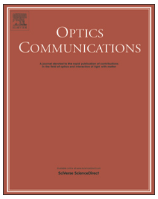
Optics Communications 342 (2015) 109–114

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom



Adaptive optimisation of a generalised phase contrast beam shaping system

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ARTICLE INFO

Article history:
Received 19 October 2014
Received in revised form
22 December 2014
Accepted 23 December 2014
Available online 26 December 2014

Keywords:
Phase contrast
Adaptive optics
Spatial light modulators

ABSTRACT

The generalised phase contrast (GPC) method provides versatile and efficient light shaping for a range of applications. We have implemented a generalised phase contrast system that used two passes on a single spatial light modulator (SLM). Both the pupil phase distribution and the phase contrast filter were generated by the SLM. This provided extra flexibility and control over the parameters of the system including the phase step magnitude, shape, radius and position of the filter. A feedback method for the on-line optimisation of these properties was also developed. Using feedback from images of the generated light field, it was possible to dynamically adjust the phase filter parameters to provide optimum contrast.

1. Introduction

Phase distributions can be converted into intensity distributions by means of a common path interferometer. This concept was used in Zernike's phase contrast microscope [1], which can be used to observe phase fluctuations introduced by transparent or semi-transparent specimens. A phase contrast system usually constitutes a 4f system where the zero order or DC component of the Fourier transform of the phase distribution is phase-shifted by $\pi/2$ in order to generate a synthetic reference wave (SRW). Once the beam is re-collimated, the SRW interferes with the spatially varying phase fluctuations, and an interferogram can be observed at the output plane. This is illustrated in Fig. 1, where $\phi(x, y)$ represents a phase disturbance across the beam, and $I(x', y')$ represents the observation plane.

While Zernike phase contrast is useful for visualising small phase fluctuations, the case of generalised phase contrast (GPC) allows for the conversion of larger phase fluctuations to intensity distributions [2]. It is advantageous to use GPC for the generation of smooth continuous intensity distributions [3]. Even when the phase modulation element is pixelated, such as when using a liquid crystal spatial light modulator, the optical transfer function of the 4f system will provide a blurring effect, which results in a smooth intensity distribution. In addition to this, GPC provides efficient conversion of the input beam to a desired intensity distribution; efficiencies of up to 85% have been reported for binary GPC of a Gaussian beam [4], while efficiencies of 74% have been reported for the generation of greyscale intensity patterns [5]. With these properties GPC has uses in applications such as targeted photo-activation of neurons [6,7], optical trapping [8,9], and quantitative measurement of an unknown phase distribution [10]. In addition to being used for intensity shaping of monochromatic beams, GPC has also been extended to broadband beams [11].

Another common method used to generate custom intensity distributions is holographic beam shaping. This technique uses phase distributions in the entrance pupil of a lens to generate an intensity pattern at the focus of the lens [12]. The appropriate pupil phase pattern can be found using methods such as the Gerchberg–Saxton algorithm [13]. While this is a powerful technique, speckle can become a problem in the focal region of the lens. GPC can overcome this difficulty as it is based around a 4f imaging system, where the output intensity distribution is conjugate to the phase modulation applied at the entrance pupil [14].

A number of other techniques have been developed for intensity shaping of both coherent and incoherent sources. These include those that use diffractive optical elements to generate intensity distributions to generate flat-top illumination [23,25,24] or more complex illumination patterns [22]. Arrays of microlenses can also be used for intensity shaping [19,20], as is described in [26], where Köhler illumination was generated using two microlens arrays. A technique using two aspheric lenses to convert a Gaussian beam to a flat-top beam has also been described [21].

A spatial light modulator is often used to generate the initial phase distribution in the entrance pupil of the system, while the

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http://dx.doi.org/10.1016/j.optcom.2014.12.059
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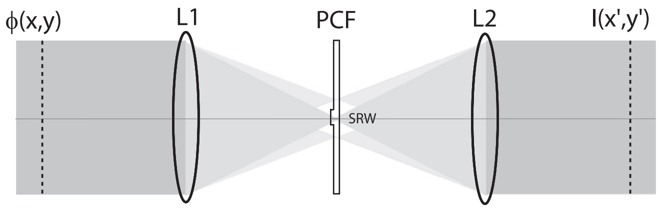

Fig. 1. Phase contrast system based on a 4f system. A phase distribution, $\phi(x, y)$, is Fourier transformed using a convex lens and a phase contrast filter (PCF) shifts the zero-order diffracted spot with respect to the rest of the diffraction pattern. After re-collimation this phase shifted spot forms a synthetic reference wave (SRW). $I(x', y')$ represents the interference between the SRW and the higher spatial frequency components.

phase contrast filter (PCF) can be constructed from a machined plate of glass, where a small area in the centre is machined such that it is thinner than the surrounding glass. Alternatively, the optical path length through the central region of the filter can be increased by the addition of a layer of material. These filters are usually static, and their parameters are chosen in advance based on theoretical calculations [2,9,6].

In this work, we used two passes on a single SLM. The first pass was used to control the pupil phase distribution, while the second generated the phase contrast filter. This provided further flexibility and stability to the system; in order to change any filter parameters no mechanical changes to the system were required, only adjustments of the phase pattern on the SLM. This setup also allowed control of the alignment of the GPC system by the optimisation of a contrast metric calculated from the output intensity distribution. This metric provided a measure of the quality of the operation of GPC setup and the suitability of the PCF parameters.

2. Background

Experimental implementation of GPC is based on a spatial filtering system [15], similar to that shown in Fig. 1, where the input phase distribution is controlled by a phase modulation device such as a spatial light modulator (SLM). Such device generates the input field, $a(x, y)$, which, for a circular aperture, is represented as follows:

$$a(x, y) = \mathrm{circ}\left(\frac{r}{\Delta r}\right)\exp(i\phi(x, y)), \tag{1}$$

where (x,y) is the coordinate system defining positions across the beam at the entrance pupil of the system, $r = \sqrt{x^2 + y^2}$, Δr is the radius of the pupil, and ϕ is the phase distribution across the beam. In the case of Zernike phase contrast, the phase distribution is approximated using the first terms of a Taylor expansion, and is valid for small phase disturbances. In the case of GPC, higher order terms in the expansion are taken into consideration, which means that GPC can be used to visualise larger magnitudes of phase than Zernike phase contrast [15].

After the phase distribution has been Fourier transformed by a lens, a phase contrast filter can be introduced, which phase shifts some of the zero-order diffracted light. This filter can be described using the following equation:

$$H(f_x, f_y) = A\left[1 + (BA^{-1}\exp(i\theta) - 1)\mathrm{circ}\left(f_r/\Delta f_r\right)\right], \tag{2}$$

where f_x and f_y are the spatial frequency coordinates in the Fourier domain and f_r is the spatial frequency radius ($f_r = \sqrt{(f_x^2 + f_y^2)}$). B is the transmittance within the diameter of the phase contrast filter, while A is the transmittance for off-axis light. θ is the magnitude of the phase step of the PCF and Δf_r is the spatial frequency radius of the filter. The central region of the PCF phase shifts a portion of the zero order of the Fourier transform with respect to the higher spatial frequency components that are diffracted off-axis.

Once the beam is re-collimated by a second lens, the phase shifted portion acts as a synthetic reference wave (SRW) that can interfere with the re-collimated higher order diffracted light. In this way the system acts as a common path interferometer which is similar to the Zernike phase contrast system. The output of the GPC system consists of the interference between the SRW and the higher spatial frequency components of the incident beam and is represented by the following expression [3]:

$$I(x', y') = A^2\left|\exp[i\phi(x', y')]\mathrm{circ}\left(\frac{r'}{\Delta r'}\right) + |\bar{\alpha}|[BA^{-1}\exp(i\theta) - 1]g(r')\right|^2, \tag{3}$$

where I is the intensity of the distribution at the output plane, (x', y') are the spatial coordinates ($r' = \sqrt{(x'^2 + y'^2)}$), $\bar{\alpha}$ is the average phase across the input phase distribution, and Δr is the radius of the aperture stop of the system. $g(r')$ represents the synthetic reference wave; for a circular aperture and circular phase contrast filter it is defined as [3]

$$g(r') = 2\pi\Delta r\int_0^{\Delta f_r} J_1(2\pi\Delta r f_r)J_0(2\pi r' f_r)\,df_r, \tag{4}$$

where Δf_r is the spatial frequency radius of the phase contrast filter and all other quantities are as previously defined.

Eq. (3) amounts to a coherent sum between its first and second terms within the modulus brackets. A number of quantities govern the expected contrast in the intensity distribution, such as the phase step of the filter, θ, the spatial frequency radius of the filter, Δf_r, the average phase across the initial phase distribution, $\bar{\alpha}$, and the transmission coefficients of the filter, A and B.

In previous work, the filter has been machined from a piece of glass and was fixed after manufacture. As a result of this, the operation of the GPC system was constrained. The experimental system, which will be described in the next section, could control all aspects of the filter, and was therefore a suitable test-bed for experiments on the effects of varying its parameters. Control over the transmission of the filter could be attained by applying a high spatial frequency pattern to the SLM, such that reflected light would be diffracted outside the aperture of the collecting lens.

3. Experimental system

The experimental system is depicted in Fig. 2. A diode laser (Edmund Optics #85-230 4.5 mW CW, $\lambda = 780$ nm) was first spatially filtered and expanded using lenses L1 and L2 and the spatial filter (SF). An iris defined the size of the beam incident on the first pass of the SLM and was set to approximately 4 mm in diameter. This was imaged onto the SLM using lenses L3 and L4. The SLM was manufactured by Boulder Nonlinear Systems (model no. P512-785), and was capable of a full wave of modulation at 785 nm. It consisted of a 512 × 512 array of pixels of size 15 μm. Turning mirrors were used to direct the beam reflected off the SLM through lens L5, which focused the beam onto an adjacent portion of the SLM. The focal length of this lens was set at 500 mm in order to keep the angles of incidence and reflection onto the SLM less than 5°. The output intensity distribution was viewed on an 8-bit CMOS camera (Thorlabs DCC1545M). In this configuration, both a pupil plane and a focal plane could be simultaneously controlled using adjacent parts of the SLM.

LABView software was written to control all aspects of the system controlled by the SLM, such as the input phase distribution