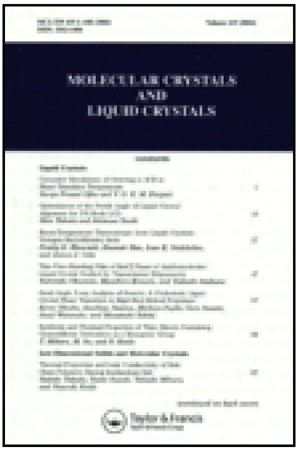

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Phase-only Spatial Light Modulation by the Reverse Phase Contrast Method

Jesper Glückstad [a] , Paul C. Mogensen [a] & René L. Eriksen [a]
[a] Department of Optics and Fluid Dynamics, Riso National Laboratory, Roskilde, DK-4000, Denmark

Version of record first published: 18 Oct 2010

To cite this article: Jesper Glückstad, Paul C. Mogensen & René L. Eriksen (2002): Phase-only Spatial Light Modulation by the Reverse Phase Contrast Method, Molecular Crystals and Liquid Crystals, 375:1, 679-688

To link to this article: http://dx.doi.org/10.1080/713738327

Mol. Cryst. Liq. Cryst., Vol. 375, pp. 679-688

1058-725X/02 $12.00 + .00

Phase-only Spatial Light Modulation by the Reverse Phase Contrast Method

JESPER GLÜCKSTAD, PAUL C. MOGENSEN and RENÉ L. ERIKSEN

Department of Optics and Fluid Dynamics, Risø National Laboratory, DK-4000 Roskilde, Denmark

A new approach to phase-only spatial light modulation is proposed in which a given amplitude pattern can be converted into a spatially identical binary phase pattern. A spatial filtering approach is applied to transform spatial amplitude modulation into spatial phase modulation using the Reverse Phase Contrast (RPC) method. The analytical method for achieving this is outlined and experimental results are shown for the generation of a binary phase-only distribution using an amplitude spatial light modulator and a phase-only spatial filter.

Keywords Wavefront generation; spatial light modulator; phase modulation; generalised phase contrast; reverse phase contrast

1. INTRODUCTION

The generation of a well-controlled phase distribution has a number of applications in contemporary applied optics and there currently exist a number of techniques for producing such phase modulation of an optical wavefront. These include for example electrically or optically addressed phase-only spatial light modulators (SLMs) which modulate the phase of a wavefront by a spatial variation in the optical path length of transmitted or reflected light. Accurate phase-only SLMs are rather complicated and expensive items, and we are thus interested in a simple practical technique for producing reconfigurable two-dimensional phase modulation.

In this presentation, we propose a technique for the conversion of a given amplitude pattern to a phase distribution by a technique which we refer to as the Reverse Phase Contrast (RPC) method [1]. In this method, a high contrast amplitude mask is used to generate a phase encoded version of the amplitude pattern. A spatial filter determines the resultant phase shift between the elements of the output wavefront. Using a liquid-crystal based phase-contrast filter the dynamic range of the phase modulation can be adjusted arbitrarily within the interval $]0;\pi]$. Thus combining an amplitude modulator with a tuneable phase filter would result in a high performance phase-only SLM in which the spatial light modulation and phase shift are effectively decoupled. The motivation for such a scheme is that we would like to achieve dynamic high-performance spatial phase modulation using relatively low-cost, widely available amplitude based spatial modulators. Reconfigurable spatial phase modulation of a light field is required in a number of areas in optics, including phase modulation for holographic multiplexing, storage and encoding [2], phase-only encryption and decryption [3] and the testing of focus in optical apparatus [4]. In addition, the RPC technique can be used with a binary amplitude mask acting as the input information to create interchangeable but static phase distributions. In the case of a fixed phase distribution, a major advantage of the use of amplitude masks to define the required phase pattern is the relative simplicity with which they can be manufactured when compared to phase-only elements. The use of standard chrome on glass mask technology would make it possible to achieve high resolution phase patterns, the phase shift of which would be controlled by the filtering system. In fact, it is possible to tune the output phase shift via the contrast ratio of the mask or by tuning the filter parameters. If a dynamic phase modulator is required, then an amplitude modulator, in the form of a commercially available liquid crystal display (LCD) projector element, or possibly a MEMS (Micro Electronic Mechanical System) type device can be used.

In the remainder of this paper, we describe the basis of the RPC technique, including a brief theoretical treatment. We discuss the requirements for a generic RPC based SLM and present experimental results for an RPC system with dynamic amplitude modulation and a fixed phase mask and discuss important criteria for the experimental implementation of the RPC technique.

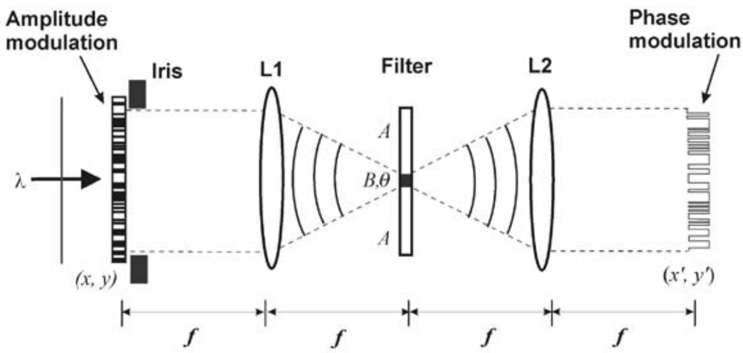

FIG. 1 RPC set-up based around a 4-f optical system.

2. OPTICAL ARCHITECTURE

The experimental set-up in which we consider the implementation of the RPC method is based on the Fourier plane spatial-filtering 4f system, which is shown schematically in Fig. 1. The output phase modulation is directly generated from an input amplitude pattern and is obtained by applying a truncated, on-axis, filtering operation in the spatial frequency domain between two Fourier transforming lenses. The first lens (L1) performs a spatial Fourier transform, so that directly propagated light is focused onto the on-axis filtering region (with transmission factor B), whereas spatially varying amplitude information generates light scattered to locations outside this central region (with transmission factor A). By tuning the differential phase shift (θ) and amplitude transmission in these two filtering regions we can optimise a filtered output pattern to display phase-only modulation with a given phase depth on a constant background light level at the observation plane by use of the second Fourier lens (L2).

3. ANALYSIS OF SYSTEM PARAMETERS

The first step in the mathematical analysis is the derivation of a relationship between the input amplitude values and the output light field, which is in general complex valued. The approach we adopt in the analysis of the RPC method is based on that used in the derivation for the optimisation of the generalised phase contrast method (GPC) [5]. However, the RPC method uses input spatial amplitude modulation and not phase modulation, which leads to a completely different behaviour from that of the GPC method.

We thus consider an arbitrary binary input amplitude modulation spatially distributed over a circular input aperture with a radius, Δr. In this case, the amplitude modulation $\alpha_{\min} \in [0;1[$ is found in the region denoted $\Re_{\min}$ and $\alpha_{\max} = 1$ (normalised to unity for maximal light throughput) is modulated in the remaining region $\Re_{\max} = (\pi \Delta r^2 - \Re_{\min})$, so we can write:

$$\alpha(x,y) = \begin{cases} \alpha_{\min} & \text{for } (x,y) \in \Re_{\min} \\ 1 & \text{for } (x,y) \in \Re_{\max} \end{cases} \tag{1}$$

The spatial average of this binary amplitude modulation over the circular input aperture is found to be :

$$\overline{\alpha} = (\pi \Delta r^2)^{-1} (\Re_{\min} \alpha_{\min} + \Re_{\max}) = 1 + F(\alpha_{\min} - 1) \tag{2}$$

where, $F = (\pi \Delta r^2)^{-1} \Re_{\min}$, indicates the fractional area or 'fill factor' of the $\Re_{\min}$ region to the overall input aperture area.

At the output of the RPC system we obtain a complex amplitude given as a function of the input in Eq. (1) and the influence of the spatial filtering operation [5]:

$$o(x',y') = A\left[\alpha(x',y') + K\overline{\alpha}|C|\exp(i\psi_C)\right] \tag{3}$$

where

$$C = |C|\exp(i\psi_C) = BA^{-1}\exp(i\theta) - 1 \tag{4}$$

describes a combined complex valued filter parameter governed by the three filter parameters (A,B,θ) indicated in Fig. 1 and

$$K = 1 - J_0(2\pi \Delta r \Delta f_r) \tag{5}$$

uses the zero-order Bessel function to describe the influence of the finite on-axis spatial frequency filtering radius, Δf_r, on the focused light in the Fourier plane of the first lens in Fig. 1. It is thus effectively included as an extra "filtering parameter" so that the four-parameter filter set (A, B, θ, K) together with the object dependent term, $\overline{\alpha}$, effectively defines the type of filtering scheme we are applying.

A principal requirement of the RPC method is that we desire a flat output intensity distribution in which the phase modulation will be present, we must therefore satisfy the following condition:

$$\left|\alpha_{\min} + K\overline{\alpha}|C|\exp(i\psi_C)\right| = \left|1 + K\overline{\alpha}|C|\exp(i\psi_C)\right| \tag{6}$$

where the output phase modulation is given by:

$$\exp(i\Delta\phi_o) = \frac{\alpha_{\min} + K\overline{\alpha}|C|\exp(i\psi_C)}{1 + K\overline{\alpha}|C|\exp(i\psi_C)} \tag{7}$$

Combining these equations we can now derive the following expression for the combined filter parameter, C:

$$C = |C|\exp(i\psi_C) = \frac{\left(-1 - \alpha_{\min} + i(1 - \alpha_{\min})\cot(\Delta\phi_o / 2)\right)}{2K\left(1 + F(\alpha_{\min} - 1)\right)} \tag{8}$$

Finally, we can produce an Argand diagram as shown in Fig.2, in which the complex vectors on either side of Eq.(6) are plotted. Referring to Fig 2 it can be seen that the angle, $\Delta\phi_o$, between the two solution vectors $o(\alpha_{\min})$ and $o(1)$ gives the depth of the output phase modulation.

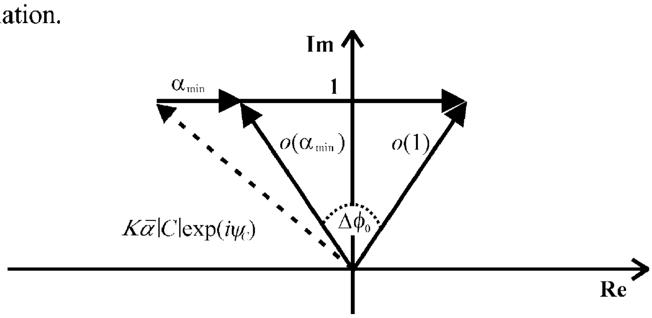

FIG. 2 Argand diagram showing the solution vectors $o(\alpha_{\min})$ and $o(1)$ for Eq. (6) with a constant intensity background and the desired phase modulation $\Delta\phi_o$.

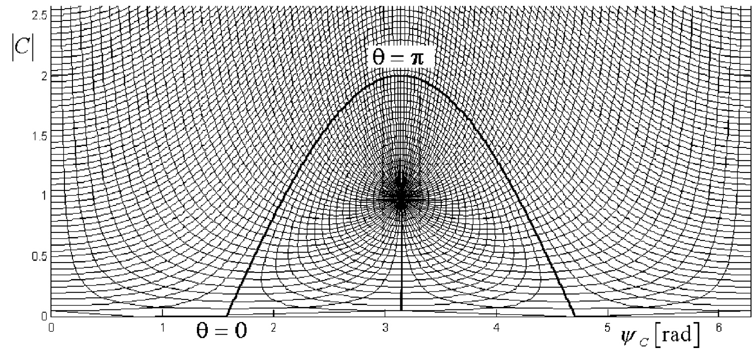

FIG 3. Complex filter space plot of the modulus of the combined filter parameter, $|C|$, against the phase ψ_C over the complete 2π phase region. The bold curve is the operating curve for a phase-only (lossless) filter, whilst the fine grid represents operating curves for differing values of the filter terms *A, B* and *θ*.

As previously pointed out, any given filter can be explicitly defined by a given value of the two parameters ψ_C and $|C|$ in Eq. (4). We can therefore use a single plot to display the location of a given filter graphically within this complex filter space. Such a plot is shown in Fig. 3 where we plot the magnitude of the combined filter parameter $|C|$ against its phase ψ_C. There exist different families of operating curves in this complex filter space each of which can be traced out by keeping a term such as BA^{-1} constant while θ is varied or vice versa (these form the fine grid like structure in Fig.3). Plotting the operating curves for C this way makes it relatively simple to identify particular operating regimes for different classes of filters. For example, we are particularly interested in the operating curve for a lossless Fourier filter, a filter in which $BA^{-1} = 1$, since this is a class of filter for which optical throughput is maximised. The lossless operating curve is shown as the bold line in Fig. 3. We can derive the expression for the shape of the lossless operating curve by using the following identity:

$$C_{lossless} = \exp(i\theta) - 1 = 2|\sin(\theta/2)|\exp(i(\theta+\pi)/2) \qquad (9)$$

leading to an expression for the lossless operating curve, for which $|C|$ is defined for two distinct regions as:

$$\begin{cases} |C_{lossless}| = 2|\cos(\psi_C)| & \text{for} \quad \psi_C \in [\pi/2; 3\pi/2] \\ |C_{lossless}| = 0 \quad \text{for} \quad \psi_C \notin [\pi/2; 3\pi/2] \end{cases} \tag{10}$$

By studying the phasor diagram in Fig. 2 it is clear that we always need a filter providing a combined filter phase within the interval $\psi_C \in [\pi/2; \pi]$ or within the interval $\psi_C \in [\pi; 3\pi/2]$. These intervals of operation are exactly covered by the phase-only filter parameters described in Eq. (10) and indicated by the bold line in Fig. 3.

Having considered the requirements for a lossless filtering operation, we are in a position to look at the operating constraints for a generic phase modulator based on the RPC method. In Fig 4, we show a schematic representation of such a phase modulator, which utilises an input amplitude modulator and a phase-only filter in which the phase step can be tuned. This type of dynamic phase-only filter can be fabricated from a homogenous parallel-aligned liquid crystal cell in which a change in the voltage drop across the cell changes the phase shift induced by the liquid crystal. A portion of one of the transparent electrodes is removed so that a region of the liquid crystal is not modulated and this region serves as the central filtering region of the phase only filter. The output from such a system would be a binary phase distribution, the phase depth of which would be tuned by adjusting the phase shift of the filter and addressing levels in the input amplitude modulator. We would ideally like the output phase depth to be variable between 0 and π which leads to a similar phase range requirement for the filter. The input modulator would ideally be of high enough contrast and resolution so as to be able to generate an adjustable virtual aperture the size of which can be adjusted to control the parameter K in Eq. (5). Fixed elements can be used for either the input mask or the phase filter, which although clearly restricting the

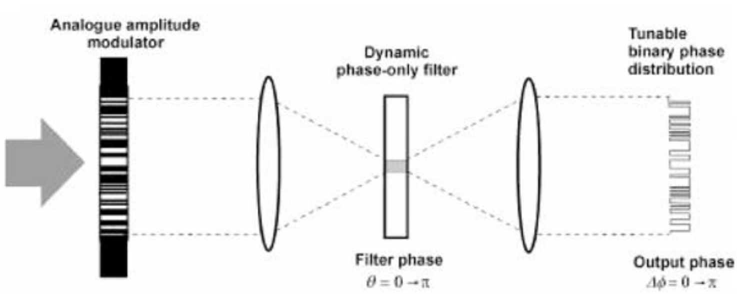

Fig. 4 Generic RPC based phase-only spatial light modulator.

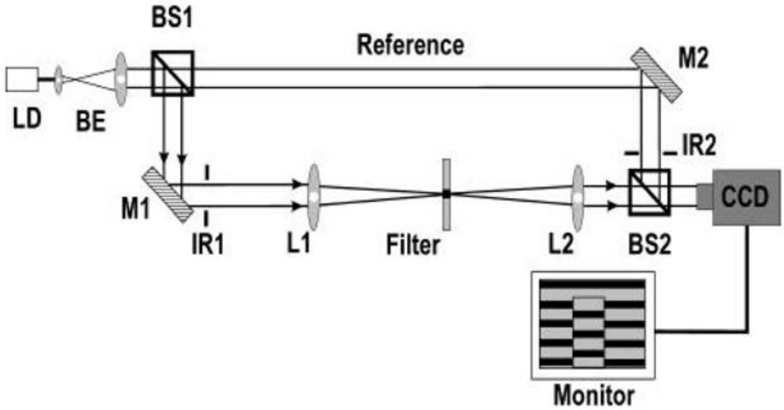

FIG 5. Experimental set-up for the implementation and characterisation of the RPC method

flexibility of the modulator, may be sufficient for simple modulating requirements.

4. EXPERIMENTAL RESULTS

We have undertaken experiments to characterise the performance of the RPC technique using both fixed amplitude masks and spatial light modulators for the input amplitude modulation. In the experimental system, shown in Fig.5, we have used a 635nm laser diode (LD) as the light source and this has been spatially filtered, expanded and collimated with a beam expander (BE) to generate an approximately plane wavefront. The 4-*f* system containing the Fourier filter is formed by lenses L1 and L2 (f=200mm) and the amplitude modulation (AM) occurs in the plane of the iris (IR1), which acts as the input aperture for the RPC system. Since we need to measure phase at the output of the system, an interferometer has been constructed so that a fringe measurement can be used to determine the region in which the output phase modulation occurs. The beam splitters (BS1 and BS2) and mirrors (M1 and M2) thus form the reference arm for a Mach-Zender interferometer in which the output fringes are recorded on a CCD camera. The second iris (IR2) is used to control the size of the reference beam. The Fourier filter used for the experiments in this paper is a phase-only filter with no amplitude damping. The central region of this

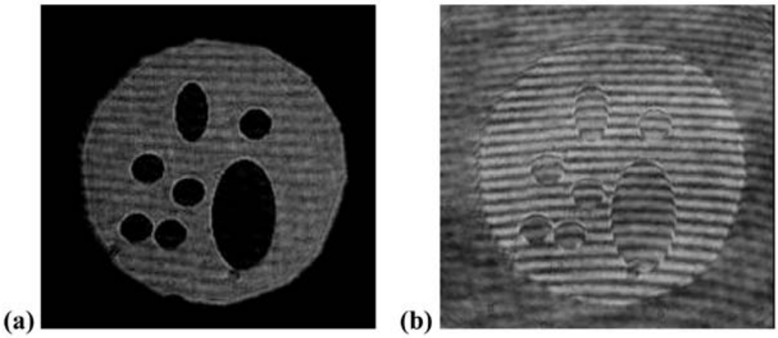

Fig. 6 Experimental results for the generation of phase modulation using an SLM operating as the input amplitude modulator. These show (a) an image of the input amplitude distribution without the filter in place and (b) interference fringe measurement of the output phase modulation.

circularly symmetric filter consists of a 60μm diameter phase shifting region, the thickness of which gives a phase shift of π at 635nm.

We used a Hamamatsu parallel-aligned liquid crystal modulator, in conjunction with polarisors to generate binary on/off modulation of the amplitude of the input wavefront with a 25 % fill factor. In general, such an SLM will have a lower contrast than a fixed mask and the resolution of the resulting phase distribution will be limited to that of the modulator.

In Fig 6(a), we show the input image without the Fourier plane filter in place. The image consists of a number of circular and ellipsoidal dark regions on a light background. The 4mm iris is slightly out of focus due to an axial displacement between the SLM and iris and some slight interference fringes are visible due to stray light scattered off the beam-splitter placed in front of the SLM. The interferometric measurement of the phase is shown in Fig. 6(b) and it can be clearly seen that there is a binary phase modulation imposed on a uniform amplitude wavefront. The fringe spacing indicates that we have a phase shift of approximately π in the output modulation and have thus successfully converted our input amplitude distribution into a spatially identical phase distribution. The fringes in the region outside the aperture are due to the small fraction of light scattered by the filtering operation.

5. CONCLUSION

We have demonstrated that the Reverse Phase Contrast technique is a viable method for the generation of a binary phase distribution by the conversion of a spatially varying amplitude distribution using Fourier plane filtering techniques. The strength of the RPC method is that it effectively decouples the output phase modulation from the input spatial distribution that one wishes to have. We have demonstrated the effectiveness of the RPC method to generate phase-only spatial light modulation by using an amplitude spatial light modulator and a phase-only spatial filter . We are able to explain the form of the output and its dependence on the input from a sound theoretical foundation and the RPC technique can compete in terms of robustness and accuracy with either fixed or dynamic phase elements.

Acknowledgements
This work is funded as part of an award from STVF, the Danish Technical Scientific Research Council.

References

1) J. Glückstad, US patent application 60/257,093 (priority date 22 Dec. 2000).
2) C. Denz, G. Pauliat, G. Roosen, T. Tschudi, Opt. Comm. **85**, pp. 171-176 (1991).
3) P. C. Mogensen and J. Glückstad, Appl. Opt. **40**, pp. 1226-1235 (2001).
4) S. Jutamulia, Appl. Opt. **33**, pp. 280-282 (1994).
5) J. Glückstad and P. C. Mogensen, Appl. Opt. **40**, pp 268-282 (2001).