Contrast in four-beam-interference lithography

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Specific configurations of four linearly polarized, monochromatic plane waves have previously been shown to be capable of producing interference patterns exhibiting the symmetries inherent in all 14 Bravais lattices. We present (1) the range of possible absolute contrasts, (2) the conditions for unity absolute contrast, and (3) the types of interference patterns possible for configurations of four beams interference that satisfy the uniform contrast condition. Results are presented for three Bravais lattice structures: Base- and face-centered cubic and simple cubic. © 2008 Optical Society of America

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There exists a number of different fabrication techniques for producing photonic crystal structures [1–4]. While many of these are capable of fabricating two-dimensional periodic structures, fabrication of three-dimensional structures can be difficult, if not impossible, using these techniques. Multibeam interference, on the other hand, offers a lithographic solution for the fabrication of three-dimensional periodic structures. Multibeam interference has been shown to produce all of the two- and three-dimensional Bravais lattices and nine of the 17 plane group symmetries [5–7]. There have also been two uniform contrast conditions defined for three-beam interference [7,8] and one uniform contrast condition for four-beam interference [9]. While a complete description of contrast and crystallography has been given for three-beam interference [7], a complete discussion of the range of possible contrasts, conditions for unity absolute contrast, and the types of interference patterns possible for four-beam interference have not been given. The present work provides these.

For the interference of N linearly polarized monochromatic plane waves, the time-average intensity distribution can be expressed as

$$I_T(\mathbf{r}) = I_0\left(1 + \sum_{i=1}^{N}\sum_{j>i}^{N} V_{ij}\cos((\mathbf{k}_j - \mathbf{k}_i)\cdot\mathbf{r} + \phi_i - \phi_j)\right), \quad (1)$$

with the constant intensity term, interference coefficient, and efficiency factor given by

$$I_0 = \sum_{i=1}^{N}\frac{1}{2}E_i^2, \quad V_{ij} = \frac{E_iE_je_{ij}}{I_0}, \quad e_{ij} = \hat{\mathbf{e}}_i\cdot\hat{\mathbf{e}}_j, \quad (2)$$

where E_i, $\hat{\mathbf{e}}_i$, $\mathbf{k}_i$, and ϕ_i are the maximum electric field amplitude, polarization vector, wave vector, and initial phase, respectively, of the ith plane wave. Proper selection of k_i's in four-beam interference has been shown to produce all 14 Bravais lattices [5]. The quality of an interference pattern can be improved by satisfying the uniform contrast condition [9]. This can be achieved by choosing the individual plane wave properties such that the interference coefficients in Eq. (1) are equivalent, that is, $V_{ij}=V_{kl}$. For four-beam interference the constraints on the plane-wave properties that result are [9]

$$e_{12}e_{34} = e_{13}e_{24} = e_{14}e_{23}, \quad (3)$$

$$\frac{E_2}{E_1} = \frac{e_{13}}{e_{23}}, \quad \frac{E_3}{E_1} = \frac{e_{12}}{e_{23}}, \quad \frac{E_4}{E_1} = \frac{e_{12}}{e_{24}}. \quad (4)$$

When these constraints for uniform contrast are met the interference term, V_{ij}, can be expressed as [9]

$$V_{ij} = V = \frac{2e_{12}e_{13}e_{23}}{e_{12}^2 + e_{13}^2 + e_{23}^2 + e_{13}^2e_{23}^2/e_{34}^2}. \quad (5)$$

Absolute contrast, V_{abs}, is a function of the intensity extrema in an intensity distribution and is defined as

$$V_{abs} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \quad (6)$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities, respectively. When the above-mentioned uniform contrast condition is satisfied, the absolute contrast is related to the interference coefficient, V, by

$$V_{abs} = \left|\frac{4}{V^{-1} + 2}\right|. \quad (7)$$

When this uniform contrast condition is satisfied, the interference coefficient can range from $-1/6 \le V \le 1/2$ (corresponding to the range of absolute contrast $0 \le V_{abs} \le 1$). The sign of V distinguishes between two fundamentally different types of interference patterns. When solutions are found such that $V > 0$, the intensity maxima in Eq. (6) are located at all lattice points. Consequently if $V < 0$, the intensity minima in Eq. (6) is located at all lattice points. It should be noted that the functional form of Eq. (1) is identical for a configuration of recording wave vectors regardless of V. Given that the uniform contrast condition has been satisfied, solutions will have identical isointensity contours (differing only in the corresponding intensity values) for all possible values of V.

If $\phi_i = 0$, lattice points are defined at the origin ($\mathbf{r}=0$) and all equivalent points in the three-

Table 1. Optimized Parameters for Lattices Maximizing Absolute Contrast with $V>0$

Lattice	$\hat{\mathbf{e}}_1$	$\hat{\mathbf{e}}_2$	$\hat{\mathbf{e}}_3$	$\hat{\mathbf{e}}_4$	V	V_{abs}
Face-centered cubic	$\begin{pmatrix}0.40825\\-0.81650\\0.40825\end{pmatrix}$	$\begin{pmatrix}0.54551\\-0.83608\\0.05811\end{pmatrix}$	$\begin{pmatrix}0.05811\\-0.83608\\0.54551\end{pmatrix}$	$\begin{pmatrix}0.68041\\-0.27217\\0.68041\end{pmatrix}$	0.37189	0.85307
Body-centered cubic	$\begin{pmatrix}0.13099\\-0.76344\\0.63246\end{pmatrix}$	$\begin{pmatrix}0.70711\\0.70711\\0\end{pmatrix}$	$\begin{pmatrix}0.70711\\0.70711\\0\end{pmatrix}$	$\begin{pmatrix}-0.13099\\0.76344\\0.63246\end{pmatrix}$	1/6	1/2
Simple cubic	$\begin{pmatrix}-0.13099\\-0.63246\\0.76344\end{pmatrix}$	$\begin{pmatrix}0.70711\\0\\0.70711\end{pmatrix}$	$\begin{pmatrix}-0.13099\\0.63246\\0.76344\end{pmatrix}$	$\begin{pmatrix}0.70711\\0\\0.70711\end{pmatrix}$	1/6	1/2

dimensional periodic interference pattern. In general, the lattice points are defined at

$$\mathbf{P} = \frac{g_{12}(\mathbf{G}_{13}\times\mathbf{G}_{14}) + g_{13}(\mathbf{G}_{14}\times\mathbf{G}_{12}) + g_{14}(\mathbf{G}_{12}\times\mathbf{G}_{13})}{\mathbf{G}_{12}\cdot(\mathbf{G}_{13}\times\mathbf{G}_{14})}, \tag{8}$$

where $g_{ij}=\phi_i-\phi_j$ and $\mathbf{G}_{ij}=\mathbf{k}_i-\mathbf{k}_j$ and all equivalent points in the three-dimensional periodic interference pattern.

Solutions that result in an interference coefficient of $V=1/2$ or $-1/6$ will exhibit unity absolute contrast ($V_{abs}=1$, $I_{\min}=0$). Using a constrained nonlinear optimization algorithm, solutions of Eq. (5) that result in unity absolute contrast [subject to the nonlinear constraints in Eq. (3)] can be found. Two sets of solutions result. The first solution is expressed as $e_{ij}=\pm 1$. This solution describes an impractical configuration for four-beam interference in which all recording wave vectors are coplanar. In fact, it results in periodicity in only two dimensions. The second solution is expressed as $e_{ij}=\pm 1/3$. This solution describes a situation in which the polarization vectors, $\hat{\mathbf{e}}_i$, define the vertices of a regular tetrahedron. This solution, while practical, cannot always be achieved for general four-beam interference. However, configurations of wave vectors that define both body-center and simple cubic lattices can satisfy this second solution and achieve unity absolute contrast ($V_{abs}=1$) with an interference coefficient of $V=-1/6$. For the general case, a constrained nonlinear optimization that maximizes absolute contrast must be performed [9].

In this Letter, results are presented for three three-dimensional lattice structures: Face- and body-centered cubic and simple cubic. A face-centered cubic lattice can be defined by four-beam interference by choosing the four recording wave vectors as $\mathbf{k}_1=k_0(1/3\sqrt{3})[3\;3\;3]$, $\mathbf{k}_2=k_0(1/3\sqrt{3})[1\;1\;5]$, $\mathbf{k}_3=k_0(1/3\sqrt{3})[5\;1\;1]$, and $\mathbf{k}_4=k_0(1/3\sqrt{3})[1\;5\;1]$. Two configurations of polarization vectors are found to maximize absolute contrast for the two fundamentally different types of interference patterns. These solutions are summarized in Tables 1 and 2. Additionally, these solutions are simulated in Fig. 1(a). In this and subsequent figures solutions are illustrated as a simulated exposure in a negative photoresist material. Isointensity contours are drawn encompassing volumes of material experiencing intensities greater than some arbitrary intensity threshold.

Table 2. Optimized Parameters for Lattices Maximizing Absolute Contrast with $V<0$

Lattice	$\hat{\mathbf{e}}_1$	$\hat{\mathbf{e}}_2$	$\hat{\mathbf{e}}_3$	$\hat{\mathbf{e}}_4$	V	V_{abs}
Face-centered cubic	$\begin{pmatrix}0.40825\\-0.8165\\0.40825\end{pmatrix}$	$\begin{pmatrix}-0.76069\\-0.59022\\0.27018\end{pmatrix}$	$\begin{pmatrix}-0.27018\\0.59022\\0.76069\end{pmatrix}$	$\begin{pmatrix}0.68041\\-0.27217\\0.68041\end{pmatrix}$	−0.05750	0.25986
Body-centered cubic	$\begin{pmatrix}-0.78868\\0.57735\\0.21132\end{pmatrix}$	$\begin{pmatrix}0.21132\\-0.57735\\0.78868\end{pmatrix}$	$\begin{pmatrix}-0.78868\\-0.57735\\0.21132\end{pmatrix}$	$\begin{pmatrix}0.21132\\0.57735\\0.78868\end{pmatrix}$	−1/6	1.0
Simple cubic	$\begin{pmatrix}-0.78868\\0.57735\\0.21132\end{pmatrix}$	$\begin{pmatrix}0.21132\\-0.57735\\0.78868\end{pmatrix}$	$\begin{pmatrix}-0.78868\\-0.57735\\0.21132\end{pmatrix}$	$\begin{pmatrix}0.21132\\0.57735\\0.78868\end{pmatrix}$	−1/6	1.0

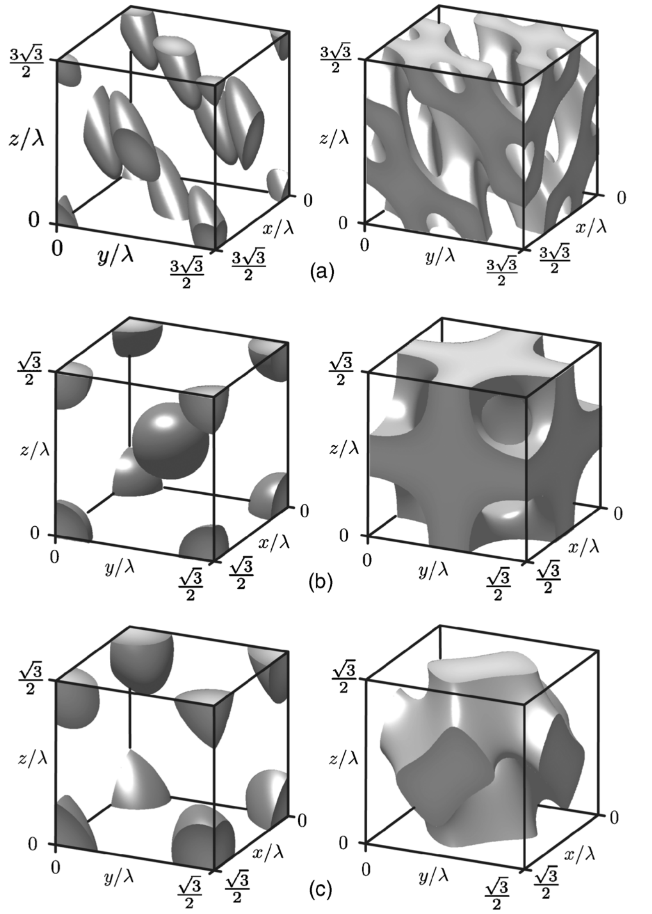

Fig. 1. (Color online) Four-beam interference resulting in (a) face-centered, (b) body-centered, and (c) simple cubic lattices. Isocontours are drawn to encompass volumes of material experiencing relatively high intensities. Solutions resulting in $V>0$ with intensity maxima (left) and in $V<0$ with intensity minima (right) located at lattice points. Optimized parameters for these solutions are summarized in Tables 1 and 2.

A body-centered cubic lattice can be defined by four-beam interference by choosing the four recording wave vectors as $\mathbf{k}_1=k_0(1/\sqrt{3})[1\ 1\ 1]$, $\mathbf{k}_2=k_0(1/\sqrt{3})[1\ -1\ -1]$, $\mathbf{k}_3=k_0(1/\sqrt{3})[-1\ 1\ -1]$, and $\mathbf{k}_4=k_0(1/\sqrt{3})[-1\ -1\ 1]$. Two configurations of polarization vectors are found as to maximize absolute contrast for the two fundamentally different types of interference patterns. These solutions are summarized in Tables 1 and 2. Additionally, these solutions are simulated in Fig. 1(b).

A simple cubic lattice can be defined by four-beam interference by choosing the four recording wave vectors as $\mathbf{k}_1=k_0(1/\sqrt{3})[1\ 1\ 1]$, $\mathbf{k}_2=k_0(1/\sqrt{3})[-1\ 1\ 1]$, $\mathbf{k}_3=k_0(1/\sqrt{3})[1\ -1\ 1]$, and $\mathbf{k}_4=k_0(1/\sqrt{3})[1\ 1\ -1]$. Two configurations of polarization vectors are found as to maximize absolute contrast for the two fundamentally different types of interference patterns. These solutions are summarized in Tables 1 and 2. Additionally, these solutions are simulated in Fig. 1(c).

Of the three simulated configurations of wave vectors, only those that produce body-centered and simple cubic lattices can result in unity absolute contrast ($V_{abs}=1$). Once more, this only occurs for solutions with $V=-1/6$ such that intensity minima are located at lattice points. In these two cases, a higher absolute contrast is achieved by maximizing contrast for $V<0$. However, when defining a face-centered cubic lattice, maximizing contrast for $V>0$ produces a higher absolute contrast. Similar to light- and dark-field masks in conventional lithography, these two fundamentally different interference patterns provide designers two complementary intensity distributions. Exposure and development in a positive photoresist using a configuration corresponding to one of the types of interference patterns will produce an identical structure resulting from using a negative photoresist and the other type of interference pattern (with an appropriately adjusted exposure). Thus, depending upon process parameters, an appropriate type of interference pattern can be chosen that best suits the designer's needs.

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