Simultaneous direct holographic fabrication of photonic cavity and graded photonic lattice with dual periodicity, dual basis, and dual symmetry

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Abstract: For the first time, to the authors’ best knowledge, this paper demonstrates the digital, holographic fabrication of graded, super-basis photonic lattices with dual periodicity, dual basis, and dual symmetry. Pixel-by-pixel phase engineering of the laser beam generates the highest resolution in a programmable spatial light modulator (SLM) for the direct imaging of graded photonic super-lattices. This technique grants flexibility in designing 2-D lattices with size-graded features, differing periodicities, and differing symmetries, as well as lattices having simultaneously two periodicities and two symmetries in high resolutions. By tuning the diffraction efficiency ratio from the SLM, photonic cavities can also be generated in the graded super-lattice simultaneously through a one-exposure process. A high quality factor of over $1.56 \times 10^6$ for a cavity mode in the graded photonic lattice with a large super-cell is predicted by simulations.

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1. Introduction

Laser holographic lithography has been one of the most attractive approaches to fabricate two-dimensional (2D) and three-dimensional (3D) micro/nano-structures [1]. These periodically modulated micro/nano-structures can be used for photonic crystal (PhC) applications. PhCs have the unique ability to manipulate electromagnetic waves and have been used for 3D PhC cavity lasers with high quality factors [2,3], photonic waveguides for integrated circuits, miniaturization of photonic devices [4], and integrated microfluidic channels for biomedical applications [5] among other applications.

Static single-optical-element based holographic lithography has significantly simplified the optical setup by replacing bulk optics used for laser beam manipulation in the holographic fabrication of 3D PhCs [6–9]. However, the static, single-optical-element approach is limited by its inability to generate spatially variant unit cells in PhCs, which are required in the emerging field of transformation optics [10,11] to achieve gradient index PhCs for device applications such as optical cloaking [12–14]. Graded PhCs have been used to realize the spatial distribution of gradient refractive index in order to confine electromagnetic waves in pre-designed light paths as governed by transformation optics [10–14]. The spatially varying unit cell in graded photonic crystals can be used to realize the spatial distribution of refractive index and control electromagnetic wave propagation more generally as well [15–18].
addition, superlattice PhCs [19,20], dual-period PhCs [21], and heterobinary PhCs [22] have been studied to improve the PhC functionalities.

Digitally programmable spatial light modulators (SLMs) have been used to control the phase profiles of laser beams for holographic fabrication of photonic structures [23–27]. Functional defects in PhCs can be fabricated by one-step holographic lithography using the SLM [23]. Computer-generated holograms can be displayed on the SLM to fabricate desired structures. It is a powerful technique that can be used to fabricate various photonic structures including graded, dual-periodic PhC structures [25]. However, the computer-generated hologram technique has low resolution and produces large feature sizes, in general, compared to pixel-by-pixel phase engineering. The authors have used specifically designed, triangularly-patterned grayscale images displayed on the SLM in order to study the relationship between the gray level and the phase of diffracted beams from the SLM [26,27]. The design has been tested by fabricating predictable, spatially varying photonic lattices [26]. However, the authors acknowledge that a triangular shape in the design is not ideal considering the square shape of pixels in the SLM.

In this paper, pixel-by-pixel phase engineering has been employed in order to achieve the highest resolution in SLM in the design and fabrication of photonic structures. We have demonstrated digital, holographic fabrication of graded superlattice photonic structures with dual periodicity, dual basis, and dual symmetry, for the first time to the authors’ best knowledge, by assigning spatially varying digital numbers to the gray level of the SLM in a pixel-by-pixel manner. The diffraction efficiency has not only been used to generate the desired pattern but also used for the simultaneous, one step fabrication of photonic cavities with high quality factor within the graded superlattice.

## 2. Experiment, design and theory of direct digital holographic lithography

All holographic structures were fabricated using a modified dipentaerythritol hexa/penta acrylate (DPHPA) monomer. The DPHPA was made to be sensitive to 532 nm light by adding Rose Bengal photo-initiator (0.32% m/m), co-initiator N-phenylglycine (0.55% m/m), and chain extender N-vinylpyrrolidone (10.33% m/m) to a container containing DPHPA (88.80% m/m). The modified DPHPA was spin-coated on glass slides at 3700 RPM for 30 seconds, and exposed to the interference pattern produced from the SLM. The laser power exposed to the sample was approximately 5.2 mW with a typical exposure time of ~2-3 seconds. After exposure the samples were developed in propylene glycol monomethyl ether acetate for 5 minutes, rinsed with isopropanol for one minute, and left out to dry in the air.

Figure 1(a) shows the experimental setup using the SLM for pixel-by-pixel phase engineering of the laser in a 4f imaging system. A 532 nm laser (total power 50 mW, Cobolt Samba) and an SLM (Holoeye Pluto phase-only SLM. The pixel size is $8 \times 8 \mu m$) were used to fabricate the structures. The phase pattern was programmed to cover all $1920 \times 1080$ pixels on the SLM. For phase patterns generated by repeating the $2 \times 2$ unit cell as shown in Fig. 1(b), first-order diffraction beams formed around the edge of the first lens as indicated by the blue dashed arrow in Fig. 1(a). For phase patterns consisting of larger periodic unit cells of $24 \times 24$ pixels as shown in Fig. 1(c), first-order diffraction beams formed closer to the optical axis as indicated by the yellow dashed arrow in Fig. 1(a). The actual designed unit cell of the pattern, as shown in Fig. 1(d), is a combination of the two unit cells. The dark region of the larger unit cell in Fig. 1(c) has been filled with the checkerboard pattern in Fig. 1(b), while the lighter region has been filled with a different colored checkerboard pattern. Such a pattern produces both sets of first-order diffraction spots as shown in the CCD image taken at the Fourier plane in Fig. 1(e). A Fourier filter was placed at the Fourier plane to let these eight desired beams go through. The diffraction spots were passed through a second lens and demagnified through a 4f imaging system ($f_1 \approx 400$ mm and $f_2 = 200$ mm). At the image plane, an interference pattern was formed, with holographic interference intensity, $I(r)$, due to the eight beams in Fig. 1(e) determined by Eq. (1):
\[ I(r) = \sum_{i=1}^{3} E_i^2(r,t) + \sum_{i<j}^{3} E_i E_j e_i \cdot e_j \cos\left[ (k_i - k_j) \cdot r + (\delta_i - \delta_j) \right]. \]

where \( k \) is the wave vector, \( \delta \) is the initial phase, which is determined by the gray level, \( E \) is the electric field amplitude, and \( e \) is the electric field polarization direction. Approximately, the interfering four beams further away from the optical axis form a square lattice with small lattice periodicity. The additional four beams near the optical axis not only modulate the interference in a 3D fashion but also form a photonic lattice with larger lattice periodicity.

The electric field strength, \( E \), is determined by the diffraction efficiency of the 532 nm laser onto the phase pattern in the SLM. The gray level in the pixel of the SLM is also translated into the phase of the laser beam using the response curve within the SLM software. The response of the SLM was calibrated by the manufacturer with a gray level of 255 corresponding to a phase of \( 2\pi \) and a gray level of 0 corresponded to 0 additional phase with a linear relationship in between. To estimate the electric field strength, \( E \), the diffraction efficiencies due to the small and large periodicities were measured and plotted as shown in Fig. 1(f) for square, supercell checkerboard patterns similar to those in Fig. 1(d). The gray level combination 158/254 was kept fixed during measurements and the second combination of gray levels was changed as in \( (192 + x)/254 \), where \( x \) is the gray level difference. The diffraction efficiencies and the ratios were plotted as a function of the gray level difference. The dashed rectangle indicates the data for the combination of 158/254 and 192/254 gray levels where the diffraction efficiencies were 9.64% and 0.77% due to the small and large periodicities, respectively, with a ratio of 12.5. The ratio of diffraction efficiencies can be digitally controlled by the gray levels and the optical functionality of these structures was investigated.

3. Holographic fabrication of graded superlattice with dual periodicity, dual basis and dual symmetry

To fabricate graded superlattices with dual periodicities, dual basis, and square symmetry, the SLM phase pattern was designed to produce outer beams with high diffraction efficiency and inner beams with low diffraction efficiency. A supercell of \( 24 \times 24 \) pixel area as indicated by
the solid blue square in Fig. 2(a) was tiled across a 1920 × 1080 image. All phase patterns were designed using GIMP (open source GNU Image Manipulation Program) and exported as PNG files to display on the SLM. The basis units of the phase pattern consist of SLM pixels (8 × 8 μm²) with gray levels 158, 192, or 254 (corresponding to phase values 1.24π, 1.51π, and 1.99π respectively). The gray level of 158 or 192 was combined with 254 in a checkerboard fashion, as shown in Fig. 2(b), to form 12 × 12 pixel “supercell subunits” with a size indicated by the solid red square in Fig. 2(a). These supercell subunits were then also tiled in a checkerboard fashion to produce the overall image displayed on the SLM. When a 532 nm laser was incident to the phase pattern, two sets of diffraction patterns were produced from the SLM. The eight first-order beams form the interference pattern as simulated in Fig. 2(c).

Fig. 2. (a) Supercell phase tiles assembled from 12 × 12 tiles of checkerboard phase patterns with gray levels of (158, 254) and (192, 254), respectively. (b) Enlarged view of (158, 254) and (192, 254) checkerboards patterns. (c) Simulated iso-intensity surface of the interference pattern. (d) A gradient lattice plus a super-basis can be combined to represent the interference structures in the red dashed square of (c). (e) SEM of fabricated sample showing large periodicity and square symmetry. The blue square indicates a supercell in the structure which corresponds to the supercell of the SLM phase pattern in blue square in (a) and simulated interference in (c). (f) Enlarged view of fabricated gradient superlattice structures showing d = 8 μm. (g) Diffraction pattern of fabricated sample from 532 nm laser.

The relationship between the pixel pitch (the pixel pitch = D = 8 μm. The period of the phase pattern = 2D) and one of lattice constants of holographic structure with dual periodicities can be derived. From the geometry in Fig. 1(a), the Bragg diffraction due to the periodic arrays of gray level in vertical direction can be written as in Eq. (2):

\[ (2D) \sin \theta_1 = \lambda. \]  

where \( \lambda \) is the laser wavelength and \( \theta_1 \) is the angle to the diffraction spot. After the diffraction spots passed through the first lens with a focal length \( f_1 \) and the second lens with a focal length \( f_2 \) in the 4f imaging system, the interference angle \( \theta_2 \) relative to the optical axis can be determined by Eq. (3):

\[ \tan \theta_2 = f_1 \tan \theta_1 \times \left( \frac{f_2}{f_1} \right) \times \left( \frac{\sqrt{2}}{f_2} \right). \]
Using the coordinate system at the image plane in Fig. 1(a), the wavevectors of the outer four interfering beams can be written as: \( k(\sin(\theta_2), 0, \cos(\theta_2)), k(-\sin(\theta_2), 0, \cos(\theta_2)), k(0, \sin(\theta_2), \cos(\theta_2)), \) and \( k(0, -\sin(\theta_2), \cos(\theta_2)) \).

The interference period, \( P \), in the x or y-direction (orientated 45 degree from the horizontal and vertical directions) due to these four beams is determined by Eq. (4), found from the interference theory and by combining Eqs. (2) and (3) and assuming \( \tan(\theta) = \sin(\theta) \) for small angle:

\[
P = \frac{2\pi}{k \sin \theta_2} = \frac{\lambda}{\sin \theta_2} = \frac{2D}{\sqrt{2}}.
\]

After considering the de-magnification due to the 4f image system, the lattice constant, \( \Lambda \), in the interference pattern after the de-magnification is related to the pixel pitch length, \( D \), by Eq. (5):

\[
P = \frac{2\pi}{k \sin \theta_2} = \frac{\lambda}{\sin \theta_2} = \frac{2D}{\sqrt{2}}.
\]

The pixel pitch of the SLM is labelled in Fig. 2(b). The supercell subunit size in the phase pattern is \( 12D \times 12D \). The small lattice constant, \( \Lambda \), of the dual periodic structures is labelled in Fig. 2(c). The direction of interference periodicity is along 45 degrees relative to the horizontal direction, as predicted by the Eq. (4). The simulated interference pattern in Fig. 2(c) corresponds to a direct holographic image of the supercell in the phase pattern indicated by the solid blue square in Fig. 2(a). The size of the interference pattern becomes half comparing with the size of the supercell, due to the de-magnification. The phase pattern inside the solid red square in Fig. 2(a) corresponds to the interference image pattern inside the solid red square in Fig. 2(c) with a size of \( 6d \times 6d \). \( d = \sqrt{2}\Lambda \) as determined by the geometry \( d = D = 8\ \mu m \) as labelled in the Figure in this study. In general, \( d \neq D \) if demagification \( \neq 0.5 \).

The interference pattern in Fig. 2(c) can be further understood by the graded photonic lattice indicated by the purple circles for the location of basis units in Fig. 2(d, top) and a basis consisting of one purple circle and one blue circle in Fig. 2(d, bottom); a combination of graded lattice and dual-basis. The SEM image in Fig. 2(e) shows the fabricated structures with graded, superlattice configuration, in agreement with the simulation in Fig. 2(c). The solid red square indicates the unit of graded superlattice corresponding to the interference pattern inside the red square in Fig. 2(c). The solid blue square with a size of \( 12d \times 12d \) indicates the unit of graded superlattice corresponding to the interference pattern in Fig. 2(c). The dual periodicity, as indicated by the solid yellow square in Fig. 2(e) connecting the centers of supercell subunits of a graded lattice of the small periodicity inside the red square, is clearly observed. Figure 2(f) shows an enlarged view of the fabricated graded dual-basis structures. The length scale \( d \) was measured to be \( 8\ \mu m \), thus the lattice period, \( \sqrt{2} \), is \( 8\ \mu m / \), in agreement with theory from Eq. (5). Figure 2(g) shows the diffraction pattern of the fabricated sample from a 532 nm laser. The pattern consists of sets of spots at the corners of the image due to the small period lattice and four bright spots at each corner due to the large period structures with the square symmetry. Due to the big feature size in the currently fabricated sample, the optical signal due to the structural resonances is out of our current spectrometer measurement range. Using a SLM with a smaller pixel pitch than the one we are using, and adding an objective lens for further demagnification, the feature size can be reduced and optical signal can be measured.

In order to form a graded photonic superlattice with simultaneous square and hexagonal lattices, the SLM phase pattern was designed with a \( 30D \times 52D \) supercell as shown in Fig. 3(a). Three blue lines (separated by 60 degrees) divide the supercell into six supercell subunits. The 158/254 and 192/254 gray levels tiled in checkerboard fashion were arranged to occupy alternate subunits. The phase pattern supercell was tiled to produce a \( 1920 \times 1080 \)
image for display on the SLM. Such an SLM pattern produced four first-order diffraction beams with four-fold symmetry due to the alternating square pixels and six first-order diffraction beams with six-fold symmetry due to the arrangement of the supercell subunits. These two sets of first-order beams (10 beams total) were passed through a Fourier filter to form the interference pattern. A simulated interference is shown in Fig. 3(b), displaying the square lattice and hexagonal arrangements of graded dual-basis structures. Figure 3(c) shows an SEM image of the fabricated samples. The solid red square with a size of $15d \times 26d$ indicates a rectangular supercell of the graded superlattice corresponding to the supercell of the phase pattern in Fig. 3(a). Again, the size of the fabricated structures in Fig. 3(c) in the supercell unit becomes half compared to the SLM phase pattern in Fig. 3(a), due to the demagnification. The hexagons in Fig. 3(c) are included for eye guidance in order to understand the large period structures. The SEM of the fabricated structures clearly show large, hexagonal symmetry and small, square symmetry, successfully combining super-basis, graded lattice, dual-periodicity, and dual-symmetry. Figure 3(d) shows the enlarged SEM of graded superlattices from the region indicated by the dashed red rectangle in Fig. 3(c). The parameter $d$ was measured to be close to 8 $\mu$m, in agreement with the prediction from theory. The diffraction pattern of the fabricated sample from a 532 nm laser is shown in Fig. 3(e). The light is diffracted into the four corners of the image due to the small period lattice and six bright spots form a hexagon at each corner due to the large period structures with the hexagonal symmetry.

It is possible to fabricate small period structures with triangular symmetry [26,27] and large period features with square symmetry. Other complex dual-periodic structures with 5-fold rotational symmetry have initially been fabricated and the results will be published in near future.

Fig. 3. (a) Rectangular supercell used to construct the SLM phase pattern for 10 beam interference. The supercell consists of triangularly alternating combinations of gray levels 158/254 and 192,254 in checkerboard patterns. (b) Simulated iso-intensity surface of the interference from the tiled SLM phase pattern in (a). (c) A large-area SEM of simultaneous square and hexagonal symmetry structures. The red square indicates a supercell in the structure which corresponds to the supercell of the SLM phase image in (a). The yellow hexagon is drawn for eye guidance of the hexagonal symmetry. (d) Enlarged view of structures in dashed red square in (c). The square symmetry and graded dual-basis are clearly visible. (e) Diffraction pattern of fabricated sample from 532 nm laser.
4. Prediction of optical functions in graded superlattices through simulations

Pixel-by-pixel phase engineering can be further utilized for the design of functional graded photonic superlattices. By tuning the ratio of diffraction efficiencies of the inner and outer beams, structures with optical functions can be realized. Optical properties were computed using the freely available MIT Photonic Bands (MPB) software package [28] in Amazon Web Services. Due to the extremely large supercell size, parallel computations in multiple-core virtual machine was used to calculate the photonic band structure up to over 200 bands. Interference patterns were converted to binary dielectric/air structures by comparing the interference intensity, $I$, with a threshold intensity, $I_{th}$, using the following step functions: $\varepsilon(r) = 1$, for air, when $I < I_{th}$, $\varepsilon(r) = 12$ (assuming structural conversion to a high refractive index material) when $I > I_{th}$. The spatial distribution of dielectric constants was output from MPB and is shown in Fig. 4(a) and 4(b), respectively, for threshold intensities = 45% and 60% of maximum intensity (the ratio of diffraction efficiencies = 12.5). Their photonic band structures for TM polarization are shown in Figs. 4(c) and 4(d) for the dielectric/air supercells in Figs. 4(a) and 4(b), respectively. The units of frequency are with respect to the parameter $a$, the distance between two neighboring points in Figs. 4(a) and 4(b). Over 200 bands in the photonic band structures were computed due to the extremely large supercell size. A full photonic band gap appeared as seen in the Fig. 4(c) while a cavity mode appeared inside the photonic band gap as seen in Fig. 4(d).

The quality factor (Q-factor) of such cavities was calculated using the harmonic inversion function [29] included in the freely available MIT Electromagnetic Equation Propagation (MEEP) software [30] in Amazon Web Services. Parallel computing using multi-core virtual machine was used for the large unit cell size. The binary dielectric/air structures shown in Fig. 4(b) with a dielectric constant of 12 for the dielectrics was inserted in the calculation cell to calculate the Q-factor. The Q-factor of the cavity was found to be $3.2 \times 10^3$. By tuning the diffraction efficiency, we are capable of producing graded photonic super-lattice cavities with even higher Q-factor. With a diffraction efficiency ratio of 30:1, the generated super-lattice cavity had a Q factor of $1.7 \times 10^4$. The Q factor can be further increased by increasing the supercell size to confine the mode in the cavity. Simulating an $18a \times 18a$ supercell produces a
cavity mode with Q factor $1.56 \times 10^6$. Such a structure can be produced by adjusting supercell parameters to $18D \times 18D$ in the SLM phase pattern. The electric field distribution of these modes can be seen in Fig. 5. The confining effects become stronger as seen in the electric field in Fig. 5(b) than in Fig. 5(a). The confinement of electric field in Fig. 5(c) is stronger than in Figs. 5(a) and 5(b). These simulations not only show the capability of digital, holographic fabrication of various graded superlattices but also predict the exciting optical functions of these structures.

Fig. 5. (a) Simulated electric field distributions of cavity modes in the $12a \times 12a$ binary dielectric/air supercells produced with diffraction efficiency ratios of 12.5:1 (a) and 30:1 (b). (c) Simulated electric field in the $18a \times 18a$ binary dielectric/air supercell produced with a diffraction efficiency ratio of 30:1.

5. Summary

In summary, the capability of a digitally programmable spatial light modulator for the holographic fabrication of graded, super-basis photonic structures has been demonstrated. The highest resolution in phase engineering of the laser by the SLM has been achieved using a pixel-by-pixel method. Spatially varying phase assignments in the phase pattern have been used to fabricate superlattice architectures with dual-symmetry, dual basis, and dual-periodicity through a one-exposure process. We have also shown the capability to fabricate cavity structures in the graded superlattices through a one-exposure process. Fabrication flexibility for various functional structures has been demonstrated by varying the diffraction efficiency of laser beams from the SLM and to realize graded superlattices with a very high Q-factor cavities.

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