Japanese Journal of Applied Physics
Vol. 44, No. 9A, 2005, pp. 6568–6570

Laser Interference Lithography with Highly Accurate Interferometric Alignment

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(Received April 28, 2005; accepted June 15, 2005; published September 8, 2005)

It is shown experimentally that in laser interference lithography, by using a reference grating, respective grating layers can be positioned with high relative accuracy. A 0.001° angular and a few nanometers lateral resolution have been demonstrated.
[DOI: 10.1143/JJAP.44.6568]

KEYWORDS: laser interference lithography, lithography, photonic structures, photonic crystals, alignment

1. Introduction

The down-scaling of integrated optical (IO) devices is of importance for both theoretical and practical reasons and has attracted much research. A major step forward in this field was the invention of photonic crystals,[1] which are periodic structures in space (refractive index lattices) with a period in the order of the wavelength of light. These structures, which may prohibit the transmission of light in any direction for a certain wavelength range, the so-called photonic bandgap, provide new opportunities for developing ultra compact key components for integrated optics, such as splitters, wavelength filters, delay lines and light sources, thus promising a size reduction of IO circuits by orders of magnitude. Several requirements regarding lattice symmetry, refractive index contrast and microstructure should be satisfied in order to obtain a full three-dimensional (3-D) photonic bandgap.

One promising way to realize a 3-D photonic crystal, is by piling submicron spheres, which self-organize into an (inverse) opal structure.[2] Another promising technique concerns the oblique deposition on a rotating substrate. This may yield spiral structures with the potential to have a relatively large bandgap.[3] The controlled introduction of arbitrary lattice defects (which act as functional structures like waveguides, etc.) in this type of structures is far from obvious. However, lithographic fabrication of photonic crystals in a layer by layer fashion provides a natural way for defining defects.

A photonic crystal (PhC) structure that is especially well suited for lithographic fabrication is the 3-D woodpile structured photonic crystal (WPC), see Fig. 1. This structure has been proposed for the first time in 1994.[4] Since that time, four-layer structures with a stop band between 1.35 and 1.95 μm,[5] eight-layer structures, created with the use of wafer bonding,[6] and even 3-D 90° waveguide bends in a woodpile structure,[7] have been demonstrated.

For the lithographic production of 3-D PhC's, a sufficiently accurate process is required. Conventional mask lithography does not provide the required resolution and alignment accuracy because PhC's with a bandgap around 1550 nm typically contain structural details smaller than 500 nm in a high-index material like silicon. By using expensive equipment for deep-UV or (relatively slow) direct e-beam writing lithography this problem can be overcome. Laser interference lithography (LIL) is a very suitable technique for defining periodic structures.

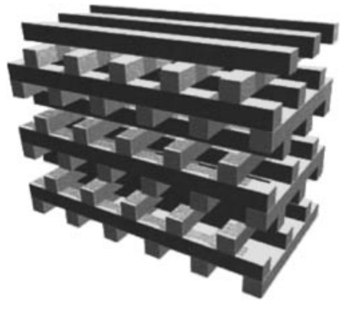

Fig. 1. Example of a 3D PhC structure: the woodpile structure.

However, an excellent alignment of these structures is essential, as has been shown for WPCs.[8] For these structures, the thickness and the width of the bars are very relevant as well, but they have significantly less impact than misalignment.[8] The influence of a deviation of 20% from the optimum thickness and width of the bars, results in a bandgap reduction of 18 and 15% respectively. On the other hand, misalignment in one direction by 10% of the lattice period, gives already a bandgap reduction of 30%.

The above also shows the importance of parallelism for a layer-by-layer fabrication method since each layer must be individually aligned with respect to the previously fabricated ones. If a relatively large photonic crystal is desired, requiring, *e.g.*, bars of length L, then a small angular misalignment θ may translate into a large, position dependent lateral misalignment up to $L \sin\theta$. For example in the case that $L = 1$ mm and $\Lambda = 650$ nm (typical for a bandgap around 1.5 μm in a silicon/air structure), the maximum allowed angular misalignment resulting in a maximum lateral error of 0.1Λ, would be around $\theta = 0.0035°$.

2. Laser Interference lithography

LIL is a maskless lithographic technique using the interference pattern of two obliquely incident beams. We used a setup based on the Lloyds interferometer,[9] schematically depicted in the inset of Fig. 2. One part of a laser beam reaches a photoresist-covered substrate directly, while a second part of that beam comes in via a mirror, thus producing a regular interference pattern in the photoresist. Because the second beam emerges from a mirror that is attached to the substrate, the setup is less sensitive to vibrations than a true dual beam interference setup. The

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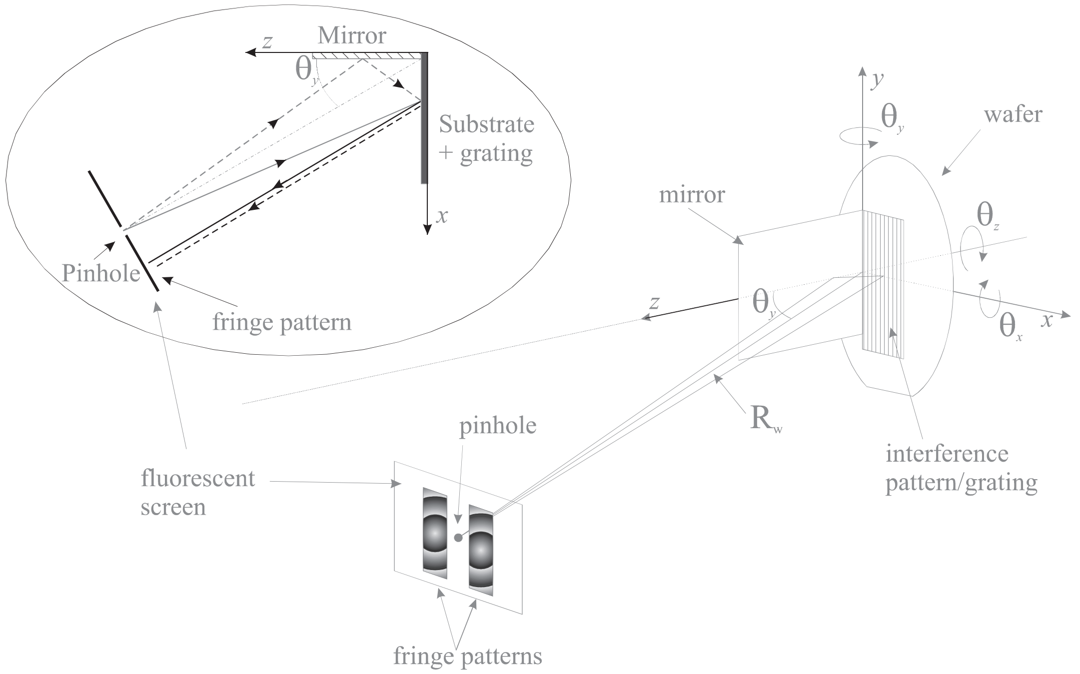

Fig. 2. Set-up for LIL-alignment of a new interference pattern with respect to an existing pattern.

period of the interference pattern on the substrate is given by $\Lambda \approx \lambda/(2\sin\theta_y)$, where λ is the wavelength and θ_y is the angle of incidence, as indicated in Fig. 2.

Here we have assumed that the angle between substrate and mirror is exactly 90° and we have neglected small variations due to the fact that the angles of incidence of the two beams vary slightly over the substrate. For a pinhole at a distance of $R_w = 2.3$ m and a grating of a few cm length the latter leads to a relative error in the grating period of typically 10^{-5}. With a 266 nm wavelength light source, periods of 150 to 500 nm can easily be made. After illumination and development of the resist, the grating can be transferred to the substrate by, *e.g.*, reactive ion etching.

3. Alignment

As mentioned before, the geometry of the structure is of major importance in order to produce a photonic crystal having a full bandgap. For the stacking of, *e.g.*, WPC's, this means that the lines of every second next layer have to be parallel within a very high degree and the periods of the gratings should be very well matched, in order to satisfy the conditions for a full 3-D bandgap everywhere in the crystal. So, on putting the sample back into the LIL set up for defining the next layer, accurate alignment is essential. To realize this, interferometric positioning can be used, as explained below.

The presented interferometric positioning method is based on analysis of the interference of two almost identical wavefronts, at two spots, next to the input pinhole (see Fig. 2), which occur when the reference grating is put back in the set-up. The occurrence of these spots next to the pinhole can be understood from geometrical optics considerations, taking into account the finite distance between pinhole and substrate, leading to a small variation of the grating period in the *x*-direction (see Fig. 2). The first (second) spot originates from the interference of the first order diffraction of the direct (reflected) beam and the zeroth order diffraction of the reflected (direct) beam.

When the substrate with the reference grating is at exactly the same position as during the production of the grating, the two wave fronts at either one of the spots coincide exactly, yielding two relatively homogenous spots on a fluorescent screen at both sides of the pinhole. Even a very small misalignment of the substrate gives rise to a deviation in the orientations of the two wave fronts. From straightforward geometrical optics considerations it can be shown that for small angular deviations, assuming substrate and mirror to be perfectly flat, two regular, striped patterns will appear next to the pinhole. The periods in the direction perpendicular to the central beam in the horizontal plane, W_h, and in the vertical direction, W_y, can be expressed as:

$$W_h = \lambda/(2\Delta\theta_y \cos\theta_y) \quad \text{and} \quad W_y = \lambda/(2\Delta\theta_z \sin\theta_y),$$

respectively. Here $\Delta\theta_y$ and $\Delta\theta_z$ are the misalignment angles. The strong dependence of the fringe pattern on the misalignment is shown in Fig. 3. Here, a grating with a period of 266 nm was re-aligned. The accuracy of realignment was limited by the resolution of the rotational stages, which is 0.001°. The deviations from straight fringes are attributed to curvature of the substrate.

In addition to the rotational realignment, also accurate positioning in lateral direction is of utmost importance. In WPC's, every second next layer has to be shifted laterally by half a period with respect to the preceding layer. After angular alignment the intensity of the fringe spots still depends on the phase shift between the two wave fronts caused by the lateral shift of the grating. Figure 4 shows a measurement (after angular alignment) of the intensity of the center of the fringe spot versus the lateral shift. This shift was realized by a piezo driven translation stage with a resolution of 1 nm. The irregularities in the figure are caused by power fluctuations of the laser beam. Relative measure-

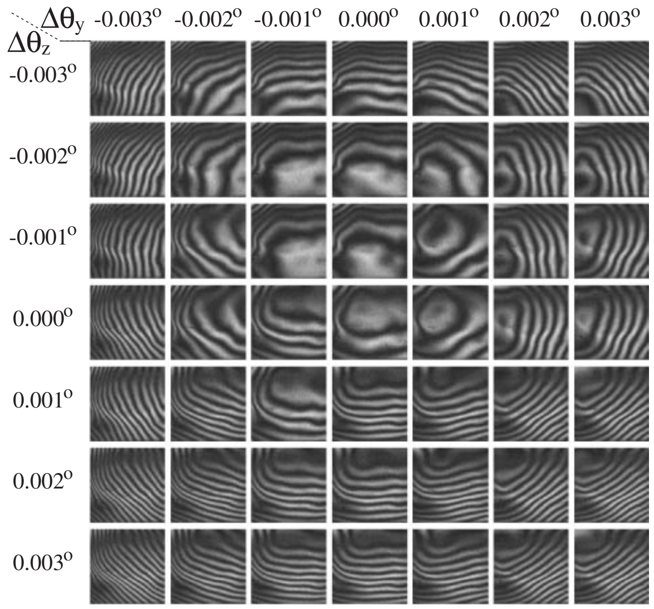

Fig. 3. Different fringe patterns for several combinations of misalignment angles $\Delta\theta_y$ and $\Delta\theta_z$ as observed when a wafer with an existing grating is repositioned in the set-up of Fig. 2.

ment of the spot intensity with respect to the beam power will give better results. The high sensitivity of the spot power as function of the grating translation is, however, very clear.

The above alignment feature can be used to produce a large number of well positioned grating structures in successive layers, whereby reference gratings enable accurate alignment.

4. Conclusions

From the above we conclude that interferometric positioning offers good possibilities for aligning a structure sufficiently accurate to make 3-D PhC's. The realized angular re-alignment accuracy of 0.001° was limited by the resolution of the rotational stages. With better rotation stages and better samples, an improvement in re-alignment accuracy with one order of magnitude is anticipated to be feasible. This is significantly better than the 0.003° mentioned in ref. 10.

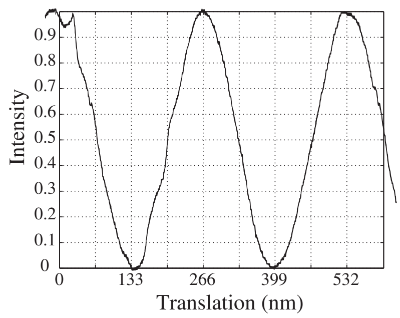

Fig. 4. Intensity of the center of the fringe pattern after angular alignment, as a function of lateral displacement.

The LIL-setup used offers a translational accuracy of only a few nanometers, which, again, is a strong improvement compared to the 17 nm accuracy, reported in ref. 10, and also compared to the 100 nm accuracy found for the procedure presented in ref. 11. It is expected that this accuracy can be improved to 1 nm or better, (limited by the translation table), by using a feedback loop from the spot intensity to the translation table controller. The achieved alignment results are sufficiently accurate for the construction of, *e.g.*, WPC's over an area of a few square mm.

Acknowledgment

This work was supported by the Dutch Technology Foundation STW (grant TMM.5554).

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