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Dynamically reconfigurable optical lattices

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Abstract: We present a theoretical framework for two approaches of generating light-efficient optical lattices via a generic Fourier-filtering operation. We demonstrate how lattice geometry can be dynamically changed from fully discrete to interconnected optical arrays conveniently achieved with virtually zero computational resources. Both approaches apply a real-time reconfigurable phase-only spatial light modulator to set up dynamic input phase patterns for a $4f$ spatial filtering system that synthesizes the optical lattices. The first method is based on lossless phase-only Fourier-filtering; the second, on amplitude-only Fourier-filtering. We show numerically generated optical lattices rendered by both schemes and quantify the strength of the light throughput that can be achieved by each filtering alternative.

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1. Introduction

Spatially periodic arrays of light beams have found useful applications that extend from optical rerouting of microflow-driven materials to periodic pinning of viscously damped particles. For microfluidics or lab-on-a-chip systems, optical lattices can supplement the functionalities of dynamically reconfigurable optical traps to achieve a greater degree of control over the activities within miniaturized fluid channels and chambers [1-8]. Aside from aiding in colloidal crystallization of dielectric microparticles [9], arrays of light spots may also be used as dipole traps for grouping cold atoms at multiple locations [10-13].

Light interference enables the sculpting of lattice-like optical landscapes that can be used for separating fluid borne particles with differing optical properties. This particle separation scheme, called “optical fractionation” [2], has recently been demonstrated experimentally by MacDonald and co-workers [3]. In optical fractionation, the trajectories of co-flowing particles with distinct optical properties are influenced by the topology of an applied optical lattice. In their work, an optical lattice was generated by a five-beam interference pattern. When mixed particles flowed across the optical interference pattern, a particular lattice topology induced deflection of selected particles from their original trajectories while others passed almost straight through. This demonstrated the ability to separate microscopic biological matter by size, specifically by separating out protein microcapsules. An exponential size selectivity was pointed out as inherently possible with a dense particle solution driven through this optical lattice. The authors also demonstrated sorting of equally sized particles of differing refractive indices, namely, silica and polymer microspheres.

Here we efficiently generate reconfigurable optical lattices using a Fourier-filtering operation of two-dimensional phase patterns that can be encoded onto a programmable phase-only spatial light modulator (SLM). The lattices have adjustable periodicity and variable interconnectivity for intensity maxima and are formed at the image plane of a 4-f lens setup that employs an appropriate spatial filter at the Fourier plane. A similar system has been used to describe the Generalized Phase Contrast (GPC) method [14,15]. In our previous works [5-8,16], we have implemented the GPC method to generate arbitrary intensity patterns for dynamic multiple-beam optical manipulation. The first lattice-generation scheme we show here is based on the GPC method and the periodic nature of the required input phase pattern is matched with a Fourier filter that enables nearly 100% light efficiency. Secondly, we analytically describe a less energy-efficient amplitude filtering approach, which is based on the same general optical setup but employs a simple iris that blocks light except the zero and four first diffraction orders at the Fourier plane.

2. Fourier-filtering setup for dynamic optical lattice generation

Our general architecture for generating real-time reconfigurable lattices of light is illustrated in Fig. 1. Periodic phase patterns that produce desired optical intensity lattices can be dynamically encoded onto a phase-only SLM. The conversion from an input phase to lattice-like intensity patterns is done by applying a simple filtering operation in the spatial frequency plane between the two Fourier transforming lenses (L1 and L2; both of focal length f) in the 4-f configuration shown in Fig. 1. The first lens performs a spatial Fourier transform so that directly propagated light is focused on-axis whereas spatially varying features of the object diffracts light off-axis. The generic Fourier filter we consider is circularly symmetric and generally imparts different amplitude transmission factors $A \in [0; 1], B \in [0; 1]$ and relative phase shift $\theta \in [0; 2\pi]$ for the various diffraction orders that fall within and outside a circular region of radius $R$. 

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3. Phase-only zero-order filtering

Assuming a circular input aperture with radius, \( \Delta r \), truncating the SLM phase pattern, \( \phi(x, y) \), modulated onto a collimated, unit amplitude, monochromatic field of wavelength, \( \lambda \), we can describe the incident field \( e(x, y) \) by,

\[
e(x, y) = \text{circ}(r/\Delta r)\exp(i\phi(x, y))
\]

at the entrance plane of the 4-f system shown in Fig. 1 using the definition that the circ-function is unity within the region, \( r = \sqrt{x^2 + y^2} \leq \Delta r \), and zero elsewhere. Here we consider a circular, on-axis centered spatial filter, which in frequency space takes the form:

\[
H(f_x, f_y) = A[1 + (BA^{-1}\exp(i\theta) - 1)\text{circ}(f_r/\Delta f_r)].
\]

The spatial frequency coordinates are related to spatial coordinates in the filter plane such that \((f_x, f_y) = (\Delta f)^{-1}(x_f, y_f) \), \( f_r = \sqrt{f_x^2 + f_y^2} \) and the region with transmittance \( B \) and phase shift \( \theta \) covers the spatial frequency range within a \( \Delta f_r \) radius, i.e. \( R = \Lambda f \Delta f_r \).

The output intensity is the squared modulus of the output field, which is obtained by performing an optical Fourier transform of the input field from Eq. (1) followed by a multiplication of the filter function in Eq. (2) and a second optical Fourier transformation. If the spatial frequency components of \( e(x, y) \) other than the zero-order are well beyond \( \Delta f_r \) radius, the optical lattice at the observation plane of the 4-f set-up is well described by:

\[
I(x', y') = A^2\left|\exp(i\bar{\alpha}(x', y'))\text{circ}(r'/\Delta r) + g(r')\right|^2,
\]

where

\[
g(r') = 2\pi\Delta r \int_{0}^{\Delta f_r} J_1(2\pi\Delta f_r) J_0(2\pi f_r) df_r,
\]

can be considered as a synthetic reference wave (SRW) and the terms \( \bar{\alpha} \) and \( \bar{\phi}(x', y') \) are given by:
The GPC method allows one to find combinations of filter parameters that render optimal visibility and high peak irradiance for the output intensity pattern. A good choice for the filter parameter values is given by the set \( \{ A = 1, B = 1, \theta = \pi \} \) [15], making the filtering operation phase-only. For this case, the output intensity is given by:

\[
I(x', y') = \left| \exp\left( i \phi(x', y') \right) \right|^2 \cdot \exp\left( 2 \alpha \phi(r') \right).
\]  

Next, we demonstrate how this phase-only filtering operation transforms binary and ternary input phase patterns into optical lattices while achieving almost perfect conversion efficiency. First, we examine in Eq. (6) the terms that define the output optical lattice. One direct interpretation is to treat the optical lattice as an interference between the real-valued \( \frac{\pi \theta}{2} \)-weighted SRW and the phase input-carrying term, which is generally complex-valued. With a priori knowledge that the phase of the complex term has periodic spatial variations over the input aperture, we expect the output to spatially exhibit intensity variations with the SRW defining an envelope term. Thus, it is worth to survey the possible SRW profiles. If we introduce a dimensionless parameter \( \eta = (0.61)^{-1} \Delta r \Delta f_r \), relating the dimensions of the input aperture and the filter [15], we can rewrite Eq. (4) as:

\[
g\left( \frac{r'}{\Delta r} \right) = 2\pi \int_0^{0.61\eta} J_1(2\pi f_r) J_0 \left( 2\pi \frac{r'}{\Delta r} f_r \right) df_r.
\]  

From Eq. (7) it is apparent that the SRW, rewritten as a function of the normalized radial coordinate, depends on the parameter \( \eta \). In Fig. 2 we plot the numerically obtained curves of the SRW for increasing values of \( \eta \). Clearly, the plot shows that the SRW profile is a low-pass filtered version of \( \text{circ}(r'/\Delta r) \) where \( \eta \) defines the filter bandwidth.

Consider a binary phase having 75% of the input aperture area encoded with \( \phi = 0 \) and 25% with \( \phi = \pi \) in a square array of identical horizontal and vertical periodicity. From Eq. (5), note that this particular binary pattern gives a real \( \alpha = 0.75 \exp(i0) + 0.25 \exp(i\pi) = 0.5 \). Within an output aperture defined by \( \text{circ}(r'/\Delta r) \), the resultant intensity from Eq. (6) brings about a dark background (for points where \( \phi(x', y') = 0 \) ) and intensity peaks \( I(x', y') = [1 + g(r')]^2 \) (for points where \( \phi(x', y') = \pi \) ). Figure 3(a) illustrates this nearly 100% light-efficient result as the area filled by intensity peaks, each of which is approximately four times the incident intensity (Fig. 3(c)), sum up to 25% of the total aperture area. Moreover, the intensity peaks of this optical lattice are spatially discrete in all lattice symmetries. A different approach based on fractional-Talbot effect has also been shown to form an array of square illumination cells [17] similar to those achieved here.

Another optical lattice with quasi-binary intensity is achieved by using the same filter parameters but with a ternary phase encoded at the input in a periodic fashion (Fig. 4). Similarly, using Eq. (5) and Eq. (6), the phase corresponding to zero intensity is found to be \( \phi_0 = \pi/2 \) (over 50% of input aperture area), and bright regions with \( \phi_1 = 0 \) (25% of input aperture), and \( \phi_2 = \pi \) (25% of input aperture).
Fig. 2. Plot of the SRW for $\eta = 2.0$ (red), $\eta = 4.0$ (green), and $\eta = 20.0$ (blue). As $\eta$ is increased, the SRW approaches a flattop profile (black).

We find that the intensity maxima for the case of this ternary phase are interconnected along the $\pm45^\circ$ symmetry directions and are approximately twice that of the incident beam, which again indicates a virtually 100% efficiency (Fig. 3(b)). A filter with $\eta = 4$ ensures that high-order spatial frequency components of the binary or the ternary phase patterns used are well beyond a $\Delta f_r$ radius. This condition must be kept in mind if a new grating period is chosen.
4. Amplitude-only higher-order filtering

Optical lattices can also be generated with the setup shown in Fig. 1 but employing a higher-order Fourier-filtering operation while maintaining binary-only phase modulation at the input. This approach is not as energy efficient as the GPC method outlined in the previous section but should be considered an option when simplicity in spatial filter design is a main concern. In this second approach, the input object of choice is a two-dimensional binary rectangular-array phase pattern such as that in Fig. 5(a).

The phase pattern is characterized by transverse period lengths, $\Delta x$ and $\Delta y$, phase cell widths, $\Delta x_c$ and $\Delta y_c$, and effective phase depth $\varphi$. A plane wave incident on this phase pattern acquires the phase distribution given by:

$$ e(x, y) = \exp(i\varphi/2) + (\exp(-i\varphi/2) - \exp(i\varphi/2)) \cdot \text{rect}\left(\frac{x}{\Delta x_c}, \frac{y}{\Delta y_c}\right) \otimes \delta(x - m\Delta x, y - \Delta y) \tag{8} $$

Fig. 5. (a) Binary rectangular-array phase pattern with fill factor $(\Delta x, \Delta y)/(\Delta x, \Delta y)$ and (b) its possible spatial Fourier components having diffraction orders indicated by indices $m, n$. The applied filter transmits only the zero-order (open circle) and the four first-orders (black filled circles).
where ⊗ indicates the convolution operation, and m and n denote the indices of diffraction orders at the optical Fourier plane. We can derive the spatial Fourier transform of \( e(x, y) \), as:

\[
E(f_x, f_y) = \exp(i\varphi/2)\delta(f_x, f_y) - 2i\sin(\varphi/2)\frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y} \sum_{m,n} \text{sinc}
\left( m \frac{\Delta x_e}{\Delta x}, n \frac{\Delta y_e}{\Delta y} \right) \delta\left(f_x - \frac{m}{\Delta x}, f_y - \frac{n}{\Delta y}\right)
\].

(9)

By choosing the filter parameter set \( \{A = 1, B = 0, \theta = 0\} \), and filter aperture size \( R \) that blocks the orders with indices \( |m| \geq 1 \) and \( |n| \geq 1 \) (see Fig. 5(b)), we obtain immediately after the filter:

\[
E_{\text{filtered}}(f_x, f_y) = \exp(i\varphi/2)\delta(f_x, f_y) - 2i\sin(\varphi/2)\frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y} \sum_{(m,n) \neq (0,0),(1,0),(0,1),(-1,0),(-1,-1)} \text{sinc}
\left( m \frac{\Delta x_e}{\Delta x}, n \frac{\Delta y_e}{\Delta y} \right) \delta\left(f_x - \frac{m}{\Delta x}, f_y - \frac{n}{\Delta y}\right)
\].

(10)

Hence, for a binary rectangular-array phase grating with \( \varphi = \pi \), we obtain:

\[
E_{\text{filtered},\pi}(f_x, f_y) = \left[i \delta(f_x, f_y) - 2 \frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y} \sum_{(m,n) \neq (0,0),(1,0),(0,1),(-1,0),(-1,-1)} \text{sinc}
\left( m \frac{\Delta x_e}{\Delta x}, n \frac{\Delta y_e}{\Delta y} \right) \delta\left(f_x - \frac{m}{\Delta x}, f_y - \frac{n}{\Delta y}\right)\right]
\].

(11)

The five resulting “point sources” appearing in the spatial Fourier domain after the spatial filter can be written as:

\[
\begin{align*}
E_{0,0}(f_x, f_y) &= \left[i - 2 \frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y}\right] \delta(f_x, f_y) \\
E_{1,0}(f_x, f_y) &= -i \left[2 \frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y} \cdot \text{sinc}\left( \frac{\Delta x_e}{\Delta x} \right) \delta\left(f_x - \frac{1}{\Delta x}, f_y\right)\right] \\
E_{0,1}(f_x, f_y) &= -i \left[2 \frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y} \cdot \text{sinc}\left( \frac{\Delta y_e}{\Delta y} \right) \delta\left(f_x, f_y - \frac{1}{\Delta y}\right)\right] \\
E_{-1,0}(f_x, f_y) &= -i \left[2 \frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y} \cdot \text{sinc}\left( \frac{\Delta x_e}{\Delta x} \right) \delta\left(f_x + \frac{1}{\Delta x}, f_y\right)\right] \\
E_{0,-1}(f_x, f_y) &= -i \left[2 \frac{\Delta x_e}{\Delta x} \cdot \frac{\Delta y_e}{\Delta y} \cdot \text{sinc}\left( \frac{\Delta y_e}{\Delta y} \right) \delta\left(f_x, f_y + \frac{1}{\Delta y}\right)\right]
\end{align*}
\]

(12)

Guided by the equations above, we can tune the generated optical lattice by controlling the strengths of these point sources. Instead of using several neutral density filters as in Ref. [3] to control the relative strengths of these first-orders to that of the zero-order, we can here simply adjust the fill factor of the SLM phase pattern, which in practice is under computer control. We can for example extinguish the zero-order beam by considering a square-array pattern, i.e., \( \Delta x = \Delta y; \Delta x_e = \Delta y_e \), with a fill factor \( F = 0.5 \) or \( \frac{\Delta x_e}{\Delta x} = \frac{\Delta y_e}{\Delta y} = \frac{1}{\sqrt{2}} \).

In the previous section, generation of optical lattices was obtained by a lossless phase-only filtering in the Fourier domain. Here, the removal of the higher diffraction orders significantly affects the light throughput. Figure 6 shows the plot of the light efficiency with
respect to $F$ by summing the intensity of the allowed orders described in Eq. (12). It can be seen from Fig. 6 that the relative strengths of the zero-order to that of the first-orders is varied by choosing $F$ either below or above the value $F = 0.5$. We note, however, that higher light efficiency is achieved for $F < 0.5$.

Fig. 6. Light throughput at various fill factor $F$ (solid curve) measured by taking the sum of the intensities of the allowed diffraction orders. The intensity axis is normalised with respect to the incident intensity.

To generate the desired optical lattices from the transmitted diffraction orders, we perform a second optical Fourier transform on $E_{\text{filtered},\pi}(f_x, f_y)$. As in the previous section, this operation is associated with the second lens of the 4-f setup. By taking the square modulus of the field, we end up with an output intensity pattern given by:

$$I(x', y') = a^2 - 2ab \cos \left( \frac{\pi}{\Delta x} (x' + y') \right) \cos \left( \frac{\pi}{\Delta y} (x' - y') \right) + b^2 \cos^2 \left( \frac{\pi}{\Delta x} (x' + y') \right) \cos^2 \left( \frac{\pi}{\Delta y} (x' - y') \right)$$

(13)

where

$$\begin{align*}
a &= 1 - 2F \\
b &= 8F \sin \left( F^{1/2} \right)
\end{align*}$$

(14)

Here we describe each of the terms at the right-hand side of Eq. (13) to analyze how the output lattice depends on the parameters $a$ and $b$ or on $F$. The first term is a DC term, which is equivalent to the intensity of the zero-order beam as seen from Eq. (12). The second and third terms are individually indicating the periodic nature of the two-dimensional intensity pattern where the latter has a periodicity along a diagonal (at ±45° with $x'$ or $y'$-axis) that is twice that of the former. The third term, which is never negative at any point in the $x'y'$-plane, is the term describing a highly discrete optical lattice formed when $F = 0.5$. 

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Figure 7 shows the optical lattices described in Eq. (13). At \( F = 0.25 \) (Fig. 7(a)), the optical lattice has a distinct maximum intensity with equal periodicity along the horizontal and vertical directions. Increasing \( F \) to 0.5 intensifies the contribution of the third term setting up a distinct periodicity along the \( (45^\circ) \) diagonal as shown in Fig. 7(b). The line profiles show the maximum intensity of each lattice relative to the input intensity \( (F = 0) \) shown in Fig. 7(c). At \( F = 0.25 \), the light efficiency is around 66\% (Fig. 6) with a maximum intensity over three times the input intensity. The light throughput is lower at \( F = 0.5 \) with an efficiency of around 51\%, such that almost half of the light is filtered at the Fourier plane.

![Figure 7: Intensity lattices taken at the observation plane formed by amplitude-only filtering at the Fourier plane. The structure of the output intensity lattices varies with different input phase fill factor, \( F \). (a) \( F = 0.25 \), (b) \( F = 0.5 \) and (c) \( F = 0 \).](image)

Previous experiments in optical fractionation showed that the tunability in interconnectivity of intensity maxima along one direction facilitated the optimization of efficient segregation of co-streaming particles in bi-dispersed solution [3]. In a laminar flow of particles, optimal deflection of one particle-species at \( 45^\circ \) with respect to the other can be achieved by optical means. To tune the degree of interconnectivity of intensity maxima only along a preferred symmetry, we simply vary the pattern’s fill factor. As we deviate from \( F = 0.5 \), all three terms of Eq. (13) affect the intensity profile of the lattice. When \( F < 0.5 \), the resulting lattice may form a periodic array of secondary intensity maxima aside from the array of primary (or global) maxima (e.g., Fig. 7(a)). One can also note the formation of secondary (or local) minima interconnecting the periodic islands of light individually centered about a primary maximum. For \( F < 0.5 \), the strengths of a primary maximum, a secondary maximum, and a secondary minimum are given by the curves in Fig. 8 for \( a^2 + 2ab + b^2 \), \( a^2 - 2ab + b^2 \), and \( a^2 \), respectively. For \( F > 0.5 \), secondary maxima are also formed but with strength of \( a^2 + 2ab + b^2 \) and strength of \( a^2 - 2ab + b^2 \) for the primary maxima. From the curves in Fig. 8, it can be noted that the secondary maxima may be completely extinguished, with the remaining light islands being interconnected. This occurs either at \( F = 0.12 \) or \( F = 0.83 \). Figure 9 shows the lattice at \( F = 0.12 \) showing no secondary maxima and interconnected intensity maxima along the horizontal and vertical directions. This case, as anticipated in Fig. 7, has higher light efficiency (73\%) as it produces a higher primary maximum than for \( F \sim 0.83 \).
Fig. 8. Dependence of the coefficients $a^2$, $-2ab$, and $b^2$ from Eq. (13) on fill factor. The intensity axis is normalized with the intensity of the input field of unity-amplitude.

Fig. 9. The optical lattice at $F = 0.12$. Unlike in Fig. 7(a), secondary intensity maxima are no longer present. The intensity islands are interconnected along the horizontal and vertical directions.
5. Conclusion

We have outlined two methods for generating tunable optical lattices using a Fourier-filtering operation and a real-time programmable phase-only SLM. In practice, commercially available SLMs have finite number of resolution pixels and the phase encoding allowed on each pixel is in quantized levels (e.g., $2^8 = 256$). The former SLM characteristic (in addition to SLM dead-spaces and modulation transfer function) can affect the overall diffraction efficiency of the device – an extension that may be incorporated into our current analyses. On the otherhand, the low number of phase levels required in the methods presented here minimizes other effects associated with phase quantization.

The two methods require spatial Fourier filtering process either by a virtually lossless phase-only filter or by an amplitude filter that selectively blocks higher-order beams. For the method that employs a phase-only zero-order filtering, encoding the SLM with binary ($0$-$\pi$) phase levels with $\pi$ filling 25% of the input aperture creates optical lattices with discretely arranged intensity peaks, in accord with the GPC scheme [15]. Still with a phase-only filter, optical lattices with interlinked intensity maxima can be achieved when the SLM is encoded with ternary phase levels. Subsequently, we showed that high-order amplitude-only filtering achieves tunability in the structure of generated lattices by modulating the fill factor $F$ of a binary-only phase pattern. In terms of spatial frequencies in the Fourier domain, the strengths of selected and transmitted first diffraction orders to that of the zero-order are controlled by $F$ to obtain desired features of the optical lattice such as degree of interconnectivity. Optical lattices formed by the GPC-based method have close to 100% optical throughput while in the operating range $F \in [0.12; 0.5]$ for the amplitude filtering method we achieve an $F$-dependent efficiency of 51-73%. We believe that, among other applications, the proposed schemes will improve the level of control in optical fractionation procedures.

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