Laser interference lithography with highly accurate interferometric alignment

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Three dimensional photonic crystals, e.g. for obtaining the so-called woodpile structure, can, among others, be fabricated by vertical stacking of multiple gratings. One of the requirements for obtaining a full photonic bandgap in such a photonic crystal is an accurate angular and lateral alignment of the successive gratings. Using laser interference lithography at 266 nm wavelength, we fabricated gratings in silicon with periods down to 300 nm. We present a method for aligning further grating exposures with respect to this grating with a 0.001 degree angular and a few nanometers lateral resolution.

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 discovery 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 propagation 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 3D photonic bandgap.

One promising way to realize a 3D 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 these defects.

Figure 1: Example of a woodpile structure [1].

A Photonic Crystal (PhC) structure that is especially well suited for lithographic fabrication is the 3-Dimensional Woodpile Structured Photonic Crystal (WPC) (see Figure 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 waveguides for a wavelength of ± 8 μm in a woodpile structure, have been demonstrated.
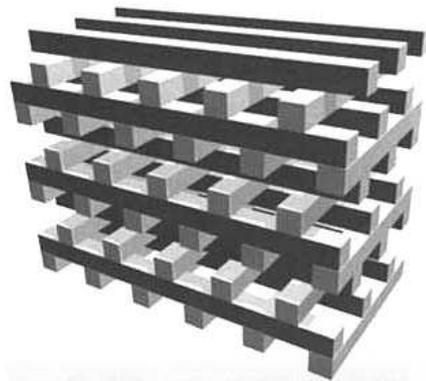
For the lithographic production of 3D PhC's, a sufficiently accurate process is required. Conventional mask lithography does not provide the required resolution and alignment accuracy because the typical structure size is less than 500 nm for PhC's with a bandgap around 1550 nm, in a high-index material like silicon. Using expensive equipment for deep-UV or (relatively slow) direct e-beam writing lithography, this problem can be overcome. As an alternative, Laser Interference Lithography (LIL) offers an excellent, relatively easy and cost-effective technique for the production of periodic structures.

However, alignment of these structures is essential, as has been shown for WPC's [7]. For these structures, the thickness and the width of the bars are very relevant as well, but they have significantly less impact than misalignment [7]. 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 20% of the lattice period, gives already a bandgap reduction of 44%, and 20% misalignment in two directions reduces the bandgap even by 58%.

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, schematically depicted in Figure 2, where a regular pattern is produced by interference of a laser beam and a "second" beam. Because the second beam is created by a mirror very close to the substrate, the setup is less sensitive to vibrations than a true dual beam interference setup. The period of the interference

Figure 2: Lloyds interferometer [8].

pattern, and thus that of the grating recorded in the resist layer on the substrate, is given by: $\Lambda_{IP} = \lambda/(2\sin\theta)$. With a 266 nm light source, periods of 150 nm to 500 nm can easily be made. For smaller periods, however, the quality of the development process and thickness of the resist have to meet some severe requirements because of the viscous character of the development liquid at submicron scale. After illumination and development of the resist, the grating can be transferred to the substrate by, e.g. reactive ion etching.
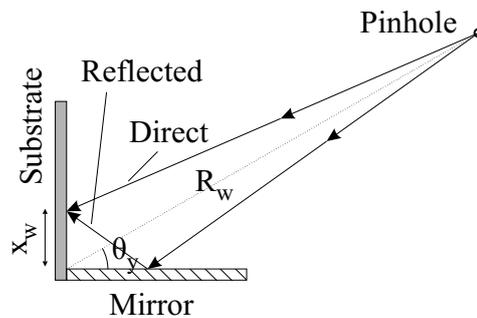
Alignment

As mentioned before, the geometry of the structure is of major importance in order to produce a photonic crystal having a full bandgap. When a grating is made with the LIL-setup, it consists of several tens of thousands of lines. This relatively large size of the grating imposes very strict requirements on alignment.

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 3D bandgap. 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 [9] at two spots, next to the input pinhole (see Figure

4). 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 grating is at exactly the same position as during the production of the grating, the two wavefronts 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, producing, in a plane wave approximation, fringe patterns with periods in the horizontal and vertical directions W_x and W_y respectively, given by [8]:

$$W_x = \frac{\lambda}{2\Delta\theta_y \cos\theta_y} \qquad W_y = \frac{\lambda}{2\Delta\theta_z \sin\theta_y}$$

Here, λ is the wavelength of the used light, $\Delta\theta_y$ and $\Delta\theta_z$ are the misalignment angles and θ_y the angle at which the grating was made (shown in Figure 2).

The strong dependence of the fringe pattern on the misalignment is shown in Figures 3. Here, a grating with a period of 266 nm was re-aligned. The accuracy of realignment was limited by the resolution of the rotation stages, which is 0.001°. The radius of curvature (here being 2.3 m.) and the sample quality are also important here, as can be seen from the distortions of the patterns in Figures 3.

In addition to the rotational realignment, also accurate positioning in lateral direction is of utmost importance. For WPC's, every second next layer is 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

Figure 3: 7x7 matrix of observations of the fringe pattern for different deviation angles with respect to the original alignment. [8].

shift between the two wave fronts caused by the lateral shift of the grating. Figure 5 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 measurement 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.

Conclusions

It can be concluded that interferometric positioning offers good possibilities for aligning a structure sufficiently accurate to make 3D PhC's. The realized angular re-alignment accuracy of 0.001° was limited by the resolution of the rotation stages. With better rotation stages and better samples, an improvement in re-alignment accuracy with one order of
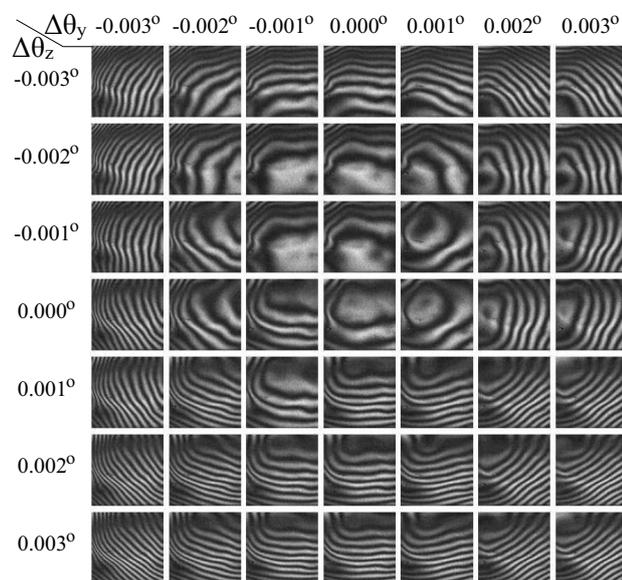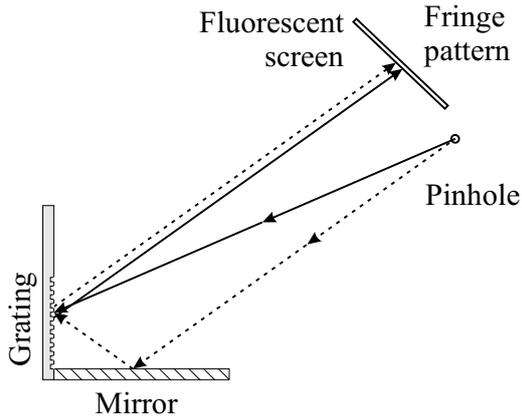
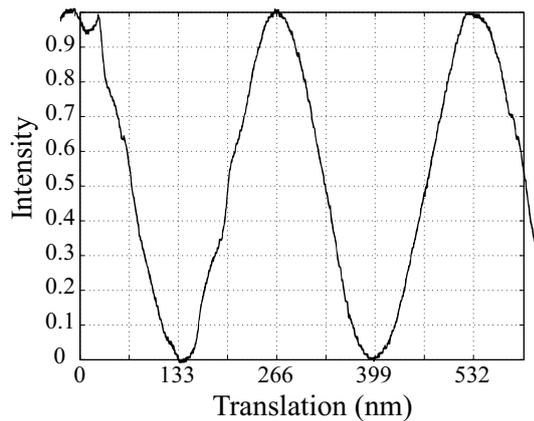Figure 4: Principle of alignment; matching reflected en diffracted wavefronts.

Figure 5: Intensity dependence of the grating translation [8].

magnitude is anticipated to be feasible. This is significantly better than the 0.003$^\text{o}$ mentioned in [9].

The LIL-setup used, offers a translational accuracy of only a few nanometers, which, again, is a strong improvement compared with the 17 nm accuracy, reported in [9]. 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.

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