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Dark GPC: extended nodal beam areas from binary-only phase

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Abstract. We show a simplified method of generating extended regions of destructive interference with near arbitrary shapes using the generalized phase contrast (GPC) method. For Gaussian input beams, GPC typically results in a 3× intensified user-defined input mask shape against a dark background. In this work, we investigate conditions wherein GPC's synthetic reference wave destructively interferes with what is typically the foreground pattern. Using alternate conditions for the input phase mask, the locations of light and darkness are interchanged with respect to typical GPC output mappings. We show experimentally how "dark GPC" allows the dark regions to be easily reshaped using a binary-only phase mask encoded on a spatial light modulator. Similar to standard GPC, the method does not require complex calculations or the fabrication of complex gray-level phase elements. The simplified approach and flexibility in the output shapes make dark GPC attractive for applications such as optical trapping of low-index particles or superresolution microscopy like stimulated emission depletion. [DOI: 10.1117/1.OE.55.12.125102]

Keywords: laser beam shaping; interferometry; binary-only phase filters; spatial light modulators.

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1 Introduction

Structured light distributions have been used in applications such as optical trapping and manipulation,[1–3] optical sorting,[4,5] advanced microscopy, and selective uncaging or excitation[6] in neurophotonics or optogenetics.[7] In some applications, however, it is desirable to divert light from a particular region, and "light shaping" techniques are used to create well-defined patterns of darkness, on top of a bright background. For example, bounded regions of darkness are used in defining potential distributions for atom trapping, optical trapping of low-index media,[8–10] and in stimulated emission depletion microscopy.[11]

Another important imaging application is coronography in astronomy. Modern uses divert light from an overpowering bright source (e.g., star) to increase the visibility of some weaker signals (e.g., an orbiting planet). Early coronagraphs use an amplitude mask and were originally designed by Lyot in the 1930s. However, Lyot's amplitude masking has inherent limitations, such as completely blocking light within its physical extent and thereby inherently blocking objects of interest.[12] A more light-efficient alternative is to implement phase-only coronography where undesired light can be canceled by destructive interference, as is the case for so-called common path interferometers. The phase-only approach typically uses a disk-shaped phase mask filter in the focal plane of a telescope. The disk-shaped phase mask filter is positioned can introduce a π-phase shift to a small portion of the Airy disk pattern.[13] The unperturbed and phase-shifted portions of the incident light can then destructively interfere at the exit pupil of the coronagraphic setup. Instead of a single-phase shifting region, an improvement in the design uses a quadrant arrangement of π-phase shifting regions, which is more robust compared with the disk phase mask.[14] A vortex spatial filter has been later introduced by Swartzlander.[15] A subwavelength surface-relief grating coined the annular groove phase mask by Mawet et al.[12] was also used to create a spiral phase of topological charge $l_p = 2$. Mawet et al. have also analytically shown the formation of a nodal area.

In the aforementioned examples, the geometry of the resulting nodal area is circular. Currently, techniques for creating structured darkness typically use optical vortices created by static phase plates[16] or computer-generated holograms.[17] Laguerre–Gaussian beams or other similar beams containing singularity have limited control over the lateral shape of the dark region. Having control over the darkness shapes while maintaining sharp transitions from dark to bright brings more possibilities and flexibility. For example, engineering such dark regions to shapes other than circular can lead to specifically designed dipole traps.[18] Potential uses in laser-materials processing can include shielding or cutting out user-defined shapes.

Recently, a $4f$ approach using optimized phase elements at the Fourier plane has been demonstrated.[19] Although successful in creating so-called "dark nodal areas," the complexity of designing and fabricating such vortex-like phase elements can be prohibitive for practical applications. In principle, any light shaping technique, even photon-inefficient amplitude modulation, can be used to form voids on top of a background of light. Furthermore, one could always mathematically and philosophically argue that any darkness is a result of destructive interference. We set our work apart by having a clearer physical description in which waves are actually destructively interfering. Further, we deliberately tweak the superposed waves, so they are out-of-phase within desired patterns that can take up a wide variety of shapes.

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2 Theory

A straightforward approach in creating a dark region is amplitude masking. This approach can be extended to project arbitrary and dynamic patterns using a spatial light modulator (SLM) such as a digital micromirror device (DMD).[20,21] The fast switching of DMD elements enables rapid adaptive beam shaping and can project grayscale images as well. Phase-only masking is an alternative way to beam shaping and can achieve much higher photon efficiencies for light projection. Phase-only masking is performed by modifying an incoming light wavefront, so constructive interference occurs at desired target locations at the output. To create a dark region by phase-only masking, a portion of the incident beam is made to be out-of-phase to form destructive interference when recombined at the output projection plane. The creation of a dark core by destructive interference is fairly easy to grasp physically if we think of it as sum of areas. If for example π-phase-shifted regions are regarded as negative areas and unmodulated regions as positive areas, then they will result in a net sum of zero after performing an optical Fourier transformation. A phase filter with π-phase-shifted radially opposite regions added at the focal plane will, however, result in a destructive interference within the geometric area of the pupil after taking the Fourier transform. This has been observed in the four-quadrant, vortex, and annular groove phase filters mentioned earlier. The disk phase mask is different as it makes the "opposite" areas cancel not straightforward. Our method similarly uses a common path interferometer setup, where we show that we can switch operation between constructive to destructive interference by placing appropriate binary masks and filters. We present calculations based on on-axis amplitude matching to obtain parameters to aid in the production of the masks and filters and to adapt to arbitrary patterns.

The generalized phase contrast (GPC) method is normally used for efficient phase-only shaping of light into speckle-free contiguous optical distributions. The method is useful for applications such as static beam shaping, optical manipulation, or excitation in two-photon optogenetics. It operates by synthesizing a reference wave that interferes with an imaged phase-modulated input light. The input $(0-\pi)$ phase modulation can have near-arbitrary or user-defined two-dimensional distributions and directly governs where constructive and destructive interferences happen at the output. Although seldom emphasized, standard "bright GPC" works by creating an extended region of destructive interference that is negative to the shaped foreground. Furthermore, one can "poke" dark holes on top of a bright GPC pattern, offering greater freedom on the location of the dark regions as used, for example, to manipulate microparticles with low refractive indices.[9,22] In this work, however, we maximize the area of destructive interference by finding alternative modalities and conditions that make the synthetic reference wave (SRW) out-of-phase with the imaged foreground pattern. A practical advantage of having a larger darkness region is the utilization of more pixels in the SLM, which leads to more detailed or well-defined darkness regions. The higher resolution may make the dark patterns practical for laser materials processing, for example.

A standard GPC light shaping setup derives from a $4f$ imaging configuration wherein a laser-illuminated phase-only mask is transformed into a corresponding shaped

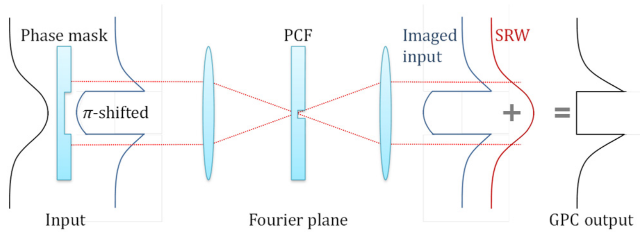

Fig. 1 A GPC configuration generating an SRW that destructively interferes with imaged input foreground pattern.

optical intensity. GPC maps the phase input into an intensity output using a binary phase contrast filter (PCF) situated at the Fourier plane that is responsible for forming the SRW. The SRW, formed from the phase-shifted low-frequency components of the input, interferes with the $4f$-imaged input phase mask, hence increasing the intensity within the mask's shaped foreground region while forming darkness outside this region. The interfering fields can be seen clearly in Fig. 1. Mathematically, the GPC output can be written as

$$E_{\text{out}}(r) = E_{\text{in}}(r) + E_{\text{SRW}}(r). \tag{1}$$

In this manner, it is easy to see that constructive or destructive interference will depend on the balance of the amplitudes between the two terms in Eq. (1). The amplitude of the SRW is dependent on the size of the phase mask and PCF and implies that an optimal pairing can be found. To optimize the light throughput (efficiency) in the shaped region, we have previously derived the optimally matching sizes of the phase mask and PCF given the laser source's Gaussian half-waist, w_0, wavelength, λ, and Fourier lens's focal length, f.[6] In practical usage, the PCF size is held fixed while the input phase mask is swappable or programmable through a dynamically reconfigurable SLM. Our theoretical analysis has previously shown that the optimal PCF phase-shifting radius, Δr_f, should be 1.1081 times the Fourier Gaussian half-waist, w_f. A matching phase mask size has also been identified for different shapes and has been demonstrated experimentally to yield efficiently shaped beams.[23]

For a GPC setup, generating darkness means finding configurations for which the SRW destructively interferes with the shaped foreground region. Since the PCF is usually fixed in our applications, we look for phase mask distributions, $\phi(x,y)$, that will cause Eq. (1) to nullify at the phase-encoded shaped region. A quick look on the effect of the size of the phase mask distribution for a circular pattern of radius $\Delta R = \zeta w_0$ is shown in Fig. 2. At some radius corresponding to $\zeta \approx 1.02$, destructive interference occurs, forming a nodal area.

From an engineering standpoint, it will be helpful to have a working relation between phase mask and PCF given in terms of the parameters η and ζ. In general, an analytic form for the SRW cannot be found easily, especially since the phase mask can take in arbitrary nonanalytic forms. However, for slowly varying phase mask distribution such as a circle, it can be approximated by a sum of Gaussian functions. Consider an input beam such as a laser beam with a Gaussian profile $a(r)$. When the laser beam passes through a phase mask containing the target pattern $\phi(r)$, it is modulated as $E_{\text{in}}(r) = a(r)\exp[i\phi(r)]$. For a circular phase mask, the modulation takes the form of $\phi(r) = \pi\text{circ}(r/\zeta w_0)$, and

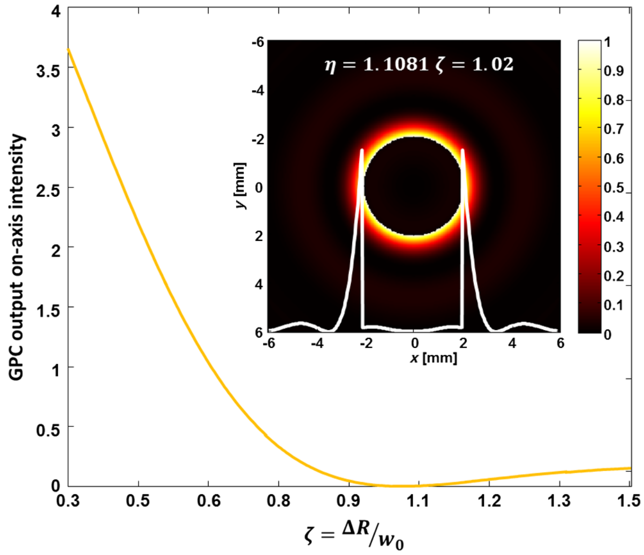

Fig. 2 GPC output central intensity as a function of the relative radius, $\zeta = \Delta R/w_0$, of a circular phase mask for a fixed PCF ($\eta = \Delta r_f/w_f = 1.1081$). Inset (Video 1): profile of the GPC output at ζ value corresponding to the lowest central intensity with line scan taken horizontally across the center of the output pattern (Video 1, QuickTime Mov, 954 KB [URL: http://dx.doi.org/10.1117/1.OE.55.12.125102.1]).

the input field becomes $E_{\text{in}}(r) = a(r) - 2\text{circ}(r/\zeta w_0)a(r)$. The first lens takes the Fourier transform of E_{in} and is multiplied by the transfer function of the PCF. The circular π-phase-shifting region of the PCF has a radius of Δr_f corresponding to frequency cutoff $\Delta f_r = \eta f_0$, and thus the transfer function is given by $H(f_r) = 1 - 2\text{circ}(f_r/\eta f_0)$. The PCF can be seen as a low-pass filter where the low-spatial frequency components are π-phase shifted. The field is once again Fourier transformed by the second lens and the output is given by

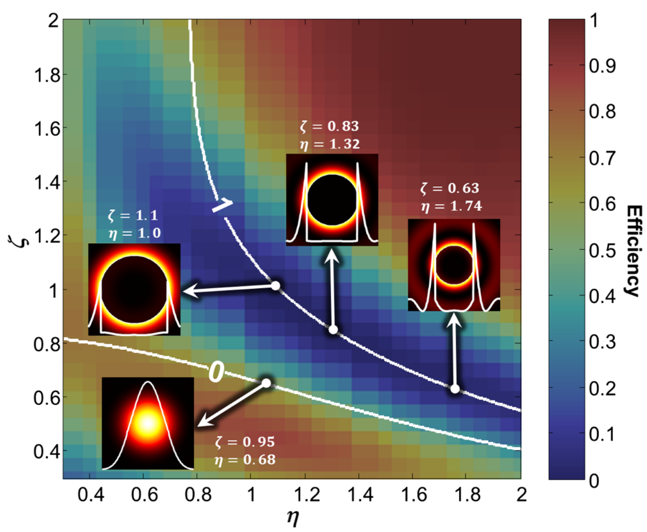

Fig. 3 Efficiency map for different η and ζ pairs. The bands show the regions of bright and dark GPCs. An overlay of Eq. (4) represented as contour lines for $E_{\text{SRW}}(0) = 1$ and 0 shows that on-axis amplitude matching can be used to get optimal parameters. Line scans of the intensity profiles are taken horizontally across the center.

$$E_{\text{out}}(r) = E_{\text{in}}(r) - \mathcal{F}^{-1}\{2\text{circ}(f_r/\eta f_0) \cdot \mathcal{F}[E_{\text{in}}(r)]\}. \quad (2)$$

The term $E_{\text{SRW}}(r) = -\mathcal{F}^{-1}\{2\text{circ}(f_r/\eta f_0) \cdot \mathcal{F}[E_{\text{in}}(r)]\}$ represents the SRW. For an input circular phase mask, $E_{\text{in}}(r)$ will have a circ function in the phase term and be multiplied with a Gaussian profile, and the $E_{\text{SRW}}(r)$ will involve convolution of Gaussian and jinc functions. To simplify the calculation, the jinc is approximated with a Gaussian function. For $\text{circ}(f_r/\eta f_0)$, which transforms into $2\pi\eta^2 f_0^2 \text{jinc}(2\pi\eta f_0 r)$, the Gaussian approximation is given by $\pi\eta^2 f_0^2 \exp(-\pi^2\eta^2 f_0^2 r^2/d_0^2)$, where $d_0 = 0.37\pi$. The parameter d_0 is chosen to match the central part of the jinc. The convolution is now between two Gaussian functions and simply results in a broadened Gaussian function. However, this does not account for the negative values in the original jinc function, and the amplitude should be corrected. The correct central amplitude can be analytically obtained[6] as $\pi f_0[1 - \exp(-\eta^2)]$. This correction is done for every instance of Fourier transform of a bounded Gaussian function. Finally, we arrive at the following approximate equation for the GPC output:

$$E_{\text{out}}(r) = E_{\text{in}}(r) - 2(1 - e^{-\eta^2})e^{-\frac{r^2}{k_\eta^2 w_0^2}} + 4(1 - e^{-\zeta^2})\left(1 - e^{-\frac{\eta^2}{k_\zeta^2}}\right)k_\zeta^2 e^{-\frac{r^2}{w_0^2}\left(\frac{k_{\eta/k_\zeta}^2}{k_\zeta^2}\right)^{-1}}, \quad (3)$$

where $k_\eta^2 = (\eta^2 + d_0^2)/\eta^2$, $k_\zeta^2 = (\zeta^2 + d_0^2)/\zeta^2$ and $k_{\eta/k_\zeta}^2 = (\eta^2/k_\eta^2 + d_0^2)/\eta^2/k_\zeta^2$. Assuming the input field has a unit on-axis amplitude, we also require the SRW to have a value equal to one. Thus, the "darkness" condition can be written as $E_{\text{SRW}}(0) = -E_{\text{in}}(0)$. For the circular π-phase shifted mask that we used, the input amplitude is $E_{\text{in}}(0) = -1$; thus,

$$-2(1 - e^{-\eta^2}) + 4(1 - e^{-\zeta^2})(1 - e^{-\eta^2/k_\zeta^2})k_\zeta^2 = 1. \quad (4)$$

To see whether Eq. (4) will lead to the creation of a dark area, we compute for the efficiency, which we define as the power within the area defined by the phase pattern divided by the incident power. Dark nodal areas are therefore those resulting in low efficiency. An efficiency map is shown in Fig. 3, where an overlay of Eq. (4) shows that on-axis amplitude matching is sufficient to identify combinations of parameters that will result in darkness. The parameters that will result in bright GPC can also be seen. The insets in Fig. 3 show the calculated GPC outputs for selected $\zeta - \eta$ pairs. Interestingly, there are parameters where the on-axis SRW amplitude is zero and the Gaussian input reappears.

3 Experiments and Results

The dynamic GPC setup used for the dark GPC experimental verifications is described in an earlier work[23] and illustrated in Fig. 4. A liquid crystal on silicon SLM (Hamamatsu Photonics) is used to generate arbitrary binary input phase patterns. The SLM has an area of $16 \times 12\ \text{mm}^2$ and pixel pitch of $20\ \mu\text{m}$. For this proof-of-principle demonstration, the SLM has been illuminated with a 532-nm filtered super-continuum laser, polarized and expanded such that $2w_0 = 4$ mm (corresponding to 200 SLM pixels). The Fourier lens used has a focal length of 100 mm, and the PCF's radius, Δr_f, is $9.4\ \mu\text{m}$. To form arbitrary patterns of

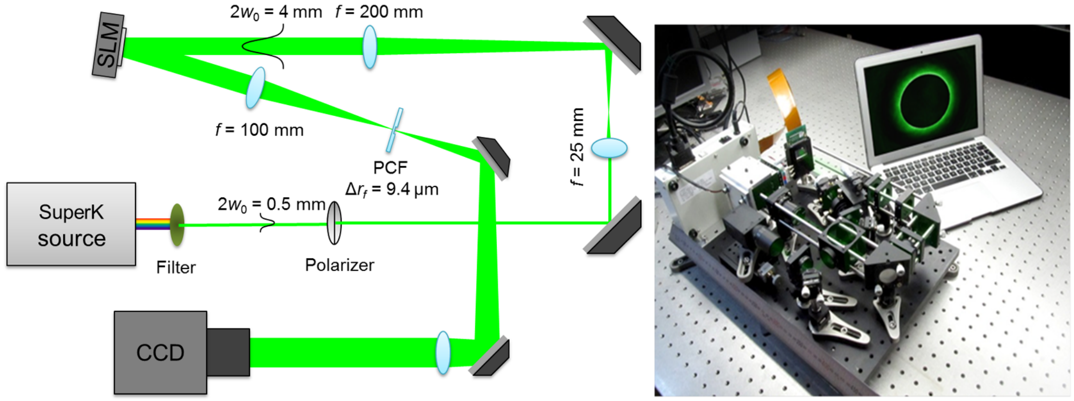

Fig. 4 Schematic illustration of the dynamic GPC light shaper used for generating dark GPC patterns (schematic based on Ref. 23) and the actual experimental setup.

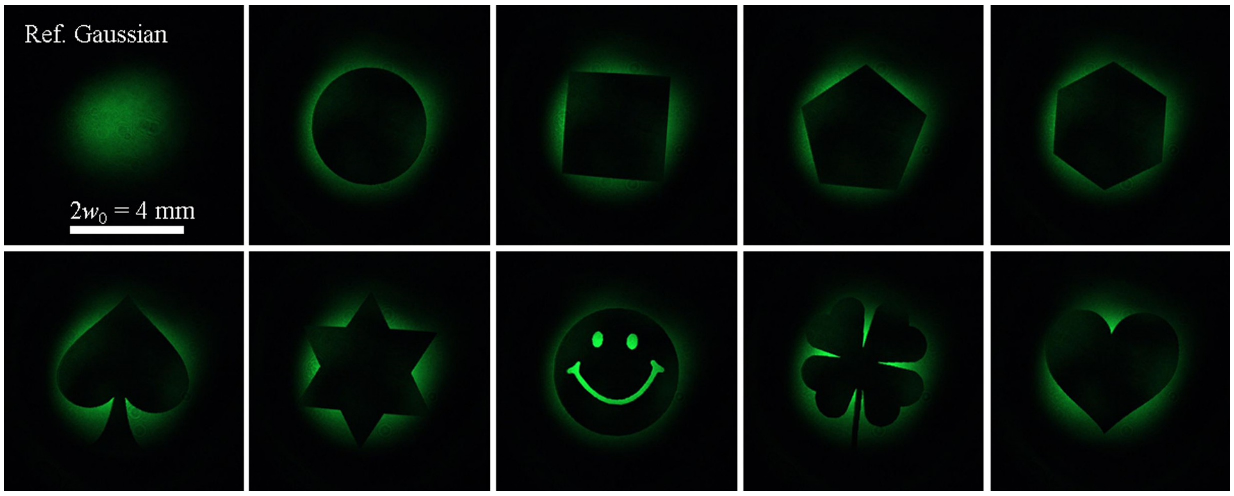

Fig. 5 Dark GPC experimental results showing different darkness shapes.

darkness, binary bitmap images were directly drawn on the SLM window and mapped to 0 and π phase shifts. The images were scaled, so the balance between the imaged input beam and the SRW can be attained. Alternatively, the phase filter can be modified by means of iterative optimization but requires a dynamic phase filter.[19] Our approach is much simpler. The experimental results are shown in Fig. 5. The results show that noncircular dark patterns are produced by designing them to have the same zero-order strength as the circular case.

The sensitivity of dark GPC makes it useful for positioning the PCF in a GPC light shaper using a calibration mask.[23] However, this sensitivity also visualizes faint amounts of light, due to the combined phase aberrations in the setup. The presence of extra rings outside the dark regions can be solved depending on the intended applications. In coronography, it is common practice to add a Lyot stop at the exit pupil plane to remove these.

4 Conclusion

We have shown how to generate extended regions of destructive interference using a GPC light shaping system by finding alternate conditions wherein the SRW is out-of-phase with the corresponding input foreground. Our direct binary mapping approach for generating dark regions is far simpler than previously reported techniques and thus allows us to experimentally demonstrate arbitrarily shaped dark regions. Instead of using multilevel phase elements or iterative optimizations techniques,[19] we take advantage of GPC's use of a simpler and reusable binary PCF and interchangeable binary phase input patterns. As GPC can operate over a broad wavelength range,[24] it would be interesting to see whether dark GPC exhibits the same robustness and can be used for multispectral applications found in microscopy.

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