A multimodal waveguide for enhanced performance in optical disc read-out

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Optical data storage tries to cope with the strong need for exchangeable super high-density, high-data rate storage memories that can be easily copied and can be produced at low cost. In this search for higher information density, different approaches are being investigated to make read-out of smaller marks possible. In this paper we propose a method to improve the optical resolution, without making the spot size on the disk smaller than the wavelength. The idea is to reconstruct the bit pattern from the complete field profile (including amplitude and phase) of the light response reflected on the disk. Phase and amplitude information are measured by picking up the wave front into different modes of a multimodal waveguide. Once picked up, these modes can be split up by a photonic integrated circuit to be measured by different detectors. By combining the information from these different responses the bit error rate can be improved substantially.

I. INTRODUCTION

A. Optical data storage: from CD to Blu-ray

Since the first compact disk (CD) 20 years ago, optical data storage technology has undergone a rapid evolution. Being originally a read only medium, recordable and rewritable disk were developed. Not only an increase in storage density from 650 Mb (CD) to 25Gb (Blu-ray) has been made possible, but also the cost has dropped down and the data rate increased enormously. In spite of this rapid evolution the main principle has however remained the same: The disk consists of tracks with bumps and holes. Using a lens system a tiny spot on this disk is illuminated. By capturing the reflection of this spot on a detector, the bit pattern can be registered electronically. The increase in density has always been obtained by decreasing the wavelength or by increasing the numerical aperture of the lens system. Further improvements of these parameters are however very difficult.

B. Our approach: a scanning waveguide

In our approach[1] the detector is replaced by a multimodal waveguide connected to different detectors by a photonic IC. When light is captured on a detector only the amplitude component is measured. By detecting phase as well as amplitude information a better resolution could be achieved. In a noise free world, bit patterns of any size could, in principle, be reconstructed by detecting the total (complex) field. But even with the noise present, it is possible to improve the bit error rate, by detecting phase as well as amplitude information.

Our approach for detecting this phase information is using a multimodal waveguide as pick-up head instead of a detector. The principles of this scanning waveguide approach will be explained in chapter II. Chapter III explains how the bit pattern on the disk is deduced from the different responses detected at the receivers. Chapter IV will give a description of the design and fabrication of the photonic IC controlling the different modes of the multimodal waveguide to the different detectors. Chapter V is a brief summary with conclusions.

II. OVERVIEW OF THE SCANNING WAVEGUIDE APPROACH

A. Basic layout

Figure 1 shows a schematic version of our scanning waveguide approach. Through the multimodal waveguide light is focused on the disk, using one of the modes of the waveguide or a linear combination of the modes. This light reflects on the disk and couples back into the different modes of the waveguide. To control those different modes in the waveguide we use a photonic IC, which excites and detects the different order modes in the multimodal waveguide from and to monomodal input and output waveguides. This way can be measured into which modes the light reflected on the disk is coupled back. In our case only the zeroth order mode was used to illuminate the disc and the light coupled into the zeroth and first order mode is captured and sent to separate detectors.

On Figure 1 a lens system is used to image the field between the waveguide and the disk. We also investigated an approach without lens system where the multimodal waveguide scans over the disk leaving a small air gap.

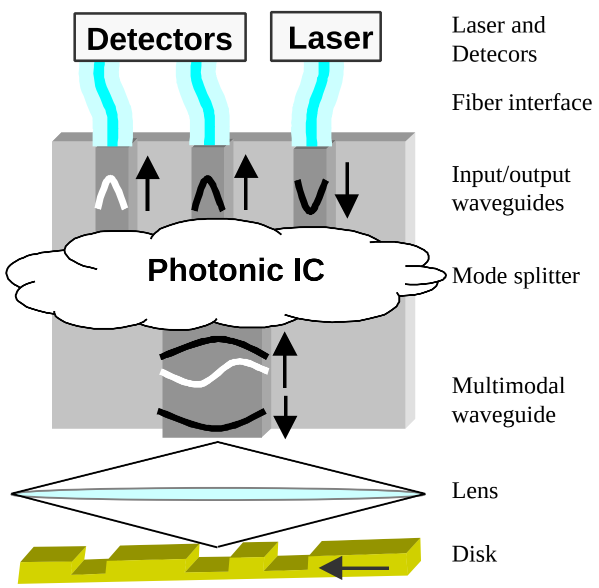

Figure 1: Schematic view of the PIC, waveguide and disk.

The scanning waveguide approach is very similar to a confocal microscope. In both cases a tiny aperture is placed at the input of the light to the sample and at the output of the reflection from the sample to the detector. In a confocal microscope a pinhole is used, while in our approach the mode of the waveguide functions as aperture. The big difference is that with our approach the different modes function as different complex apertures. The light captured with the zeroth order mode gives a response equivalent with that of a confocal microscope. The response of the higher order modes gives additional information of the light reflected from the sample.

In the current design the waveguide is only multimodal in the direction along the tracks on the disc. In the direction perpendicular on the tracks the waveguide is monomodal. In principle our method for improving the resolution could be extended to this second dimension, by using a waveguide multimodal in two directions.

B. *Modulation transfer function*

A common way of measuring and comparing resolution of different imaging systems is determining the point spread function (PSF) and the modulation transfer function (MTF).

The scanning waveguide approach is a coherent detection system, which means the detected power as a function of the bit pattern along the scanning direction x_s is:

$$P(x_s) = \left| \int_z \left[bitpattern(x_s - z) \cdot psf(z) \right] \right|^2$$

The MTF, which is the Fourier transform of the PSF, shows which spatial frequencies in the sample can be resolved at the detector side. Figure 2 shows the MTF of the zeroth and the first order response. The MTF of the zeroth order responses is nearly identical to triangular shaped MTF of a confocal microscope. The MTF of the first order response is relatively bigger at the higher spatial frequencies. Both MTFs become zero at a spatial frequency of $2 \cdot NA/\lambda$. It is clear that the diffraction limit cannot be passed with this method. The aim is however to find a clever combination of the zeroth and the first order response in order to use the given bandwidth more entirely.

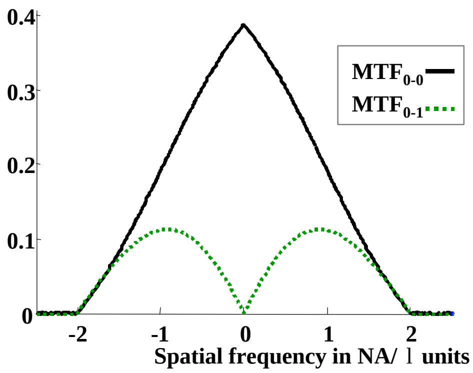

Figure 2: Modulation transfer function for zeroth and first order response.

III. Finding the correct bit pattern

A. *Mapping the responses with calculated values*

As the waveguide scans over the disk, the detectors registers both the signal from the zeroth order mode and from the first order mode. Figure 3 schematically shows the detected responses D_0 and D_1 from a sample bit pattern. Both responses suffer from crosstalk from neighboring tracks, inaccuracies on the disk itself or induced by the tracking servo.

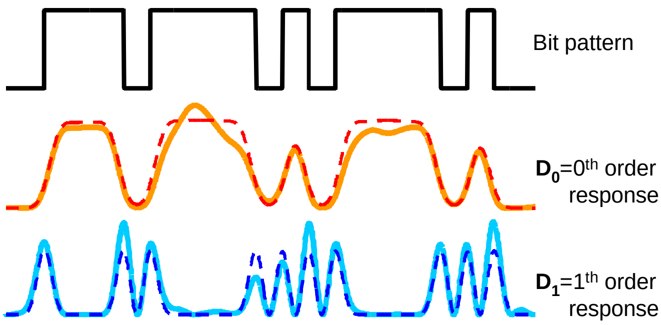

Figure 3: Bit pattern with zeroth and first order response. In dashed line: the original response. In solid line: with added noise.

The underlying bit pattern is sequentially calculated by fitting the measured response onto a series of calculated candidates as shown on Figure 4. Those calculated candidates are the theoretical responses of candidate bit patterns. In general there are 2^n candidates when n bits are set as unknowns. The other bits are either filled in by values found from previous measurements or set to a mean value in between a 0 and a 1 bit.

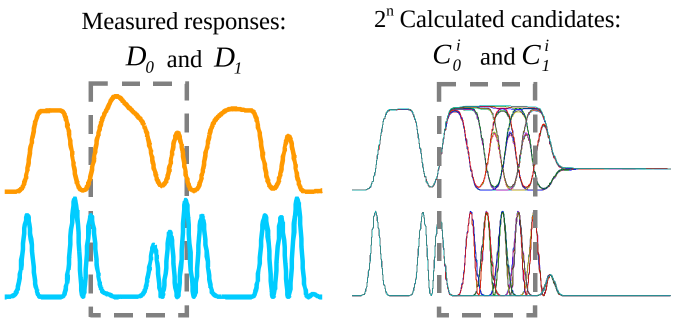

Figure 4: Measured responses and calculated candidates for zeroth and first order mode

The fitting of the measured response from the zeroth order mode with its respectively 2^n candidates gives 2^n overlap values, and so does the fitting of the first order response:

$$S_0^i = \int \left(D_0 - C_0^i \right)^2 \text{ and } S_1^i = \int \left(D_1 - C_1^i \right)^2 \quad \left(i = 1..2^n \right)$$

One could use either the lowest overlap value from the zeroth order response, S_0^i, or from the first order response, S_1^i. Both should give the correct bit pattern. The best results however, i.e. the lowest bit error rate is obtained by taking the lowest value of a well chosen (linear) combination $S_T^i = a \cdot S_0^i + b \cdot S_1^i$. This way it is possible to reduce the bit error rate below what would be possible with the zeroth order or first order response alone as can be seen on Figure 5.

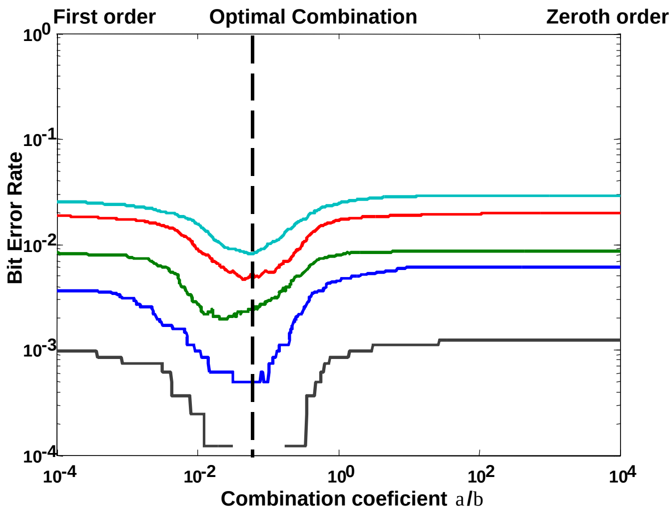

Figure 5: Bit error rates as a function of the linear combination of the two responses. The different curves denote different amount of noise.

The ultimate resolution of the systems relies heavily on the amount of noise in the system. Because of the diffraction limit and the finite simulation window, bit sizes smaller than λ/4·NA, will always result in a bit error rate will larger than zero, even in a noise free system. When adding noise the bit error rate will increase significantly. As shown in Figure 6 the optimal combination performs better than either the zeroth order or the first order response. Decreasing this bit error rate opens the way to discs with smaller bit sizes.

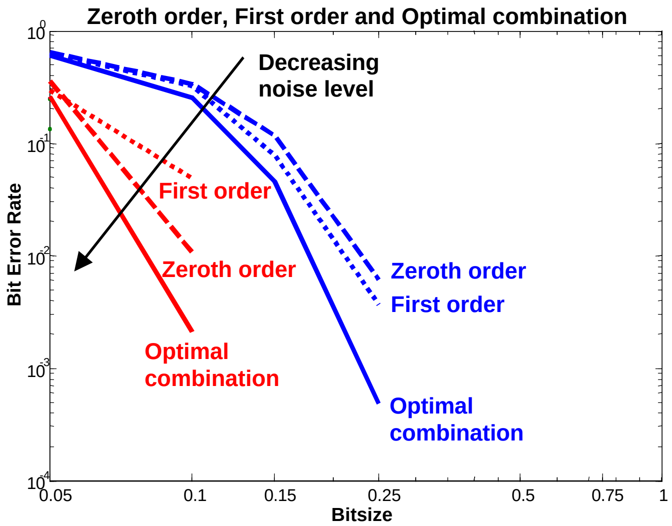

Figure 6: Bit error rate as a function of bit size (in λ/NA) units

IV. The Photonic IC

A photonic IC has been designed to split up the zeroth and first order mode to different detectors. As mentioned above a low crosstalk for the splitting of the different modes is very important. A component that splits off zeroth and first order mode has been designed and fabricated. The principle of this mode splitter is based on restricted interference in a multimode interferometer[2][3]. The components were fabricated out of a GaAs/AlGaAs-wafer with an etch depth of 180nm.

The components were measured extensively. Measurements on the isolated chip showed crosstalk from the zeroth order mode to the outer output waveguides and from the first order mode to the central output as low as –20dB, as shown on Figure 7. The component also proved to be relatively intolerant to small fabrication inaccuracies. Measurements on the ability to resolve small features written on a mask are underway

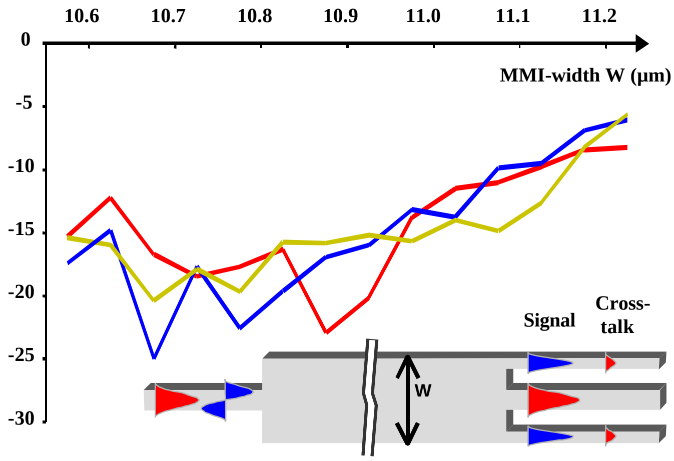

Figure 7: Measured crosstalk from the zeroth order mode to the output of the first mode, for a range of components with varying MMI width

V. Conclusion

The scanning waveguide approach can be a new method for read-out of optical disks. By detecting in parallel two different responses phase as well as amplitude information can be extracted from the reflected field. Combining the results of the two responses, the bit error rate can be improved significantly. This opens the way for read-out of smaller features and higher data density.

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