THE GENERALIZED PHASE CONTRAST METHOD IN A PLANAR OPTICS SYSTEM IMPLEMENTATION

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Introduction

The imaging and visualisation of optical phase, such as wavefront disturbances or aberrations is a challenging yet often vital requirement in optics. A number of techniques can be applied in fields ranging from optical component testing through to wavefront sensing whenever a qualitative or quantitative analysis of an optical phase disturbance is required. In general, a phase disturbance can not be directly viewed and a method must therefore be sought to extract information about the wavefront from an indirect measurement. An example of this is the generation of fringe patterns in an interferometer, which gives information about the flatness of an optical component without requiring a physical measurement of the component surface. In this presentation, we describe a powerful phase-contrast technique that we have developed at Risoe National Laboratory (called the Generalized Phase Contrast (GPC) method) for the visualisation of phase disturbances and outlining the various applications such as wavefront sensing, programmable optical tweezers and all-optical encryption. Finally, a very recent system miniaturisation of the GPC method on a planar optics technology platform developed at University of Hagen, is outlined.

The GPC method

The approach we use is based on a generalisation of the phase contrast approach of Zernike[1], which is not restricted by the so-called "small-scale" phase approximation, which limits the original method. The GPC method[2] can deal with a full 2π dynamic range of phase input and by a careful choice of the parameters for the Fourier filter to match the phase disturbance it is possible to convert the phase information into a high contrast intensity distribution[3,4]. The linearity of the technique has also been extended when compared to earlier work. A key point in the GPC method is the identification of the operating regime where a match can be achieved between the strength of the focused light in the filtering domain and the Fourier filter parameters (see Fig. 1).

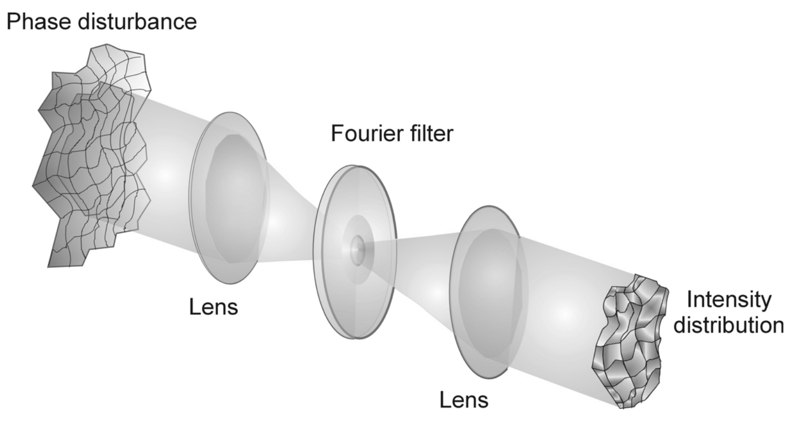


Figure 1: A schematic representation of the GPC setup based on a 4-f optical system. A region of a given input phase disturbance is sampled and generates an intensity distribution, in the image plane of the optical system by a filtering operation in the Fourier plane. The values of the filter parameters determine the type of filtering operation. A typical versatile and efficient filter would have 100% transmission and a π phase shifting central region.

If the system is applied to wavefront sensing or the visualisation of unknown phase objects the GPC method specifies the filter parameters for achieving optimal performance in extracting and displaying the phase information carried by the incoming wavefront. In the case where we have control over the incoming wavefront or phase modulation the method provides extra means of optimisation by encoding the phase distribution itself in addition to the filter parameters. This approach is particularly useful when the filter parameters have a restricted dynamic range or are fixed. The rigorous derivation of the equations for choosing these parameters can be found in refs. [3,4] and the references therein.

By controlling the input phase distribution using a phase-only spatial light modulator (SLM) a system for visualising phase objects becomes a highly effective system for the generation of intensity distributions. One particular application for the GPC technique is thus energy efficient pattern generation an example of which is shown in Fig. 2. In this case, a 2D phase pattern generates a controlled "phase disturbance" (as shown in Fig. 1) and from this filtered imaging operation a high contrast intensity pattern is obtained, the structure of which is determined by that of the phase pattern.

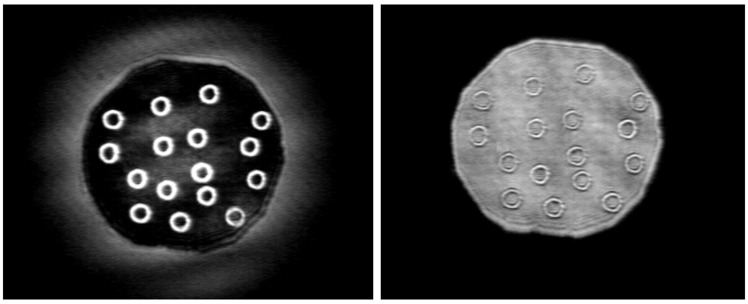


Figure 2(a): The GPC method with a phase-only SLM generating the input phase object, in this case a random distribution of doughnuts. The outer aperture is due to an iris at the input of the optical system.

Figure 2(b): With the filter removed from the optical system, contrast is lost and the input phase object is not visualised. Residual amplitude modulation in the SLM accounts for the slight visibility of the pattern.

The GPC method for programmable optical tweezers

The recent development of optical tweezers represents an extremely interesting and useful application of optics to the field of cell biology and micro-manipulation in general. Optical tweezers use the radiation pressure effect from a highly focussed laser beam to trap and manipulate micron-sized cells and particles with Pico-Newton sized forces. It is often desirable to simultaneously operate a number of optical tweezers to independently control the relative movement or placement of molecules and a number of different techniques for achieving this have been suggested. We wish to apply the GPC method in conjunction with a phase-only SLM to generate a dynamic, reconfigurable and computer controlled multiple beam tweezer system[4,5]. In such a system, the number, shape and position of tweezer beams can be modified to best suit the trapping task at hand. Using our approach, a phase-only liquid-crystal SLM encodes an image directly in the phase component of the collimated monochromatic wavefront of an expanded laser beam. This phase-encoded information serves as the input for a phase-contrast system, in which the phase-contrast filter (PCF) generates a high-contrast amplitude pattern as described in the preceding section. This amplitude pattern can then be focussed down using a microscope objective in order to produce a suitable wavefront for the optical trapping of microscopic particles. A short Real Player movie sequence of our first preliminary results with optical single-beam trapping and manipulation can be seen at the web-site:
http://www.risoe.dk/aktuelt/video/aktuelt.htm

The GPC method for optical encryption

There is widespread interest in the development of encryption systems, which operate in the optical domain. The advantages inherent in an optical approach to encryption, such as a high space-bandwidth product, the difficulty of accessing, copying or falsification and the possibility of including biometrics are widely recognised. In an encryption system, we wish to encode information in such a fashion that even if it is viewed or copied only the application of the correct key will reveal the original information. Our encryption approach is based on the direct mapping of an encrypted phase-mask and a decrypting phase key, resulting in the decryption of information completely within a phase-only domain[6]. In this system, an encrypted phase mask is decrypted with a reconfigurable phase-only key and the decoded information is subsequently visualised using the GPC method. A plane polarised monochromatic wavefront illuminates the encrypted phase mask, which consists of a random array of phase-shifting pixels. This phase-mask is produced by electronically scrambling the original pattern information we wish to encrypt with a random pattern and using this to generate an encrypted phase mask. The decrypting key effectively reverses the scrambling operation in the optical domain and results in the production of a wavefront in which the information of interest is encoded as a relative phase shift between different sections of the wavefront, in this case corresponding to the pixels[7].

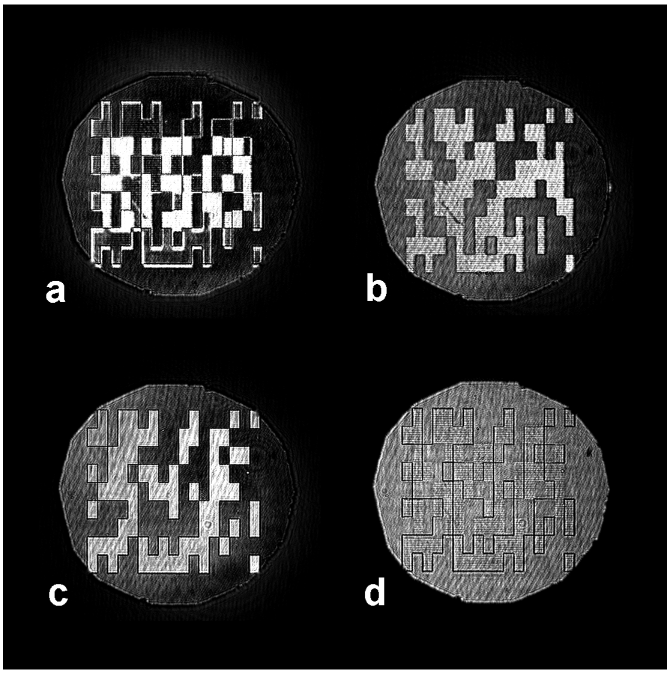
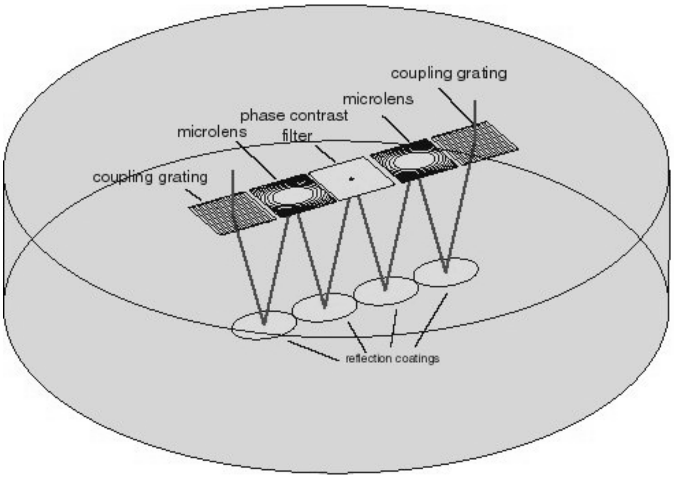


Figure 3: Decryption of a 17x9 pixel fixed mask with a 17x9 pixel dynamic key. (a) shows a successful decryption which reveals the text RISØ, (b) shows an image of the fixed phase mask viewed with the PCF and (c) shows the corresponding image for the decrypting key. If the PCF is misplaced then the decrypted information is not visualised (d). The fixed mask size is 3mm square.

Planar optics system implementation of the GPC method

Planar optics is a viable approach to micro optical system integration and is a technological platform that allows for the full integration of multiple optical components in a single transparent substrate[8]. The light propagation follows a ‘zig-zag path’ inside the substrate from a two-dimensional distribution of light modulating elements onto a matching array of detector elements. Various features make a planar optics implementation interesting e.g. monolithic integration of passive components, a folded optical axis, lithographic fabrication, hybrid integration of the optoelectronics and cost effective manufacturing through replication techniques. It is also worth pointing out that no optomechanics is required leading to stable, rugged and compact realisations.

A planar optical integration of the 4f-filtering geometry illustrated in Fig. 1 has been recently implemented at University of Hagen. Fig. 4(a) shows a schematic of the system. A perpendicularly incident wavefront, modulated with a two-dimensional phase pattern, is coupled into the substrate through a binary phase grating. The angle of propagation inside the substrate is 11.77^o for the in-coupled phase-modulated wavefront. After a zig-zag propagation through the substrate the beam is collimated by the first micro lens (with a diameter of 5 mm) which is integrated as a reflection coated 4-phase-level diffractive optical element at the top surface of the 12 mm thick substrate. After a second zig-zag propagation the beam reaches the spatial Fourier plane where a reflection coated phase contrast filter is integrated performing a π phase-shift of the focussed part of the light. An inverse spatial Fourier transform is performed by the second micro lens in a symmetric spatial configuration to the first micro lens. The final result is a GPC mapped conversion of the wavefront performed between the planes of the in-coupling and out-coupling phase gratings. The aim is to take an implemented planar optics module (as illustrated in the Fig. 4(b) photograph) and perform a range of test measurements subsequently leading to the applications described in the previous sections, experimentally demonstrated by use of macro-optics.



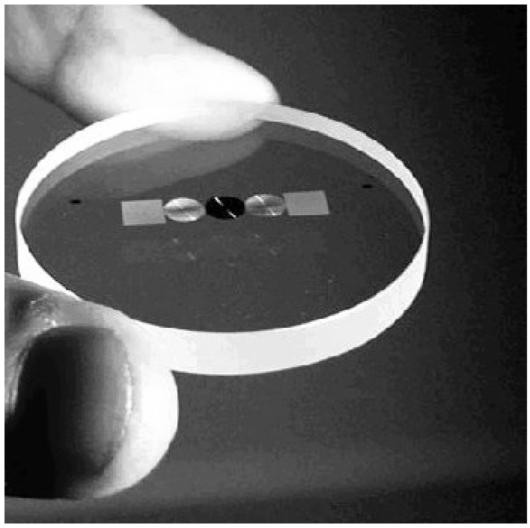


Figure 4: (a) Planar optics layout of the GPC filtering system, (b) Example implementation of 4f-filtering setup.

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