Line defects in two-dimensional four-beam interference patterns

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Abstract. We have studied laser interference patterns, which consist of line defects on the surface of a GaAs substrate, generated by four-beam interference lithography. The orientation and periodicity of the defects are shown to depend on the configuration of the incident laser beams, while the widths of the defects are modified by varying the beam intensity. Influences of the phase and polarization on the simulated patterns are discussed.

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1. Introduction

Photonic crystals (PhCs) exhibit characteristic energy bandgaps and give rise to interesting physical phenomena. They are thought to be promising materials for fabricating all-optical integrated circuits [1, 2]. In particular, PhCs with artificial defects introduced into their structures are the topics of many theoretical [3]–[5] and experimental investigations [6]–[9]. Electron beam lithography (EBL) and focused ion beam (FIB) lithography are the most common techniques employed to prepare surface reliefs for PhCs with defects, but they are time-consuming and expensive to use. Interference lithography (IL), in contrast, is a quick and cost-effective approach. IL is often regarded as being a competitive method to EBL and FIB for preparing periodic surface structures, but not for making patterns with defects. We show in this paper, theoretically and experimentally, that IL can be added to the list of processing surface features with line defects. When compared with EBL and FIB, which can make step-type defects, IL only produces grade-type defects. PhCs with grade-type defects can be used for tapered transmission line defect resonators [8], graded PhCs [10] and tapered PhC microcavities embedded in photonic wire waveguides [11].

2. Simulation

2.1. Model

When considering a periodic surface relief with line defects generated by a four-beam laser interference method (figure 1), the first step is to calculate the interference patterns. In our calculations, the beam azimuthal and polar angles (i.e. the incident angles) are labelled $\varphi_j$ and $\theta_j$ ($j = 1, 2, 3, 4$), respectively, while the orientation (polarization) of the electric field for each laser beam is taken into account as $\vec{p}_j$ ($j = 1, 2, 3, 4$). Optical intensity on the sample in the $z = 0$ plane is given by

$$I = \left| \sum_{j=1}^{4} (a_j \cdot e^{-i(2\pi/\lambda)\sin\theta_j (\cos\varphi_j \cdot x + \sin\varphi_j \cdot y) + \psi_j \cdot \vec{p}_j}) \right|^2,$$  \hspace{1cm} (1)
where $\lambda$ is the laser wavelength, $a_j$ and $\psi_j$ are the amplitude and initial phase of the electric field of the individual beam $j$. We first consider transverse electric (TE)–transverse magnetic (TM) polarization and set

$$
\lambda = 308 \text{ nm}, \quad \varphi_j = (j - 1)\pi/2, \quad a_j = 1, \quad \psi_j = 0 \quad j = 1, 2, 3, 4,
$$

$$
\vec{p}_1 = \cos \theta_1 \hat{i} + \sin \theta_1 \hat{k}, \quad \vec{p}_3 = -\cos \theta_3 \hat{i} + \sin \theta_3 \hat{k}, \quad \vec{p}_2 = \vec{p}_4 = \hat{i}.
$$

(2)

2.2. Periodicity of linear defects

When the beams are incident on the sample at the same polar angle $\theta_j$ for all $j$, a uniform intensity distribution is obtained. The resultant pattern is a four-square array of dots with pitch ($p$) of $\lambda/(\sqrt{2} \sin \theta)$ in size [12, 13]. The pitch is 436 nm for $\theta_1 = \theta_2 = \theta_3 = \theta_4 = 30^\circ$. The $x$- and $y$-components of the pitch are determined by $p_x$ and $p_y$ each equal to $\lambda/\sin \theta$.

If the configuration of the incident beams (CIB for short) is changed but still symmetric ($\theta_1 = \theta_3, \theta_2 = \theta_4$), no defects appear in the pattern. Such a result is shown in figure 2(a), in which the polar angles are taken as $\theta_1 = \theta_3 = 38^\circ, \theta_2 = \theta_4 = 30^\circ$. Comparing with the pattern described above, the resultant pattern differs only in $p_x$ and preserves $p_y$.

In contrast, for an asymmetric configuration which is not satisfied by the condition $\theta_1 = \theta_3, \theta_2 = \theta_4$, periodic or quasi periodic linear areas with low intensity, called ‘linear defects’, appear in the pattern; see figures 2(b) and (c). The parameters $p_n$ ($n$ refers to $x$ or $y$) can be expressed as

$$
p_x = \frac{2\lambda}{|\sin \theta_1 + \sin \theta_3|}, \quad p_y = \frac{2\lambda}{|\sin \theta_2 + \sin \theta_4|}.
$$

(3)

Distribution of the linear defects is more complicated. We define $td_n$ as

$$
td_x = \frac{2\lambda}{|\sin \theta_1 - \sin \theta_3|}, \quad td_y = \frac{2\lambda}{|\sin \theta_2 - \sin \theta_4|}, \quad td = \frac{d_x d_y}{\sqrt{d_x^2 + d_y^2}}.
$$

(4)
Figure 2. Simulated intensity distribution of four-beam interference at $\psi_1 = \psi_2 = \psi_4 = 0$ and (a) $\theta_1 = \theta_3 = 38^\circ$, $\theta_2 = \theta_4 = 30^\circ$ and $\psi_3 = 0$; (b) $\theta_1 = 38^\circ$, $\theta_2 = \theta_3 = \theta_4 = 30^\circ$ and $\psi_3 = 0$; (c) $\theta_1 = 38^\circ$, $\theta_2 = 34^\circ$, $\theta_3 = \theta_4 = 30^\circ$ and $\psi_3 = 0$; (d) $\theta_1 = \theta_3 = 38^\circ$, $\theta_2 = \theta_4 = 30^\circ$ and $\psi_3 = \pi$.

and $d_x$, $d_y$ as distances (including the width of one linear defect, $W_d$ (defined in section 2.3)) of two adjacent linear defects along the $x$- and $y$-directions, while $d$ is measured in the direction perpendicular to the defect line (figure 2(c)). Then we have

$$d_n = t d_n / 2, \quad \text{when} \quad t d_n / p_n = 2 m + 1, \quad (5a)$$

$$d_n = \text{int} \left( \frac{t d_n}{2 p_n} \right) \cdot p_n \pm \frac{p_n}{2}, \quad \text{when} \quad t d_n / p_n \neq 2 m + 1, \quad (5b)$$

$$m = 1, 2, 3, \ldots, \quad n = x, y,$$

where ‘int( )’ refers to the integral part. In most cases, $d_n$ changes with position and the linear defects do not exhibit strict periodicity. The mean value of $d_n$ must equal one half of $t d_n$.

The results of (5) are shown in figures 3(a) and (b) as examples, in which $\theta_1$ is taken to be 33.204° and 33.367°, respectively, while all other parameters are the same as those used in figure 2(b).

2.3. Width of linear defects

When a material is exposed to four laser beams, the surface pattern only appears in the regions where the intensity is higher than the threshold ($I_{th}$) needed for modification of the sample surface. On the contrary, linear defects can emerge at intensities lower than the threshold. The width of linear defects depends on the ratio of incident intensity ($I_0$ for each beam) to
2.4. Effect of phase changing

The intensity profile of the pattern varies, as the initial phase $\psi_i$ is varied \([12, 13]\). If we set $\theta_1 = \theta_3 = 38^\circ$ and $\theta_2 = \theta_4 = 30^\circ$ and changed $\psi_3$ from zero to $\pi$, while having $\psi_1 = \psi_2 = \psi_4 = 0$, the density of the intensity peaks would be doubled (cf figure 2(a) with figure 2(d)). Clearly, the phase $\psi_j$ should be controllable in this symmetric CIB yielding a uniform interference pattern without defects. On the other hand, for an asymmetric CIB, variation in $\psi_j$ causes no change in intensity profile but results in an offset of the whole pattern. The offset is $d/2$ in the direction normal to the defect lines if the initial phase of one beam $\psi_j$ is changed by $\pi$.

2.5. Polarization

The above results are valid for TM–TM polarization as well, for which we can write

$$
\begin{align*}
\vec{p}_1 &= \cos \theta_1 \vec{i} + \sin \theta_1 \vec{k}, & \vec{p}_3 &= -\cos \theta_3 \vec{i} + \sin \theta_3 \vec{k}, \\
\vec{p}_2 &= \cos \theta_2 \vec{j} + \sin \theta_2 \vec{k}, & \vec{p}_4 &= -\cos \theta_4 \vec{j} + \sin \theta_4 \vec{k}.
\end{align*}
$$

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A very different phenomenon takes place if one considers TE–TE polarization, which is defined as $\vec{p}_1 = \vec{p}_3 = \vec{j}$, $\vec{p}_2 = \vec{p}_4 = \vec{i}$.

Now, in TE–TE mode, varying $\psi_j$ causes no change at all in the pattern. It only moves the position of the pattern. Varying $\theta_j$ causes no linear defects. So, if a uniform interference pattern without linear defects is desired, TE–TE mode is an ideal choice.

3. Experimental results

We now proceed to compare the linear defects predicted theoretically with the corresponding experimental patterns. A pulsed XeCl excimer laser emitting at $\lambda = 308$ nm with a single pulse with duration of 20–40 ns was used to create the patterns. The laser beam was split into four component beams and focused on the sample.

The polar angles in this particular experiment were $\theta_i \approx 20^\circ$ and the azimuthal angles $\varphi_j = (j - 1)\pi/2$, with $j = 1, 2, 3, 4$. The intensity profiles were Gaussian, and the total average power was up to 105 mJ pulse$^{-1}$. A 20-nm thick SiO$_2$ layer was deposited on the GaAs wafer with PECVD to act as the recording material. Considering manual operation of the IL system gave rise to a slight unintentional asymmetric configuration for $\theta_j$, the four beams interfered in the way as shown in figure 2(c). In the peak areas where the intensities are higher than the threshold $I_{th}$ (figures 3(a) and (b)), the heat generated by IL patterns melted the SiO$_2$, decomposed GaAs and evaporated As to the gas phase underneath the SiO$_2$ layer. The As gas expanded quickly and created SiO$_2$ bubbles. The temperature ramped down quickly and the shape of SiO$_2$ was preserved after the laser pulse. The SiO$_2$/GaAs sample was chosen here just because it offered us an easy way to record the interference pattern. A whole set of processing with photoresist and optimized laser intensity is needed to create PhCs according to the IL patterns.

Figure 4 shows the atomic force micrographs (AFM) of the patterns produced by IL. The pattern A in (a) was formed near the centre of the exposed area while pattern B in (b) was 2 mm away from A. Because the beams exhibited Gaussian distributions, site A was irradiated much more strongly than site B. Height profile curves in figure 4 show the modification depth of surface reliefs along the dashed white line drawn on the left-hand panels. The curves are in good agreement with the simulated intensity distribution in figure 3.

Because the two patterns were generated by the same incident beams in TE–TM mode, they had the same pitch ($p_x \approx 689$ nm) along the x-direction, which can be confirmed by $d_i$ ($i = 1, 2, 3, 4$) marked in figure 4. Judged by the present data, $td_x$ is about $22p_x$ in both cases A and B. Confirming of the exact $td$ needs a larger image. Due to the difference in incident intensities, the defect widths along the x-direction are different for A and B ($W_1 = 1.727 \mu$m $\approx 2.5p_x$ and $W_2 = 2.434 \mu$m $\approx 3.5p_x$, respectively). All the experimental results are in good agreement with the simulation.

4. Summary

To summarize, we have simulated and experimentally investigated the formation of periodic linear defects generated by four-beam interference lithography. The pitch (corresponding to equation $(5a)$) or quasi pitch (corresponding to $(5b)$) and orientation of the defects can be controlled by the incident beam angles $\theta_j$ in accordance with $(4)$ and $(5)$. The width of the
defects varies with laser intensity and with the threshold of the target material. Varying the beam initial phase $\psi_j$ rigidly moves the whole interference pattern. The linear defects may appear in TE–TM and TM–TM modes, but not in TE–TE mode; therefore, TE–TE polarization can be used to produce uniform periodic surface patterns.

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