3-21-2006

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Recommended Citation

Jianming Zhou, Yongfa Fan, Bruce W. Smith, "Three-dimensional imaging of 30-nm nanospheres using immersion interferometric lithography", Proc. SPIE 6154, Optical Microlithography XIX, 61544M (21 March 2006); doi: 10.1117/12.656544; https://doi.org/10.1117/12.656544

Three-dimensional imaging of 30-nm nanospheres using immersion interferometric lithography

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ABSTRACT

Immersion interferometric lithography has been applied successfully to semiconductor device applications, but its potential is not limited to this application only. This paper explores this imaging technology for the production of three-dimensional nano-structures using a 193 nm excimer laser and immersion Talbot interferometric lithographic tool. The fabrication of 3-D photonic crystals for the UV spectrum is still considered to be a challenge. A systematic analysis of immersion lithography for 3-D photonic crystal fabrication will be provided in this paper. Significant progress has been made on optical immersion lithography since it was first proposed. Two-beam immersion interferometric lithography can provide sub-30nm resolution. By changing the exposure parameters, such as the numerical aperture of the exposure system, the polarization states and wavelength of the illumination source, 30 nm polymeric nanospheres with different crystal structures can be fabricated.

Keywords: immersion lithography, photonic crystals, interferometric lithography

1. INTRODUCTION

Photonic crystals, also known as photonic band gap materials, are periodic structures of dielectrics. Due to destructive interference, certain wavelength can not propagate through them. After all the previous theoretical treatments, Yablonovitch et al proved that photonic crystals are indeed possible in 1991.[1] An artificial crystal structure was obtained by drilling holes into a high refractive index solid material. Microwave ranges from 13 GHz to 15 GHz can not propagate through this structure. Since then, much research has been done to investigate the fabrication of 2-D and 3-D photonic crystals. Two-dimensional photonic crystals can be achieved by conventional lithography and deep anisotropic etching. However, fabrication of 3-D microstructure is more challenging. Layer-by-layer stacking technique can be used for 3-D structure fabrication, however, its application can only extend to infrared regime.[2] Three-dimensional structures can also be obtained by self-organized materials. The main problems with this method are lack of uniformity and unwanted defects.[3] Holographic lithography has proven to be a practical method for fabricating 3-D photonic crystals by Campbell. With this method, a 3-D polymeric template with sub-micrometer periodicity was fabricated and utilized to create complementary structures with high refractive-index contrast.[4] Here we present a novel method using two-beam interferometric lithography for 2-D and 3-D photonic crystals fabrication by utilizing standing wave. The alignment of this technique is much easier compared with holographic lithography. Different crystal structures, features sizes can be achieved by changing the exposure parameters such as the illumination wavelength, polarization state and the numerical aperture. The simulation was done with ILSim software.[5] The analysis will show that with proper arrangement and materials, 3-D structures with different periodicity ranging from sub-30 nm to visible are possible.

2. STANDING WAVE EFFECT

For a dielectric film coated over reflective substrate, when exposed to coherent illumination source, the interference between the reflected beam and the incident beam will form a distribution of intensity within the photoresist. The nodal spacing is $\lambda/2n_i$, where n_i is the refractive-index of the photoresist and λ is the illumination wavelength. The pattern resulted from standing wave effect is determined by the resist absorbance, resist thickness and the reflection at the resist substrate interface.[6] The standing wave effect is not desired for lithographic process since it will degrade the pattern profile and it is controlled by applying bottom anti-reflective coating (BARC) and post exposure bake (PEB). Here we investigate the effect of standing wave from a different point of view. If the intensity of the wave reflected from the bottom of the resist is comparable with the incident wave, the interference pattern will be close to a 2-D photonic crystal. With two pass exposure, 3-D structures could be achieved with great flexibility and easy alignment. The large coherence length and high transparency of chemically amplified resist make the fabrication of 3-D structure feasible.

3. METHODOLOGY

The interference of two mutually coherent impinging beams forms a sinusoidal intensity distribution in the intersection. The pitch of the resulted pattern is:

$$\Lambda = \frac{\lambda_{vacuum}}{2n_{medium}\sin\theta} \qquad (1)$$

where λ_{vacuum} is the illumination wavelength, n_{medium} is the refractive index of the immersion media and θ is the incident angle in the immersion media. In order to best satisfy the mutual coherence requirement, a symmetric Talbot interference system was built, as shown in Figure 1. In this interferometer, a laser beam is expanded and polarized. The polarization state can be adjusted by rotating the polarizer. The phase grating serves as the beamsplitter. The 1^{st} and the -1^{st} diffraction orders are used as the interference waves. They are directed perpendicularly into a quartz half ball, and finally form the sinusoidal intensity distribution on the center of the half ball. The turning mirrors, combined with the phase grating pitch, define the arrival angle θ on the wafer. On the image side, the effective NA is $n_{quartz}\sin\theta$. By changing the impinging angle, the resulted pitch size can be calculated from Equation 1.

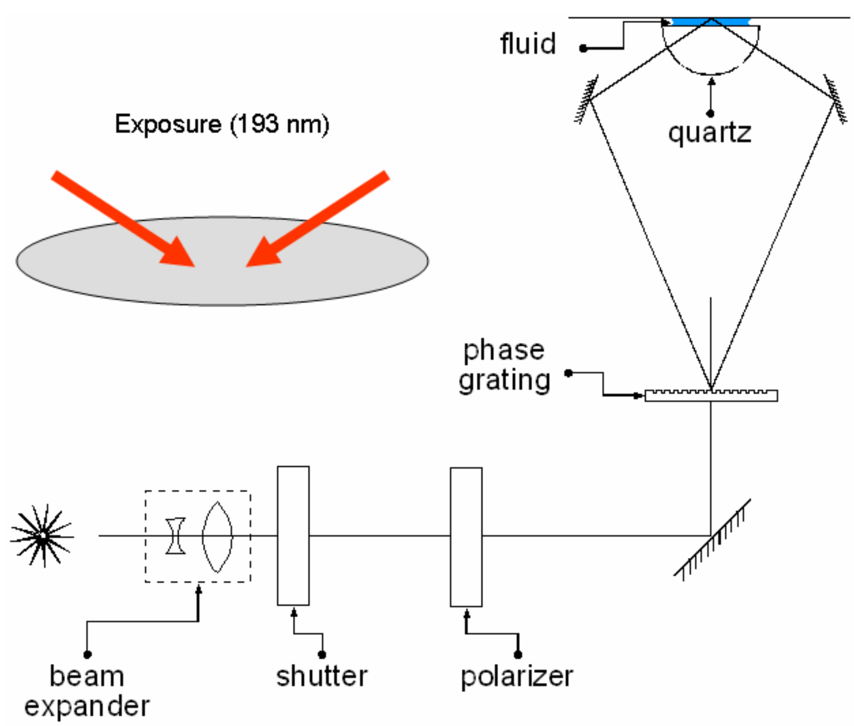


Figure 1. The experimental setup for two-beam interferometric lithography

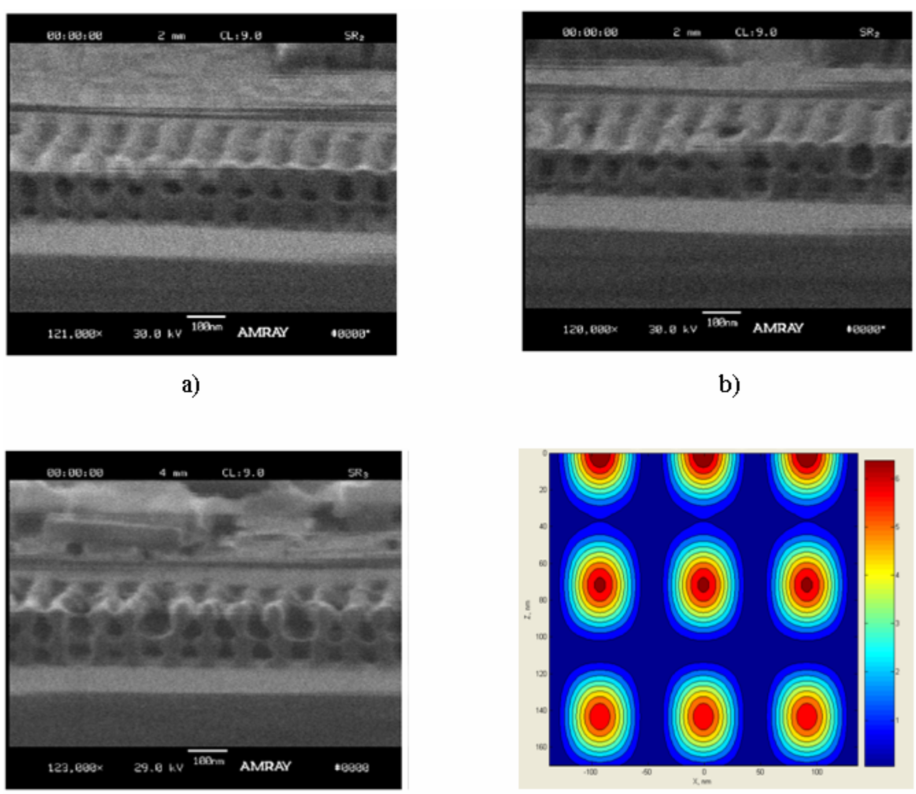
4. TWO-DIMENSIONAL IMAGING

TOK012, a chemical amplifying photoresist, was used for exposure. To avoid line collapse, the topcoat (TSP3A) was used during exposure, and kept on the top of the resist during development. The wafer was cleaved and the resist was developed from the side. To achieve high reflection from the bottom of the resist, no BARC was coated on the wafer. The resist is coated on a bare silicon substrate directly with a thickness of 170 nm. A 40 nm non-developable TSP3A topcoat was coated on the top of the resist film. The reflection was simulated to be 63% for TE polarization and 50% for TM polarization. Table 1 is the summary of the film stack for the exposure.

Table 1. Film stack for 2-D photonic crystal fabrication

Layer	Material	Complex refractive index	Thickness
Topcoat	TSP3A	1.414	40 nm
Resist	TOK012	1.71-0.039i	170 nm
Substrate	Silicon wafer	0.87-2.76i	-

Figure 2 shows the experimental results and simulation comparison for TE polarization exposure. With a resist thickness of 170nm, two and half standing wave nodes could be observed. The resultant SEM cross-sectional photographs for TE polarization at various exposure times are shown in Figure 2. The expose time is increased from photograph (a) to (c). The simulated light intensity distribution within the resist layer for 1.05NA using TE polarization is shown in Figure 2 (d). The exposure contours in the figure agree well with the SEM cross-sectional photographs. The filling fraction can be varied by using different dose until the pattern collapse.



a) b) c) d)

Figure 2. Two-dimensional nanostructure fabricated with 2-beam interferometric lithography with TE polarization, 1.05NA

With TM polarization, different intensity distribution pattern can be obtained with different numerical aperture as shown in Figure 3.

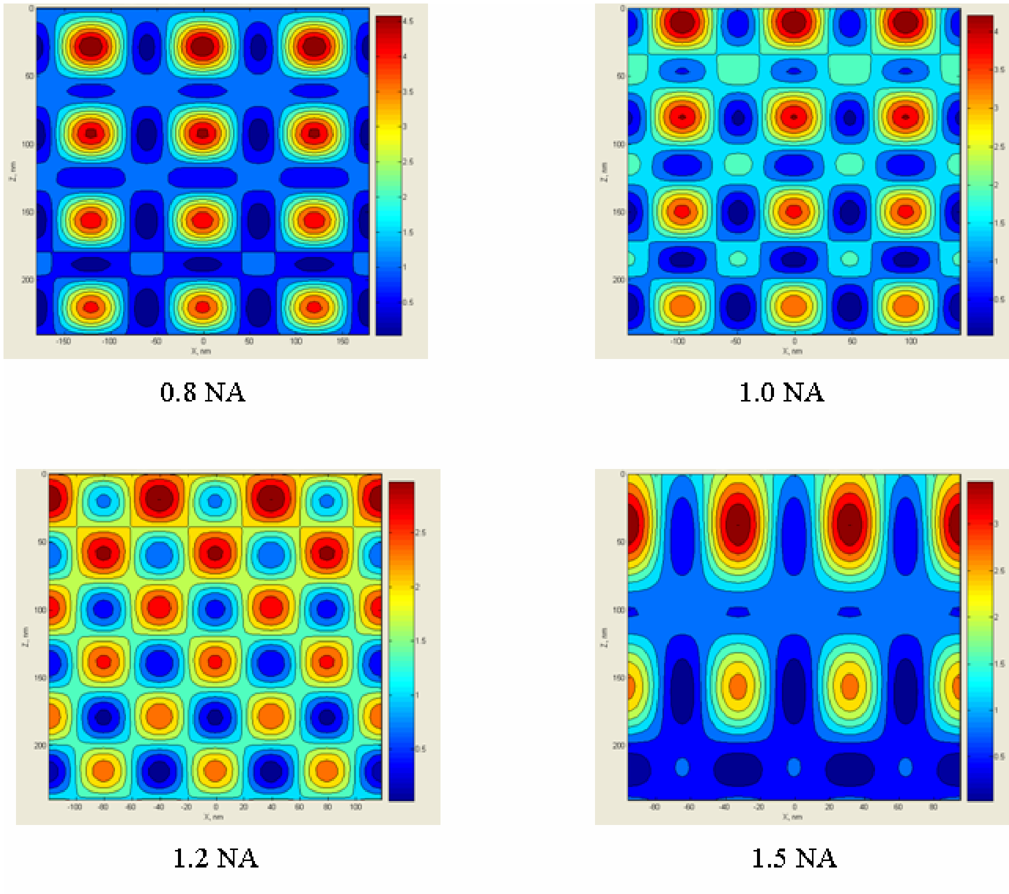


Figure 3. Various two-dimensional nanostructure may be fabricated by 2-beam interference with TM polarization at different numerical aperture (interference angle)

The different structure between TE and TM polarization is due to the polarization effect at high NA. For TE and TM polarization, the intensity distribution can be expressed as:

$$I_{TE} \propto 2|E|^2[1+\cos(2kx\sin\theta)] \qquad (2)$$

$$I_{TM} \propto 2|E|^2[1+\cos(2kx\sin\theta)\cos(2\theta)] \qquad (3)$$

Define the image contrast as:

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \qquad (4)$$

So the image contrast for TE and TM are

$$C_{TE} = 1 \qquad (5)$$

$$C_{TM} = \cos(2\theta) \qquad (6)$$

The contrast for TE polarization is always 1 while the contrast for TM polarization is a function of the interference angle θ. When θ is less than 45° the contrast decrease with θ and reaches zero when θ is equal to 45°. The contrast is negative for θ>45°, which means that the fringe bright stripes and dark stripes reverse.[7] This phenomenon enables the fabrication of different 2-D and 3-D structures with TM polarization.

5. THREE-DIMENSIONAL IMAGING

While two-beam exposure will result in 2-D structures, four-exposure will result in 3-D structures. After the first exposure, if the wafer can be rotated 90 degrees and exposed again, the superposition of the intensity will result in a 3-D structure. This is illustrated in Figure 4.

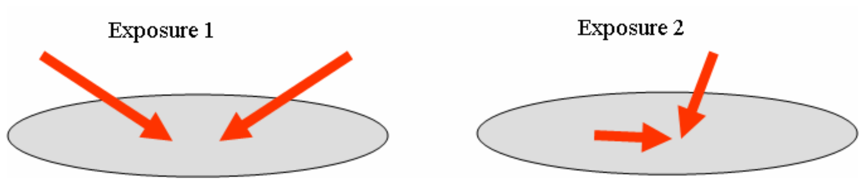


Figure 4. Two beam exposure for 3-D structure fabrication

Figure 5 shows the simulation for two-pass two-beam exposure with 193 nm TE polarized illumination source. The NA is chosen to be 1.2 to achieve equal pitches along x, y, and z direction.

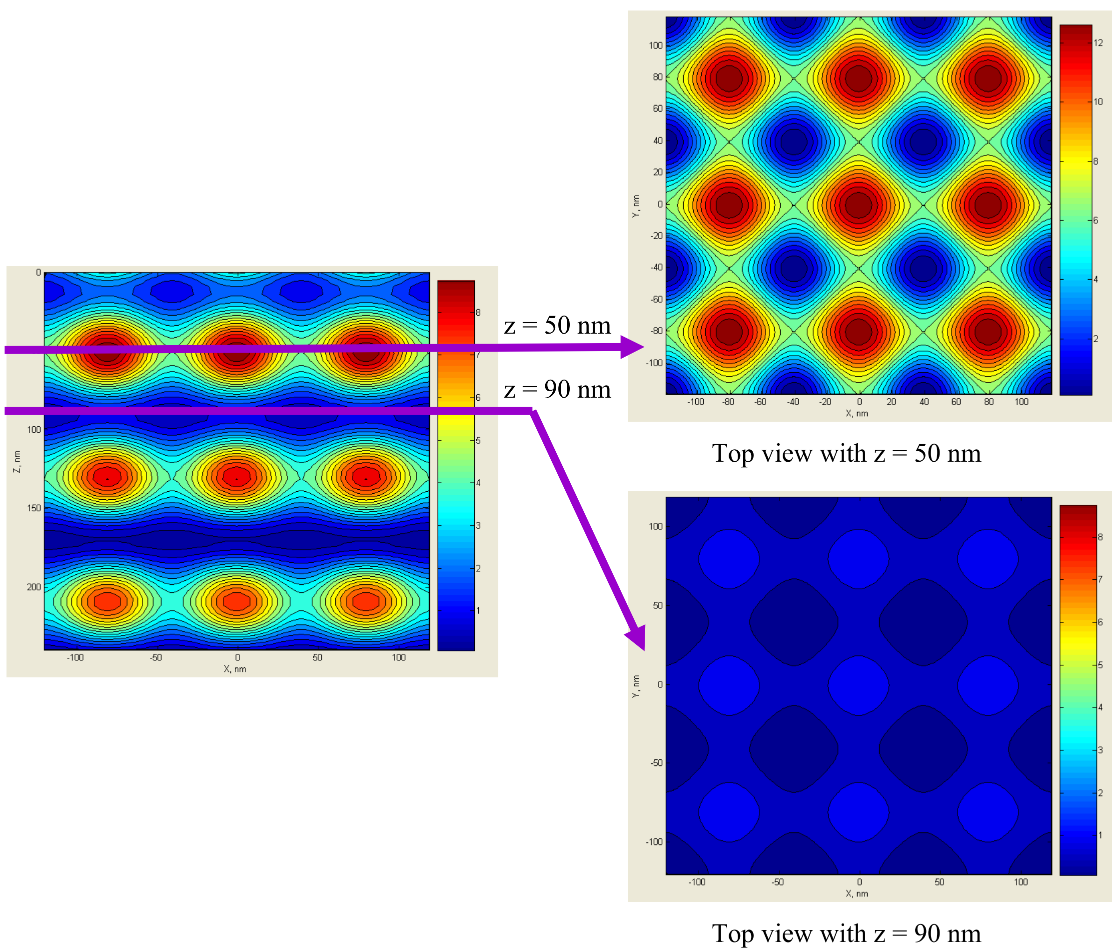


Figure 5. Two pass exposure with TE polarization at 45^{o} interference angle results in a simple cubic structure

With TE polarization, simple cubic structure can be achieved with lattice constant:

$$\Lambda = \frac{\lambda_{vacuum}}{2n_{resist}\sin 45^{o}} \qquad (7)$$

Therefore 40-nm lattice constant simple cubic structure is feasible with 193 nm illumination wavelength. The pitch along x and z may be different depending on the numerical aperture. Figure 6 is the simulation result for TM polarization, NA is 1.2. At this NA, due to image reversal, a body centered cubic structure can be achieved. The pattern is not uniform along z direction. This is due to the absorbance of the photoresist.

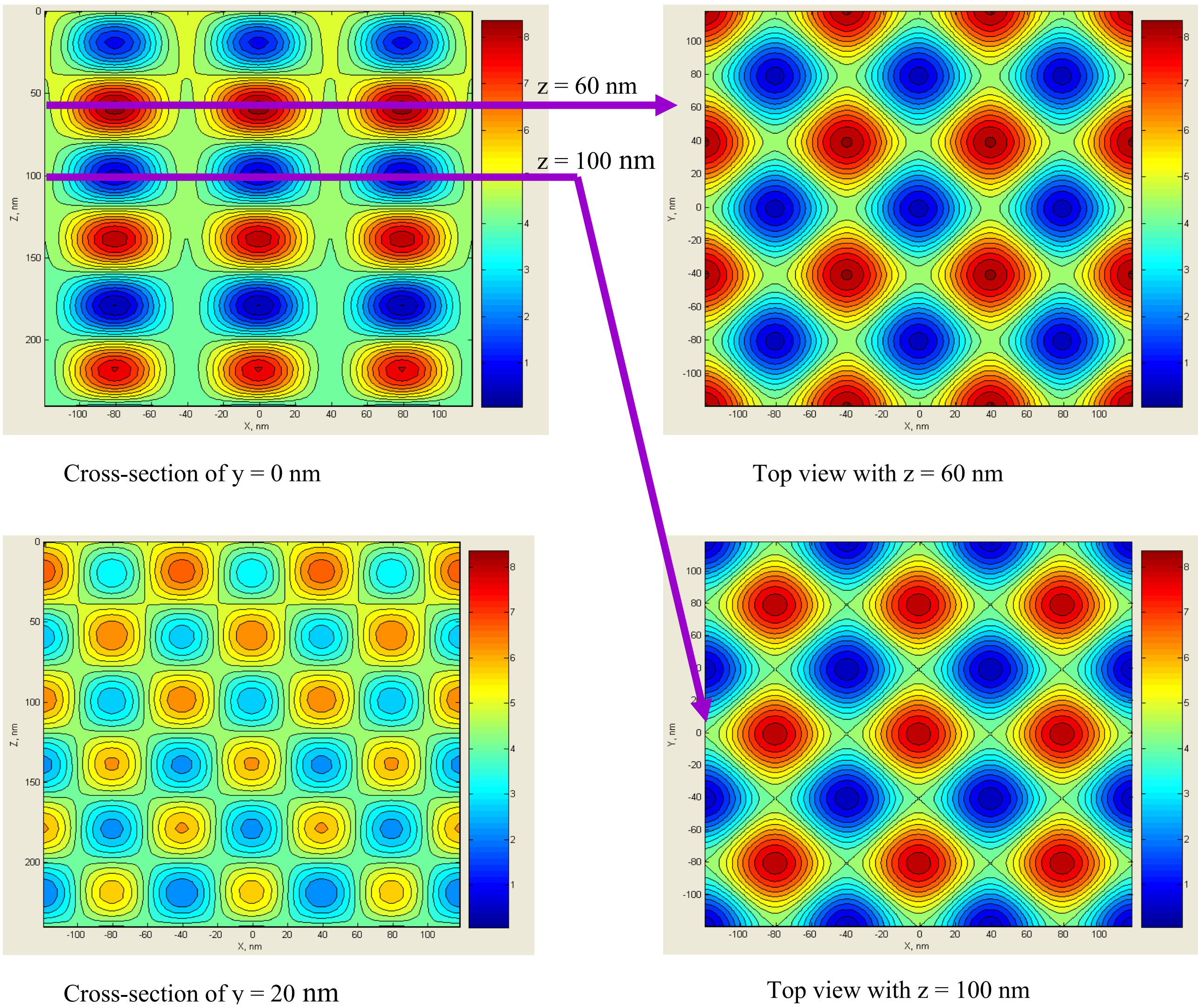


Figure 6. Two pass exposure with TM polarization at 45o interference angle results in a body-centered cubic structure.

All the simulations were done with 193 nm wavelength. Photonic crystals for visible wavelength can be obtained by scaling the illumination wavelength. For longer wavelength, a highly reflective coating may be needed to enable interference. A low absorption coefficient photoresist is desired to obtain uniform multiple periods along z direction.

By choosing different immersion media and high refractive-index photoresist, the fabrication of 30 nm nanospheres is possible. The resulted polymeric structure can be further utilized as template to create complementary structures of high refractive index dielectrics.

6. CONCLUSION

In this work, we showed that the standing wave could be utilized to fabricate photonic crystals. A two-dimensional nanostructure was successfully fabricated with two-beam interferometric lithography by utilizing standing wave with TE polarized illumination source. The numerical study for TM polarization exposure shows that different structures may be achieved with certain NAs. The simulation of two-pass two-beam interference shows that 3-D nanospheres with different period and crystal structure can be fabricated.

ACKNOWLEDGEMENT

The authors thank SRC for supporting this research through Task Number 1083 and DARPA/AFRL through contract number F33615-03-1-1472

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