtracts the power of the left and right halve plane of the Fourier transform of the reflected field form the disc, which means it subtracts the power in respectively the positive and the negative frequencies. For a real function the power in the negative and positive frequencies is however always equal, which means the push-pull signal must be zero for such a grating. As shown in equation (13), this is not the case for the P_1 response of the waveguide system. In conclusion: the split detector in a DVD system and the first order mode in the waveguide system behave differently. Whether one is better than the other depends on the specific disc characteristics.

Simulation Method

The simulation of the scanning waveguide can be divided into three parts: the waveguide with the waveguide-air interface, the imaging system or air gap and finally the reflection of the disc. We restricted ourselves to 2D calculations, omitting the dimension along the y-axis. The optical properties along the y-axis are identical to those described along the x-axis, but as the waveguides are monomodal along this axis, there is only the P_0 response. We used TE-polarized light, i.e. the electric field is parallel to the x-axis in Fig. 2, and all dimensions have been scaled by λ/NA with λ the wavelength of the light and NA the numerical aperture of the illumination system (NA=1 in the case where the waveguide moves at a small air gap over the disc without imaging system).

For the modeling of the waveguide and the waveguide-air interface, a full-vectorial eigenmode expansion tool, CAMFR (CAvity Modelling FRamework)[12], was employed. This tool rigorously solves the Maxwell equations in two dimensions and was used to calculate the field profile of the waveguide modes and their transmission at the waveguide-air interface. The propagation from the waveguide interface to the disc is most easily described in the spatial Fourier domain. The optical field is decomposed into propagating and evanescent plane waves. In our simulations we investigated two different designs: the first is an aberration free lens with numerical aperture equal to *NA* (seen from the disc). In such a case the imaging system acts as a low pass filter in the Fourier domain. In the spatial domain this is equivalent with a convolution with $psf_{opt}(x) = sinc(2\pi NA\,x/\lambda)$ or $psf'_{opt}(x) = sinc(2\pi NA\,x/(M\,\lambda))$, when looking from the disc or the waveguide respectively. In an alternative design the waveguide is scanned over the disc with a narrow gap w_{gap} in between. The propagating plane waves undergo a phase shift and the evanescent plane waves a decrease in amplitude and the point spread function is given by $psf_{opt}(x) = \mathcal{F}\left(e^{-j\beta(f)w_{gap}}\right)$.

In this equation $\beta(f)$ is defined as:

$$\beta(f) = 2\pi\sqrt{\frac{1}{\lambda^2} - f^2} \quad \left(for|f| \leq \frac{1}{\lambda} \right) \text{ and } \beta(f) = -j2\pi\sqrt{f^2 - \frac{1}{\lambda^2}} \quad \left(for|f| \geq \frac{1}{\lambda} \right)$$

Finally, the 3D disc structure has been modeled by a 1D amplitude response. In a real disc system the laser spot covers the holes and parts of the surrounding lands. The reflection of these holes and lands is different in phase and/or amplitude. The interference of these results in a modulation of the reflection, which can be modeled by a complex function $bp(x)$. The simulation results in the next paragraph are based on a strong amplitude modulation: $bp(x) = 1$ for ones and $bp(x) = 0$ for zeros. Results for other modulation functions are however very similar.

Simulations

In our simulations we focussed on the following case: the zeroth order mode is used to illuminate the disc (α_0=1, α_i=0 in equation (1)) and the reflected light is captured by the zeroth and the first order mode, which result respectively into the responses P_0 and P_1 at the detector. Fig. 4 shows results for three configurations. In all three configurations the multimodal waveguide has a core and cladding refractive index of *3.5* and *3.0* respectively. These values are somewhat arbitrary and were chosen because our experimental work is based on the gallium arsenide material system.[9] In principle any multimodal waveguide can be used, as long as one also selects an appropriate magnification factor in the lens system. In practice a silica or polymer based waveguide would be an appropriate choice, because transparency for blue light is needed. The lens system in between the waveguide and the disc has a numerical aperture *NA*. For configuration *A* and configuration *C* the waveguide width is $1.5\lambda/NA$, for configuration *B* it is $0.5\lambda/NA$. The magnification factor M is 1 in configuration *A* and *B*, and equals 3 in configuration

C. On the left the MTF of responses P_0 and P_1 is shown in solid and dashed line respectively. The dotted line represents the shape of the MTF of a confocal microscope.[13,14] The right column of Fig. 4 shows the effective detection apertures $m_0^{detect}(Mx)$ and $m_1^{detect}(Mx)$. The illumination aperture is given by $m_0^{illum}(Mx)$ and equals $m_0^{detect}(Mx)$. As the properties of the imaging system are identical in all three configurations, the MTF depends solely on these effective apertures. The effective apertures themselves depend on the width of the waveguide, the index contrast between core and cladding layer and the magnification of the imaging system.

A comparison of the three configurations in Fig. 4 indicates that a system with a large effective aperture, as in configuration A, has a worse MTF at larger spatial frequencies than those with smaller effective apertures, as in configuration B and C. In these last two cases the shape of the MTF for P_0 is nearly identical to that of a confocal microscope. Compared to configuration A, there is however a significant lower overall light throughput given by the value $MTF(0)$. Taking into account the trade-off between the resolution at high spatial frequencies and the overall light throughput, the optimal width for the effective apertures lies around $\lambda/(2 \cdot NA)$, as in configuration B or C. Compared to the MTF of the P_0 response the MTF of the P_1 response has a lower average light throughput and favors the higher spatial frequencies.

Fig. 5 shows the MTF for the case where the waveguide detector is scanned directly over the disc with only a small air gap in between them instead of a lens system. For this simulation the waveguide configuration of Fig. 4B is used. For an air gap of width $\lambda/4$, the waveguide picks up parts of the evanescent waves and the MTF extends beyond the diffraction limit $2/\lambda$ (note that in this case $NA=1$). For an air gap of λ (Figure 4B), this increase has become negligible while the overall light throughput decreased considerably. Therefore this solution is only viable if the distance between waveguide detector and disc can be kept below $\lambda/4$ and in the remainder of this text we will focus on the case with the imaging system in between disc and waveguide detector.

As described above the response P_0 of the waveguide scanning system is essentially the same as for a confocal system. With the scanning waveguide read out system it is however possible to retrieve in parallel information from the other responses P_j. In the next section we will describe how the information of the response P_0 and the other responses P_j can be combined to result in a lower bit error rate.

Extracting the recorded information from the measured responses

Description of the bit pattern extraction method

In a conventional CD- or DVD-system, the zero and one values from the bit sequence are extracted from the signal at the detector by sampling the signal at specific points. A 'zero-crossing' marks a change from a 'one' to a 'zero' and vice versa.[12] This method is fast and reliable, but a large part of the information contained in the detected signal is dropped. Enhanced methods for reading out bits make it possible to increase the data density as for instance in multilevel modulation methods.[15] In principle it is even possible to resolve features smaller than the cut off frequency of the MTF, $\lambda/(2NA)$.[3] There exist methods based on inverse filtering and analytic continuation of the image spectrum that can reconstruct the information outside the MTF-band. These methods are however very sensitive to small errors in the measured signal, which means it is eventually noise that limits the effective resolution.

In this paper we will not look into the details of these methods but starting from a simple parameter fitting algorithm we will prove that the waveguide scanning system can read out bits at a lower bit error rate than a conventional system would do in an equivalent situation. The results in the previous section show that the response P_0 of the waveguide detector is essentially the same as that of a confocal system. The second response, P_1, is detected simultaneously without decreasing the power of P_0. In addition measurements have shown that reading out bits from a DVD with a confocal system results in the same jitter values as a conventional DVD system.[16] Hence the potential of the scanning waveguide system can be shown by demonstrating that a combination of multiple responses, P_j $(j=0 \ldots N-1)$, reduces the bit error rate compared to a system using only the response P_0.

As the broad range of coding schemes makes it harder to compare the different results, we intended to use a method independent of the possible coding schemes and chose a simple least square parameter fitting method to extract the bits from the measurements in groups of n consecutive bits. For each of the modes a response P_j is captured at the detectors. Because of noise, crosstalk and errors in the tracking of the servo system these responses will be a distorted version of the theoretical response as calculated in the previous section. In the left part of Fig. 6 a sample bit pattern is shown with the corresponding P_0 and P_1 responses. The dashed line gives the theoretical response; the solid line shows the distorted signals. The aim is to recover the n bits inside the dashed rectangle from the distorted signal. For n bits, there are 2^n possible bit pattern candidates. For each of these, the theoretically expected responses are calculated and will be written as C_j^k (where $k=1 \ldots 2^n$ denotes the 2^n bit patterns and $j=0 \ldots N-1$ describes the order of the mode used to capture the response). These candidate bit patterns and their respective calculated responses are shown in the right part of Fig. 6. To improve the fitting of the distorted responses, not only knowledge of the parameters of the optical system but also knowledge of the bit sequence extracted in previous steps is used to calculate the responses C_j^k from the candidate bit patterns.

To select the correct bit pattern (denoted by the index $k_{correct}$) from the 2^n candidate bit patterns, a least square fitting algorithm is used: the squared differences of each calculated response C_j^k with the detector responses P_j are integrated over a certain range of s, the scanning position along the disc and form the overlap matrix S. This matrix has N rows and 2^n columns and the individual elements are given by:

$$S_j^k = \int \left| P_j(s) - C_j^k(s) \right|^2 ds \quad (k=1\ldots 2^n, j=0\ldots N\text{-}1) \tag{14}$$

For each response j we define k_j as the k for which S_j^k has the lowest value, i.e.:

$$S_j^{k_j} = \min_{k=1..2^n} S_j^k \tag{15}$$

As long as the distortion on the signals P_j is low, any of the responses can be used to find correct bit pattern, which means $\forall j : k_j = k_{correct}$. For larger distortion this may no longer be true and we may have $k_j \neq k_i$ for some i, j. In such a case it is no longer straightforward to decide which one of the responses predicts the correct bit pattern. Therefore a decision-making algorithm, maximizing the probability of selecting the correct bit pattern, has to be constructed. We propose to do this by taking a well-chosen (linear) combination of the individual responses:

$$S_T^k = \sum_{j=1}^{N} \beta_j S_j^k \tag{16}$$

which is subsequently minimized. The index k corresponding with the lowest value of S_T^k, will be called k_T and will be used to select the most probable bit pattern. Fig. 7 explains the principle behind this method for the case N=2: the couples $\left(S_0^k, S_1^k\right)$ for all $k=1\ldots 2^n$ are plotted on a grid with S_0^k and S_1^k as the horizontal and vertical coordinates respectively. The point k which is located the closest to the horizontal axis – i.e. with the smallest value S_0^k then defines the index k_0, and in the same way, the point located the closest to the vertical axis will define k_1. For low distortion values, as explained above, these points will coincide, which means $k_0=k_1$ and represents the most probable candidate for the correct bit pattern $k_{correct}$. For increasing distortion however, it is possible that $k_0 \neq k_1$ and such a selection is not possible anymore. Instead we chose k_T , the minimal value of S_T^k as defined in equation (14), which is the couple that lies at the bottom left corner along the gray diagonal line $\sum_{j=1}^{N} \beta_j S_j^k = constant$. Note that the angle of this line is determined by the relative weight β_j given to each response S_j^k and is a parameter to be optimized. Simulations in the next paragraph show that this method results in a better chance of finding the correct bit pattern then taking into account only one of the separate modes.

Simulations

For the actual simulations we concentrate again on the case where the disc is illuminated with the zeroth order mode and is read out by the zeroth and first order mode. For the waveguide and the imaging system the configuration as shown in Fig. 4B was used. The bit error rates for the responses P_0 and P_1 have been simulated for different types of noise. In an actual system, noise may originate from several sources: crosstalk from neighboring tracks, inter symbol interference between the bits within one track, inaccuracies on the disc itself, noise induced by the tracking servo, or detector noise. In the current simulations only noise independent of the light power has been implemented. The power of the P_0 response is not lower than the signal from a confocal microscope with a similar aperture, which means the P_0 response and the confocal microscope will have similar signal to noise ratio. The P_1 response is however relatively weak and the noise impact may be heavier. the On Fig. 8 and Fig. 9 the influence of noise on the BER for two types of noise is shown: ‘white noise’, which is random noise added to the bit patterns and ‘inter track crosstalk’, which is modeled by adding the response from random bit patterns to the original signal. BER_0 (dashed line) and BER_1 (dotted lines) are respectively the bit error rate from the P_0 and the P_1 response separately. Fig. 8 shows bit error rates for two simulations with a different noise level, as a function of the minimal bit size in the bit patterns. For calculating the bit error rate, 10^4 bit patterns have been tested. This means bit error rates below 10^{-4} are not detected and explains the cut off of the curves on Fig. 8. The bit error rate increases rapidly with smaller bit sizes. Depending on the type and the amount of noise the zeroth order mode can outperform the first order mode or vice versa.

Fig. 9 shows how using a combination of the responses P_0 and P_1 can lead to a lower bit error rate than by using the two responses separately. The curves represent the bit error rate as a function of the ratio between the coefficients β_0/β_1 defined by equation (15). For the white noise as well as for the inter track crosstalk, there is a combination $S_T^k = \sum_{j=1}^{N} \beta_j S_j^k$ that results in a minimum bit error rate (BER_{opt}), lower than the bit error rate achieved with the separate responses, BER_0 and BER_1. The gain of the combination in case of white noise is however much bigger than in the case of inter track crosstalk. Moreover the values of the coefficients for optimum linear combination are not identical for the two types of noise. This means a trade-off for choosing the linear combination is necessary. Using these results we calculated the bit error rates as a function of bit size and noise. The solid lines on Fig. 8 show the bit error rate of this combination, BER_{opt}, as a function of minimum bit size. For both types of noise the BER_{opt} is much lower than the BER_0. The optimal ratio of β_0/β_1 is smaller than 1, which is logical as the response P_1 is weaker than the P_0 response and has to be amplified. This last point might still be an important drawback as it poses strong constraints on the mode splitter. Mode splitters as in described in ref. 8 and ref. 9 have a theoretical efficiency of 100% for the zeroth order mode and 50% efficiency for the first order mode. Also the crosstalk can in principle be made negligible. Practically, it might however be hard to split off the weak first order signal from the strong zeroth order signal without adding crosstalk on the first order signal.

Conclusions

The scanning waveguide approach is a new method for read-out of optical discs. By illuminating the disc and picking up the reflected light with a waveguide with a few guided modes, phase as well as amplitude information can be extracted from the field reflected from the disc. The response from the zeroth order mode is equivalent to that of a confocal microscope, which itself has similar results as the conventional read-out DVD system. As the different modes are measured in parallel, the results of the different modes can be combined. A well-chosen linear combination leads to a bit error rate that outperforms the results from the different modes separately. This means that for a given bit error rate the scanning waveguide system can read out bit patterns with smaller bit sizes and allow for an increase of the data density on the disc. In this respect the waveguide scanner is a potential candidate for use in future read-out systems for optical discs.

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References

1. G. Bouwhuis, J. Braat, A. Huijser, J. Pasman, G. van Rosmalen, K. Schouhamer Immink, *Principles of Optical Disc Systems* (Adam Hilger, Bristol, 1985).
2. M. Mansuripur and G. Sincerbox, "Principles and Techniques of Optical Data Storage," Proceedings of the IEEE **85**, 1780-1796 (1997).
3. A. J. den Dekker and A. van den Bos, "Resolution: a survey", J. Opt. Soc. Am. A **14**, 547-557 (1997).
4. H. Awano, N. Ohta, "Magnetooptical Recording Technology Toward 100 Gb/in2", IEEE Journal of Selected Topics in quantum Electronics **4**, 815-820 (1998)
5. T.D. Milster, "Near-field optics: A new tool for data storage", Proceedings of the IEEE **88,** 1480-1490 (2000)
6. U. Brand, G. Hester, J. Grochmalicki, R. Pike, "Super-resolution in optical data storage", Journal of Optics A-Pure and applied Optics **1**, 794-800 (1999)
7. M. Eberler, R. Dorn, B.Münzer, S. Quabis, G. Leuchs, "Characterization of sub-wavelength structures using phase-singularities," in *Proceedings of the World Conference on Systematics, Cybernetics and Informatics*, (IIIS, Orlando, 2001)
8. J. Leuthold, R. Hess, J. Eckner, P.A. Besse and H. Melchior, "Spatial mode filters realized with multimode interference couplers", Optics Letters **21**, 836-838 (1996.)
9. F. Fransoo, D. Van Thourhout, L. Van Landschoot, A. Verbiest, W. Van Parys, P. Van Daele, R. Baets, "A method for detecting sub-wavelength features by means of a multimode waveguide and a mode splitting photonic IC," in *Proceedings of the LEOS annual meeting* (Institute of Electrical and Electronics Engineers, Glasgow, 2002), pp. 750-751.

10. B.E.S. Saleh, M.C. Teich, in *Fundamentals of Photonics*, (John Wiley and Sons, New York, 1991), pp. 139-143.

11. A. Korpel, "Simplified diffraction theory of the video disk", Applied Optics **17**, 2037-2042 (1978).

12. P. Bienstman, R. Baets, "Advanced boundary conditions for eigenmode expansion models", Optical and Quantum Electronics **34**, 523-540 (2002).

13. R.H.Webb, "Confocal optical microscopy ", Reports on Progress in Physics **59**, 427-471 (1996).

14. M. Gu, D. Day, "Three-dimensional coherent transfer function for reflection confocal microscopy in the presence of refractive-index mismatch", Journal of the Optical Society of America A **16**, 2002-2008 (2001)

15. T. Zhou, C. Tan, C. Leis, I. Harvey, G. Lewis, T. Wong, M. O'Neill, "Multilevel amplitude-modulation system for optical data storage," in *Advanced Optical Storage Technology, Proc. SPIE* **4930**, 7-20 (2002).

16. S. Stallinga, "Confocal detection and pupil masks for data storage on optical discs" in *Proceedings of EOS Topical Meeting on Advanced Imaging Techniques*, (European Optical Society, Delft, 2003), pp. 49-51.

List of Figure captions

Fig. 1. Schematic view of the PIC, waveguide and disc. The different subparts have not been drawn to scale.

Fig. 2. Schematic view of light path from waveguide to disc and back to wave-guide. The illumination and detection side have been unfolded.

Fig. 3. Normalized modes of a waveguide (width=0.5λ, n_{core}=3.5 n_{clad}=3.0). The dotted line shows the zeroth order mode, the dashed line gives the first order mode and the solid line shows the spatial derivative of the zeroth order mode.

Fig. 4. The left column shows the modulation transfer function for P0 and P1 response, in solid and dashed line respectively. The dotted line gives the shape of the MTF of a confocal microscope. On the right side, the respective effective detection apertures $m_{air}^{0}(M\,x)$ and $m_{air}^{1}(M\,x)$ are shown in solid and dashed line.

(A: width=1.5, M=1 B: width=0.5, M=1 C: width=1.5, M=3)

Fig. 5. Modulation transfer function of the waveguide scanning system with the waveguide sliding over the disc at a flying height of λ/4 and λ respectively.

Fig. 6. The left column shows the original bit pattern and the distorted signals P_0 and P_1. The right part of the figure shows the candidate bit patterns and the calculated superimposed responses C_0^k and C_1^k.

Fig. 7. A graph of the couples $\left(S_0^k, S_1^k\right)$ for k=1…2^n: S_0^k along the horizontal axis, and S_1^k along the vertical axis.

Fig. 8. Bit error rate in case of white noise (upper graph) and inter track crosstalk (lower graph). The dashed lines show the BER_0, dotted lines show the BER_1, solid lines give the BER of

the optimum combination. In each graph the upper three curves describe a higher noise level than in the lower three curves.

Fig. 9. Bit error rate in case of white noise (upper graph) and inter track crosstalk (lower graph), plotted as a function of the linear combination. The different curves represent simulations with decreasing noise levels. The curves start at the left with the value of BER_1 go through an optimum and end at the right with the value of BER_0. The simulated bit patterns have a minimum bit sizes of $0.25\lambda/NA$.