Advanced Electromagnetics:
21^{st} Century Electromagnetics

Holographic Lithography

Lecture Outline

- Photolithography
- Two beam interference
- Multiple beam interference
- Holographic lithography
- Beam synthesis
- Near-field nano-patterning

Photolithography

(Fabrication of a Rib Waveguide)

What is Photolithography

Usually ultra-violet light is used to expose a photosensitive material. For negative tone photoresists, the resist becomes polymerized where the light dose exceeds a threshold. A positive tone photoresist becomes polymerized where the light dose is below a threshold.

Photolithography is typically used to fabricate small 2D features from thin film.

Soft Bake (Oven)

3°C/min to 65°C. 25 min hold.
3°C/min to 95°C. 30 min hold.
3°C/min to room temp.

Exposure

Photoresist: SU-8 2007 (7 μm film)
Wavelength: 365 nm
Dose: 40 mJ/cm²

Post Exposure Bake (Hot Plate)

65°C for 2 min.
95°C for 90 sec.
65°C for 3 min.

Develop

Time: 4 minutes
Developer: PGMEA

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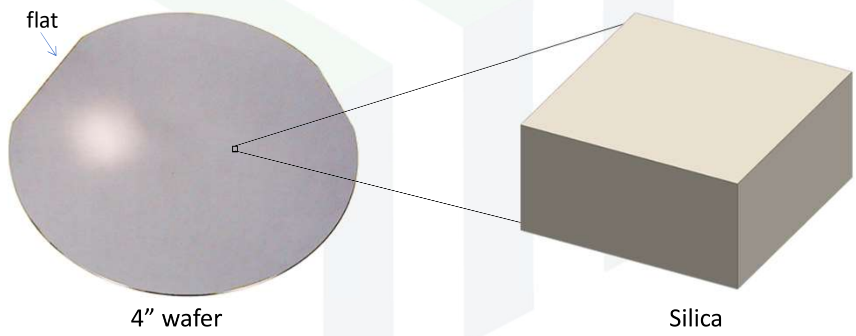
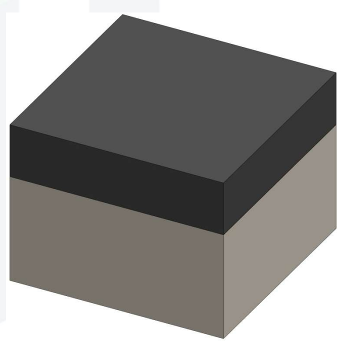
Close-Up View of Wafer

Typically, fabrication starts with a cleaned fused silica substrate. A 4” wafer is common in research labs. Fused silica has a refractive index of $n = 1.52$.



Deposition of High-Index Layer

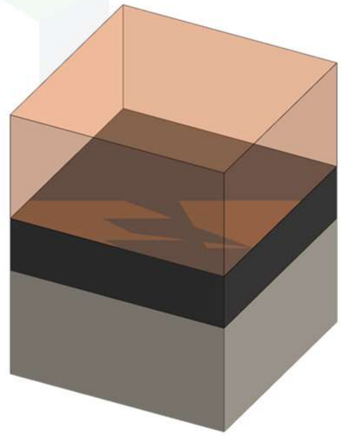
Second, a layer of high index material is deposited onto the silicon wafer. A common process is *plasma enhanced chemical vapor deposition* (PECVD). A common high index material is silicon nitride (SiN) which has a refractive index of $n = 1.9$.



Silica substrate with SiN

Spin Coat Photoresist

Third, a photoresist is spun onto the wafer using a spinner. A common photoresist is PMMA.



Silica substrate with SiN
and photoresist

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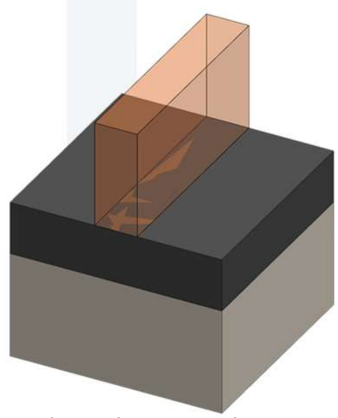
Develop Photoresist

Fourth, the resist is exposed to ultraviolet radiation through a mask in the pattern of the eventual optical integrated circuit. The exposed resist is then washed away leaving behind the unexposed resist.



Silica substrate with SiN
and developed photoresist

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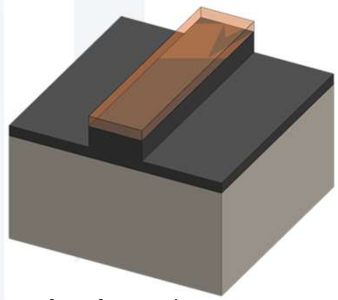
Plasma Etch

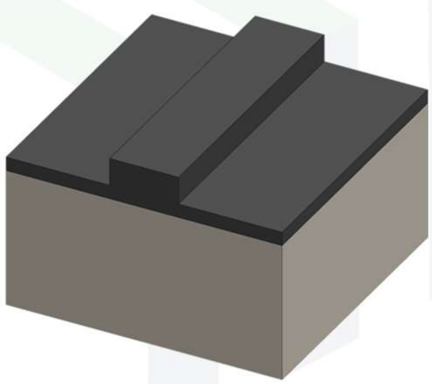
Fifth, the wafer is etched using a plasma etching process. Both the resist and SiN are etched, but the remaining resist prevent etching of the SiN material directly underneath.



Wafer after etching process

Clean Wafer

Sixth, the wafer is cleaned by removing the remaining resist. The optical integrated circuit (and our rib waveguide) is complete*!*



Rib Waveguide

Two Beam Interference

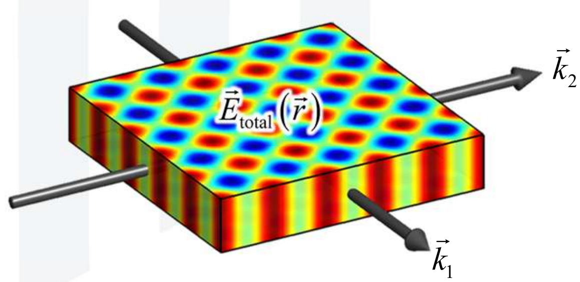
Electric Field Amplitude

The electric field associated with each of two separate beams

$$\vec{E}_1 e^{-j\vec{k}_1 \bullet \vec{r}} \quad \text{and} \quad \vec{E}_2 e^{-j\vec{k}_2 \bullet \vec{r}}$$

The overall electric field resulting from the interference of these two beams is

$$\vec{E}_{\text{total}}\left(\vec{r}\right) = \vec{E}_1 e^{-j\vec{k}_1 \bullet \vec{r}} + \vec{E}_2 e^{-j\vec{k}_2 \bullet \vec{r}}$$



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Beam Intensity

The intensity is essentially the magnitude squared of the total electric field.

$$I(\vec{r}) = \frac{1}{2\eta}\left|E_{\text{total}}(\vec{r})\right|^2 = \frac{1}{2\eta}\left|\vec{E}_1 e^{-j\vec{k}_1\bullet\vec{r}} + \vec{E}_2 e^{-j\vec{k}_2\bullet\vec{r}}\right|^2 = I_0\left\{1 + V\cos\left(\vec{K}\bullet\vec{r}+\phi\right)\right\}$$

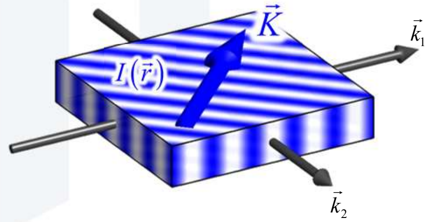
$\eta \equiv$ impedance of the medium

$I_0 = \frac{1}{2\eta}\left(\left|\vec{E}_1\right|^2 + \left|\vec{E}_2\right|^2\right)$ Overall intensity

$V = \frac{1}{2\eta I_0}\left|\vec{E}_1 \bullet \vec{E}_2^*\right|$ Visibility

$\vec{K} = \vec{k}_1 - \vec{k}_2$ Grating vector

$\phi = \text{Phase}\left[\vec{E}_1 \bullet \vec{E}_2^*\right]$ Phase

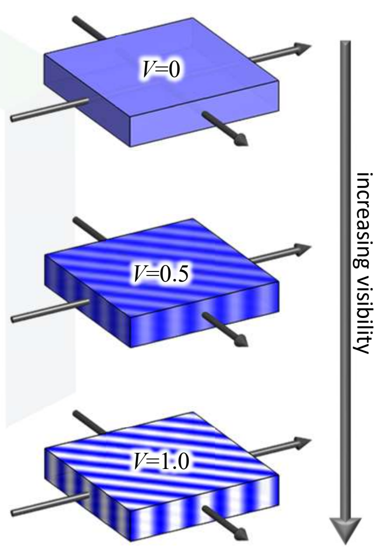


Visibility

Beams that are orthogonally polarized will not interfere and will have zero visibility.

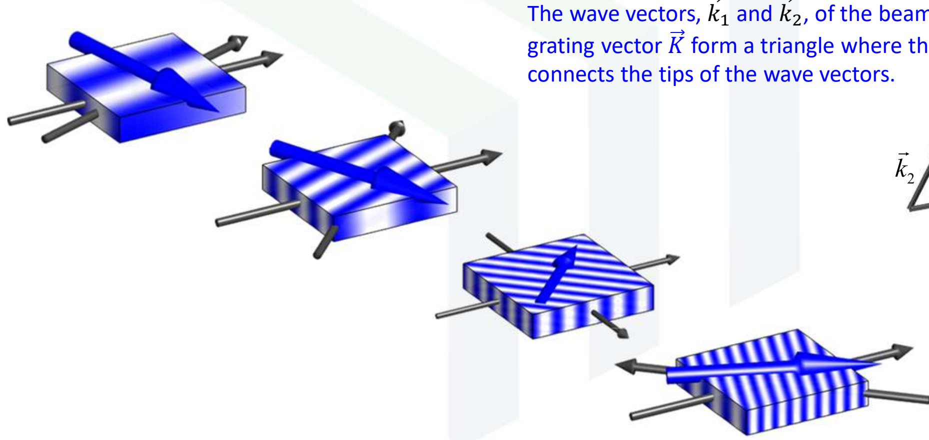
Beams that are not orthogonally polarized, but not completely the same, will interfere with moderate visibility.

Beams with the same polarization will have 100% visibility. That is, the interference will have completely dark regions and completely bright regions.

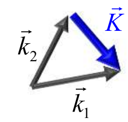


Induced Grating Vector

When two beams interfere, the resulting intensity is a sinusoidal pattern with a period and orientation that can be characterized by a grating vector $\vec{K}$.



The wave vectors, $\vec{k}_1$ and $\vec{k}_2$, of the beams and the induced grating vector $\vec{K}$ form a triangle where the grating vector connects the tips of the wave vectors.



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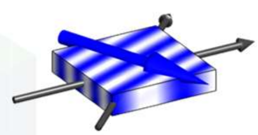
Conclusions on Two-Beam Interference



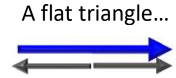
- The lines of the induced grating bisect the wave vectors.
- A small angle between the wave vectors produces a long period interference pattern.
  - There is no upper limit to how long the period can be.
- A large angle between the wave vectors produces a short period interference pattern.
  - There is a lower limit on the period.

$$\left|\vec{K}_{\max}\right| = 2\left|\vec{k}\right|$$

$$\frac{2\pi}{\Lambda_{\min}} = 2\frac{2\pi n}{\lambda_0} \rightarrow \Lambda_{\min} = \frac{\lambda_0}{2n}$$

$n \equiv$ refractive index of the photoresist

A flat triangle…



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Multiple Beam Interference

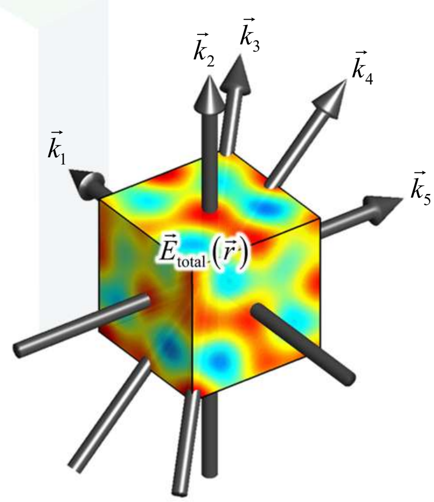
Electric Field Amplitude

Suppose there are N beams overlapping in the same volume of space and producing interference.

$$\vec{E}_1 e^{-j\vec{k}_1 \bullet \vec{r}}, \vec{E}_2 e^{-j\vec{k}_2 \bullet \vec{r}}, \cdots \vec{E}_N e^{-j\vec{k}_N \bullet \vec{r}}$$

The interference between all N beams is the sum of all the constituent beams

$$\vec{E}_{\text{total}}(\vec{r}) = \sum_{n=1}^{N} \vec{E}_n e^{-j\vec{k}_n \bullet \vec{r}}$$



Beam Intensity

It follows that the intensity of the interference of all N beams is

$$I(\vec{r}) = \frac{1}{2\eta}\left|E_{\text{total}}(\vec{r})\right|^2 = \frac{1}{2\eta}\left|\sum_{n=1}^{N}\vec{E}_n e^{-j\vec{k}_n\bullet\vec{r}}\right|^2 = I_0\left[1+\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}V_{ij}\cos\left(\vec{K}_{ij}\bullet\vec{r}+\phi_{ij}\right)\right]$$

$\eta \equiv$ impedance of the medium

$I_0 = \frac{1}{2\eta}\sum_{n=1}^{N}\left|\vec{E}_n\right|^2$ Overall intensity

$V_{ij} = \frac{1}{2\eta I_0}\left|\vec{E}_i \bullet \vec{E}_j^*\right|$ Visibility of the interference between the i^{th} and j^{th} beams
Overall visibility $\rightarrow V = \sum_{i,j} V_{ij}$

$\vec{K}_{ij} = \vec{k}_i - \vec{k}_j$ Grating vector of the interference between the i^{th} and j^{th} beams

$\phi_{ij} = \text{Phase}\left[\vec{E}_i \bullet \vec{E}_j^*\right]$ Phase of the interference between the i^{th} and j^{th} beams. This term controls the offset of the interference pattern.

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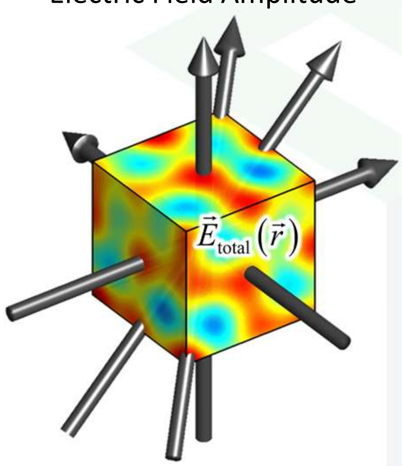
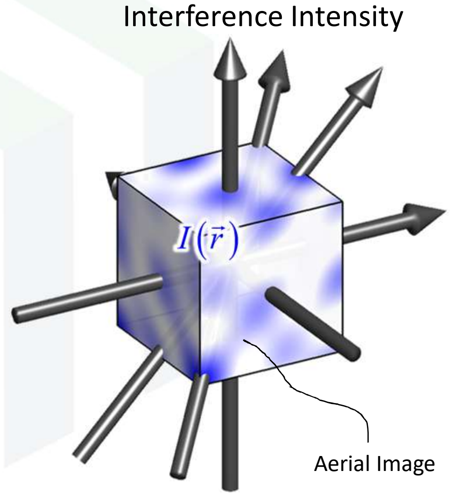
Beam Amplitude Vs. Intensity

Electric Field Amplitude



Interference Intensity



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Induced Grating Vectors

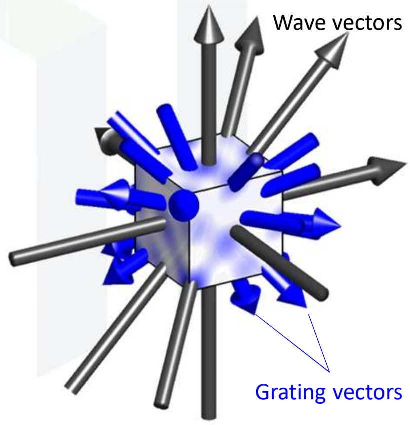
Each pair of wave vectors induces one sinusoidal interference pattern characterized by a grating vector. For the interference of N beams, the number of induced grating vectors is

$$\#\ \vec{K}\text{'s} = \frac{N^2 - N}{2}$$

Example

If five beams are interfered, ten gratings result.

$$\frac{5^2 - 5}{2} = 10 \text{ gratings}$$



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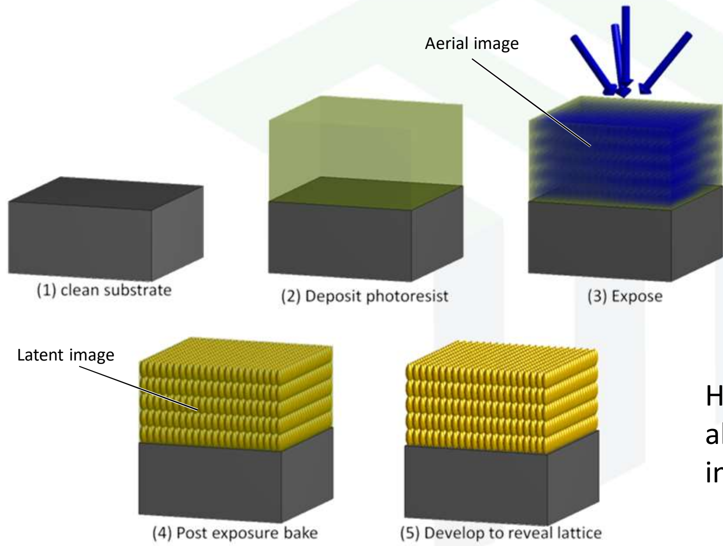
Holographic Lithography

What is Holographic Lithography?



Holographic lithography is almost always performed by interfering four optical beams.

4 Beams = 6 Gratings

If four beams produce interference, six planar gratings are created.

$$\#\ \text{gratings} = \frac{N^2 - N}{2} = \frac{4^2 - 4}{2} = 6 \qquad N \equiv \text{number of beams}$$

The six gratings are

$$\vec{k}_1 - \vec{k}_2 = \vec{K}_{12}$$
$$\vec{k}_1 - \vec{k}_3 = \vec{K}_{13}$$
$$\vec{k}_1 - \vec{k}_4 = \vec{K}_{14}$$
$$\vec{k}_2 - \vec{k}_3 = \vec{K}_{23}$$
$$\vec{k}_2 - \vec{k}_4 = \vec{K}_{24}$$
$$\vec{k}_3 - \vec{k}_4 = \vec{K}_{34}$$

Note that $\vec{K}_{ij}$ describes the same grating as $\vec{K}_{ji}$ so only one of these has to be considered.

~~$\vec{K}_{21}$~~ ~~$\vec{K}_{31}$~~ ~~$\vec{K}_{41}$~~ ~~$\vec{K}_{32}$~~ ~~$\vec{K}_{42}$~~ ~~$\vec{K}_{43}$~~

Determining Lattice Symmetry

It is known from previous lectures that any of the 14 Bravais lattices can be uniquely described by just three lattice vectors.

The reciprocal lattice vectors can be interpreted as grating vectors.

Only need three grating vectors are needed to completely determine the symmetry of the induced lattice, but four-beam interference produces six gratings. Choose any three grating vectors that contain information from all four wave vectors. These three determine the symmetry of the induced lattice.

Most common choice…

$$\vec{k}_1 - \vec{k}_2 = \vec{K}_{12}$$
$$\vec{k}_1 - \vec{k}_3 = \vec{K}_{13}$$
$$\vec{k}_1 - \vec{k}_4 = \vec{K}_{14}$$

Another valid choice…

$$\vec{k}_1 - \vec{k}_2 = \vec{K}_{12}$$
$$\vec{k}_2 - \vec{k}_3 = \vec{K}_{23}$$
$$\vec{k}_2 - \vec{k}_4 = \vec{K}_{24}$$

Incorrect choice…

$$\vec{k}_1 - \vec{k}_2 = \vec{K}_{12}$$
$$\vec{k}_1 - \vec{k}_3 = \vec{K}_{13}$$
$$\vec{k}_2 - \vec{k}_3 = \vec{K}_{23}$$

Where is $\vec{k}_4$?

Four Beams → All 14 Bravais Lattices

Using just four beams, all four Bravais lattices can be formed.

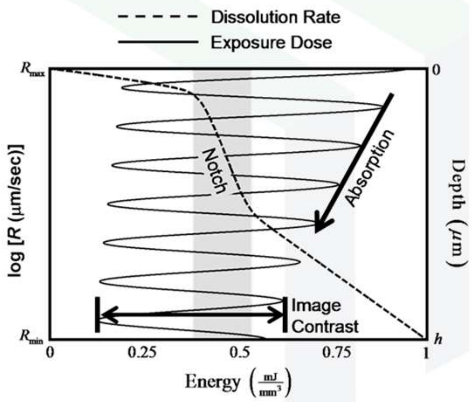
<u>Why?</u>
From theory just presented, any three grating vectors can created from just four beams.

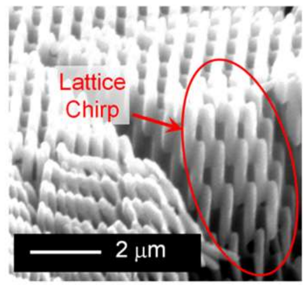
From solid state physics, all 14 Bravais can be described by three grating vectors.

<u>How?</u>
Determining what four beams are needed is called "beam synthesis."

Lattice Chirp

Lattices formed by holographic lithography are inherently chirped. This is due to absorption of the photoresist. Low absorption and high contrast resists help reduce chirp, but it is always present.





Raymond C. Rumpf and Eric G. Johnson," Fully three-dimensional modeling of the fabrication and optical properties of photonic crystals formed by holographic lithography," Journal of the Optical Society of America A, Vol. 21, No. 9, pp. 1703-1713, Sept. 2004.

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Beam Synthesis

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Step 1 – Design the Unit Cell

The beam synthesis procedure begins by choosing a Bravais lattice and calculating its reciprocal lattice vectors.

It is sometimes more intuitive to begin by defining the axis vectors of the direct lattice to control size and orientation of the unit cell more intuitively.

$$\begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vec{a}_3 \end{bmatrix} = \begin{bmatrix} \Lambda & 0 & 0 \\ 0 & \Lambda & 0 \\ 0 & 0 & \Lambda \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix}$$

Example
A cubic photonic crystal with lattice constant Λ will have these axis vectors.

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Step 2 – Choose the Lattice Symmetry

The primitive translation vectors can be calculated from the primitive axis vectors if the symmetry of the lattice is known.

Simple

$$\begin{bmatrix} \vec{t}_1 \\ \vec{t}_2 \\ \vec{t}_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vec{a}_3 \end{bmatrix}$$

Body-Centered

$$\begin{bmatrix} \vec{t}_1 \\ \vec{t}_2 \\ \vec{t}_3 \end{bmatrix} = \begin{bmatrix} -1/2 & 1/2 & 1/2 \\ 1/2 & -1/2 & 1/2 \\ 1/2 & 1/2 & -1/2 \end{bmatrix} \begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vec{a}_3 \end{bmatrix}$$

Face-Centered

$$\begin{bmatrix} \vec{t}_1 \\ \vec{t}_2 \\ \vec{t}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1/2 & 1/2 \\ 1/2 & 0 & 1/2 \\ 1/2 & 1/2 & 0 \end{bmatrix} \begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vec{a}_3 \end{bmatrix}$$

Proper choice for face-centered-cubic (FCC)

Base-Centered

$$\begin{bmatrix} \vec{t}_1 \\ \vec{t}_2 \\ \vec{t}_3 \end{bmatrix} = \begin{bmatrix} -1/2 & 1/2 & 0 \\ 1/2 & 1/2 & 0 \\ 0 & 0 & 1/2 \end{bmatrix} \begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vec{a}_3 \end{bmatrix}$$

Trigonal

$$\begin{bmatrix} \vec{t}_1 \\ \vec{t}_2 \\ \vec{t}_3 \end{bmatrix} = \begin{bmatrix} 1 & 1/3 & 1/3 \\ -1/3 & 1/3 & 1/3 \\ -1/3 & -1 & 1/3 \end{bmatrix} \begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vec{a}_3 \end{bmatrix}$$

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Step 3 – Calculate the Reciprocal Lattice Vectors

The reciprocal lattice vectors can be calculated directly from the direct lattice vectors using the following equations:

$$\vec{T}_1 = 2\pi \frac{\vec{t}_2 \times \vec{t}_3}{\vec{t}_1 \bullet \left(\vec{t}_2 \times \vec{t}_3\right)} \qquad \vec{T}_2 = 2\pi \frac{\vec{t}_3 \times \vec{t}_1}{\vec{t}_1 \bullet \left(\vec{t}_2 \times \vec{t}_3\right)} \qquad \vec{T}_3 = 2\pi \frac{\vec{t}_1 \times \vec{t}_2}{\vec{t}_1 \bullet \left(\vec{t}_2 \times \vec{t}_3\right)}$$

Example

A FCC lattice has the following primitive translation vectors…

$$\begin{bmatrix} \vec{t}_1 \\ \vec{t}_2 \\ \vec{t}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1/2 & 1/2 \\ 1/2 & 0 & 1/2 \\ 1/2 & 1/2 & 0 \end{bmatrix} \begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vec{a}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1/2 & 1/2 \\ 1/2 & 0 & 1/2 \\ 1/2 & 1/2 & 0 \end{bmatrix} \begin{bmatrix} \Lambda\hat{x} \\ \Lambda\hat{y} \\ \Lambda\hat{z} \end{bmatrix} = \begin{bmatrix} 0.5\Lambda\hat{y} + 0.5\Lambda\hat{z} \\ 0.5\Lambda\hat{x} + 0.5\Lambda\hat{z} \\ 0.5\Lambda\hat{x} + 0.5\Lambda\hat{y} \end{bmatrix}$$

The primitive translation vectors are…

$$\vec{T}_1 = 2\pi \frac{\vec{t}_2 \times \vec{t}_3}{\vec{t}_1 \bullet \left(\vec{t}_2 \times \vec{t}_3\right)} = \frac{2\pi}{\Lambda}\left(-\hat{x} + \hat{y} + \hat{z}\right)$$

$$\vec{T}_2 = 2\pi \frac{\vec{t}_3 \times \vec{t}_1}{\vec{t}_1 \bullet \left(\vec{t}_2 \times \vec{t}_3\right)} = \frac{2\pi}{\Lambda}\left(\hat{x} - \hat{y} + \hat{z}\right)$$

$$\vec{T}_3 = 2\pi \frac{\vec{t}_1 \times \vec{t}_2}{\vec{t}_1 \bullet \left(\vec{t}_2 \times \vec{t}_3\right)} = \frac{2\pi}{\Lambda}\left(\hat{x} + \hat{y} - \hat{z}\right)$$

Step 4 – Calculate Three Grating Vectors (1 of 2)

The correct symmetry will be induced as long as the grating vectors are an integer combination of the reciprocal lattice vectors.

$$\begin{bmatrix} \vec{K}_A \\ \vec{K}_B \\ \vec{K}_C \end{bmatrix} = \underbrace{\begin{bmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{bmatrix}}_{\mathbf{Q}} \begin{bmatrix} \vec{T}_1 \\ \vec{T}_2 \\ \vec{T}_3 \end{bmatrix} \qquad q_{ij} = -\infty, \cdots, -2, -1, 0, 1, 2, \cdots, \infty$$

Rules:

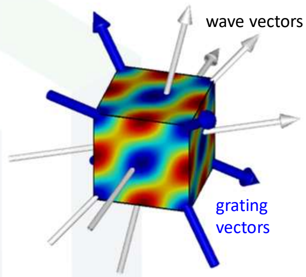
1. Each lattice vector must be used at least once, so no columns in $\mathbf{Q}$ can be all zeros.
2. Each grating vector must be unique so no row in $\mathbf{Q}$ can be an integer combination of other rows.

Step 4 – Calculate Three Grating Vectors (2 of 2)

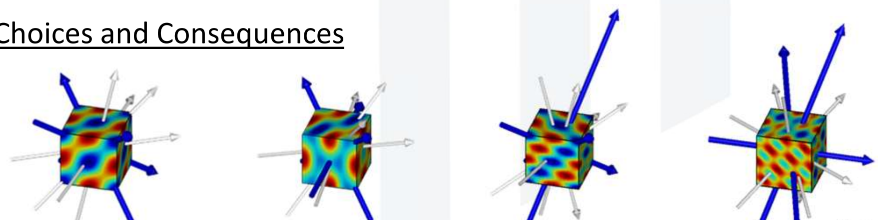
<u>Example</u>

The easiest and most common choice of $\mathbf{Q}$ is

$$\begin{bmatrix}\vec{K}_A\\ \vec{K}_B\\ \vec{K}_C\end{bmatrix}=\underbrace{\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}}_{\mathbf{Q}}\begin{bmatrix}\vec{T}_1\\ \vec{T}_2\\ \vec{T}_3\end{bmatrix}\quad\Rightarrow\quad\begin{aligned}\vec{K}_A&=\vec{T}_1=\frac{2\pi}{\Lambda}\left(-\hat{x}+\hat{y}+\hat{z}\right)\\ \vec{K}_B&=\vec{T}_2=\frac{2\pi}{\Lambda}\left(\hat{x}-\hat{y}+\hat{z}\right)\\ \vec{K}_C&=\vec{T}_3=\frac{2\pi}{\Lambda}\left(\hat{x}+\hat{y}-\hat{z}\right)\end{aligned}$$



<u>Other Choices and Consequences</u>



$\mathbf{Q}=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$ $\mathbf{Q}=\begin{bmatrix}1&0&0\\0&1&0\\1&0&1\end{bmatrix}$ $\mathbf{Q}=\begin{bmatrix}2&2&1\\0&1&0\\0&0&1\end{bmatrix}$ $\mathbf{Q}=\begin{bmatrix}2&2&1\\0&1&1\\2&0&1\end{bmatrix}$

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Step 5 – Choose How $\vec{k}$'s and $\vec{K}$'s Relate (1 of 2)

It is necessary to choose how the grating vectors relate to the wave vectors.

There are 120 possible combinations, but these can be reduced to a set of just five that are valid and unique.

Rule #1 – The grating vectors must contain information from all four wave vectors.

$\left[\vec{K}_{12},\vec{K}_{13},\vec{K}_{14}\right]$ Valid choice

$\left[\vec{K}_{12},\vec{K}_{13},\vec{K}_{23}\right]$ Invalid choice
Where is $\vec{k}_4$?

Rule #2 – The choice of how the grating vectors relate to the wave vectors must be unique.

$\left[\vec{K}_{12},\vec{K}_{13},\vec{K}_{14}\right]$ Valid choice

$\left[\vec{K}_{24},\vec{K}_{34},\vec{K}_{14}\right]$ Redundant choice
This is the same configuration. All we did was swap the numbering of beams 1 and 4.

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Step 5 – Choose Relation Between k and K (2 of 2)

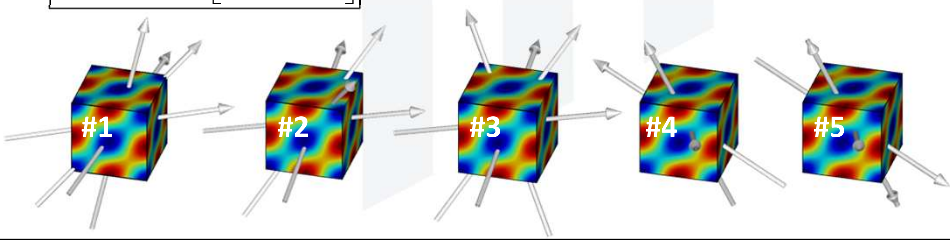
There exist only five valid and unique choices for how the grating vectors relate to the wave vectors. This saves you a lot of time and effort by preventing exploration of redundant configurations.

Choice #1 $\rightarrow$	$\left[\vec{K}_{12}, \vec{K}_{13}, \vec{K}_{14}\right]$
Choice #2 $\rightarrow$	$\left[\vec{K}_{12}, \vec{K}_{13}, \vec{K}_{24}\right]$
Choice #3 $\rightarrow$	$\left[\vec{K}_{12}, \vec{K}_{13}, \vec{K}_{34}\right]$
Choice #4 $\rightarrow$	$\left[\vec{K}_{13}, \vec{K}_{14}, \vec{K}_{24}\right]$
Choice #5 $\rightarrow$	$\left[\vec{K}_{14}, \vec{K}_{23}, \vec{K}_{24}\right]$

Example

The most common choice is $\left[\vec{K}_{12}, \vec{K}_{13}, \vec{K}_{14}\right]$.

$$\vec{k}_1 - \vec{k}_2 = \vec{K}_{12} = \vec{K}_A$$
$$\vec{k}_1 - \vec{k}_3 = \vec{K}_{13} = \vec{K}_B$$
$$\vec{k}_1 - \vec{k}_4 = \vec{K}_{14} = \vec{K}_C$$



Step 6 – Calculate the Four Wave Vectors (1 of 3)

It is not possible to calculate all four wave vectors from just three grating vectors because there are more unknowns than knowns.

$$\vec{k}_1 - \vec{k}_2 = \vec{K}_A$$
$$\vec{k}_1 - \vec{k}_3 = \vec{K}_B$$
$$\vec{k}_1 - \vec{k}_4 = \vec{K}_C$$

Additional information is needed and this comes from the condition that all four wave vectors have the same magnitude.

$$\left|\vec{k}_1\right| = \left|\vec{k}_2\right| = \left|\vec{k}_3\right| = \left|\vec{k}_4\right|$$

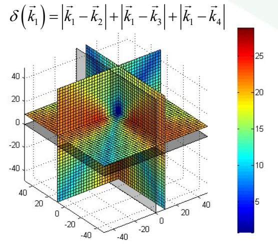
The above set of equations cannot be solve analytically.

Step 6 – Calculate the Four Wave Vectors (2 of 3)

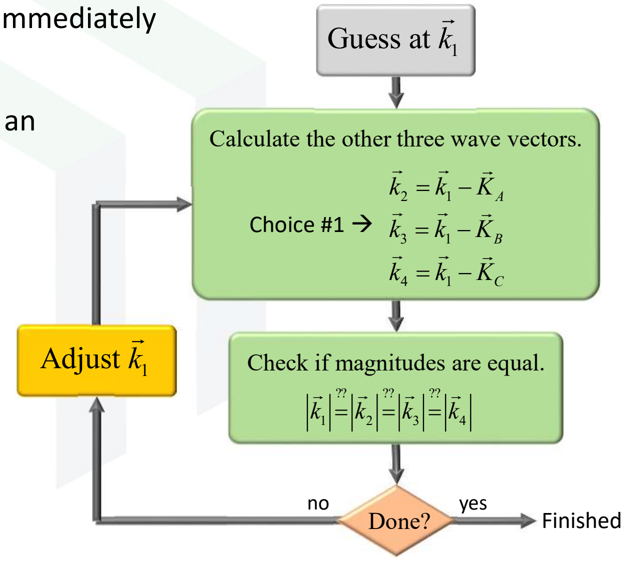
If one wave vector is known, the rest can be immediately calculated.

Determining the first wave vector reduces to an optimization problem.

$$\delta(\vec{k}_1) = |\vec{k}_1 - \vec{k}_2| + |\vec{k}_1 - \vec{k}_3| + |\vec{k}_1 - \vec{k}_4|$$



The solution space is rather smooth and continuous. This implies the use of efficient methods like gradient descent can be used.



Step 6 – Calculate the Four Wave Vectors (3 of 3)

Example

Given the following grating vectors and their chosen relation to the wave vectors…

$$\vec{K}_A = \vec{T}_1 = \frac{2\pi}{\Lambda}(-\hat{x} + \hat{y} + \hat{z})$$
$$\vec{K}_B = \vec{T}_2 = \frac{2\pi}{\Lambda}(\hat{x} - \hat{y} + \hat{z})$$
$$\vec{K}_C = \vec{T}_3 = \frac{2\pi}{\Lambda}(\hat{x} + \hat{y} - \hat{z})$$

$$\vec{k}_1 - \vec{k}_2 = \vec{K}_{12} = \vec{K}_A$$
$$\vec{k}_1 - \vec{k}_3 = \vec{K}_{13} = \vec{K}_B$$
$$\vec{k}_1 - \vec{k}_4 = \vec{K}_{14} = \vec{K}_C$$

The four wave vectors are found to be

$$\vec{k}_1 = \frac{\pi}{\Lambda}(3\hat{x} + 3\hat{y} + 3\hat{z}) \qquad \vec{k}_3 = \frac{\pi}{\Lambda}(\hat{x} + 5\hat{y} + \hat{z})$$
$$\vec{k}_2 = \frac{\pi}{\Lambda}(5\hat{x} + \hat{y} + \hat{z}) \qquad \vec{k}_4 = \frac{\pi}{\Lambda}(\hat{x} + \hat{y} + 5\hat{z})$$

Step 7 – Calculate Exposure Wavelength

Given the refractive index n of the photoresist, the exposure wavelength λ_0 is calculated from the magnitude of the wave vectors as

$$\left|\vec{k}\right| = \left|\vec{k}_1\right| = \left|\vec{k}_2\right| = \left|\vec{k}_3\right| = \left|\vec{k}_4\right| = \frac{2\pi n}{\lambda_0} \longrightarrow \lambda_0 = \frac{2\pi n}{\left|\vec{k}\right|}$$

Example

The magnitude of the wave vectors is

$$\left|\vec{k}\right| = \frac{27}{\sqrt{3}}\frac{\pi}{\Lambda}$$

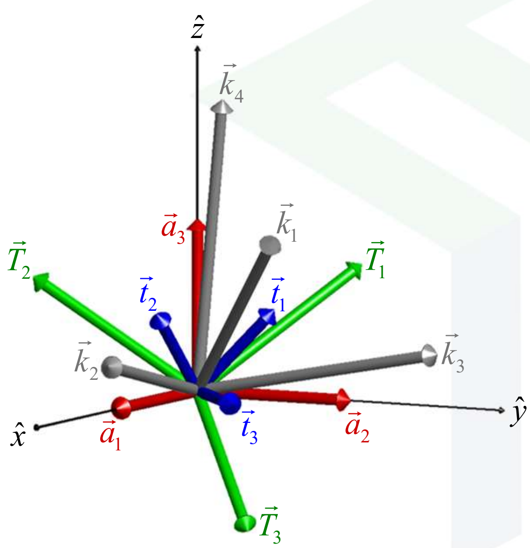
This equation relates the exposure wavelength λ_0 to the lattice constant Λ.

$$\frac{\lambda_0}{\Lambda} = \frac{2\sqrt{3}n}{27} \cong 0.1283n$$

Given a wavelength of 365 nm (i-line), what will the lattice constant be in a photoresist with refractive index 1.59 (i.e. SU-8)?

$$\Lambda \cong \frac{\lambda_0}{0.1283n} = \frac{365\text{ nm}}{(0.1283)(1.59)} = 1789\text{ nm}$$

Step 8 – Reorient Beams (1 of 2)



Axis Vectors: $\vec{a}_1, \vec{a}_2, \vec{a}_3$

Translation Vectors: $\vec{t}_1, \vec{t}_2, \vec{t}_3$

Grating Vectors: $\vec{T}_1, \vec{T}_2, \vec{T}_3$

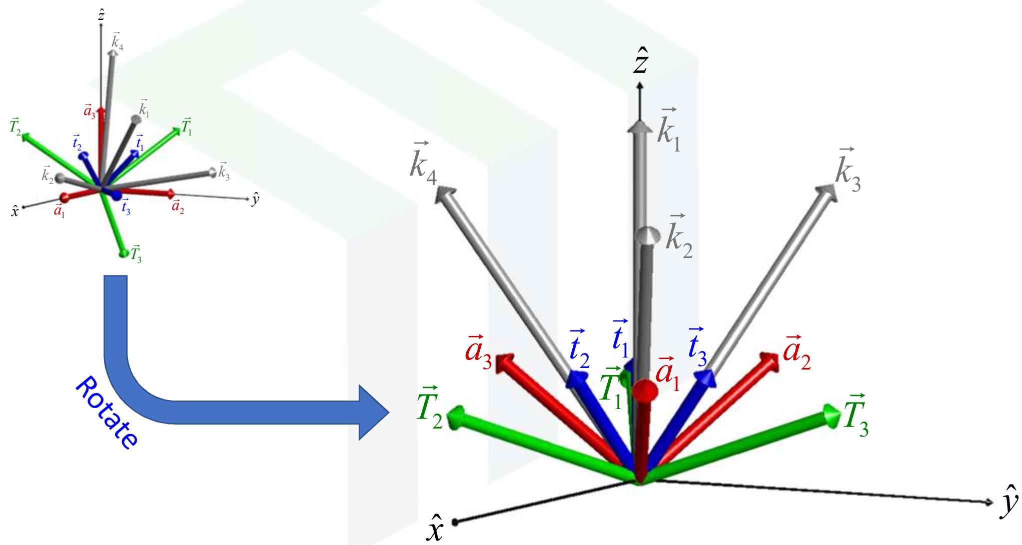
Wave Vectors: $\vec{k}_1, \vec{k}_2, \vec{k}_3, \vec{k}_4$

The resulting beams are shown in gray. They may not be in a convenient orientation for fabrication.

These can be reoriented, but this operation will reorient the lattice in the same manner.

This can be tolerated in many applications.

Step 8 – Reorient Beams (2 of 2)



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Step 9 – Determine Beam Polarization (1 of 2)

Polarization of the beams can have a dramatic impact on image contrast, lattice connectivity, and shape of objects in the lattice.

Most often, polarization should attempt to maximize the visibility of the three chosen gratings while minimizing the visibility of the others.

<u>Example</u>

$$\underbrace{\vec{K}_{12}, \vec{K}_{13}, \vec{K}_{14}}, \underbrace{\vec{K}_{23}, \vec{K}_{24}, \vec{K}_{34}}$$

Polarization should try to maximize the visibility of the chosen three.

Polarization should try to minimize the visibility of the other three.

Note: circumstances may very well exist where it is beneficial not to minimize the visibility of the other grating(s).

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Step 9 – Determine Beam Polarization (2 of 2)

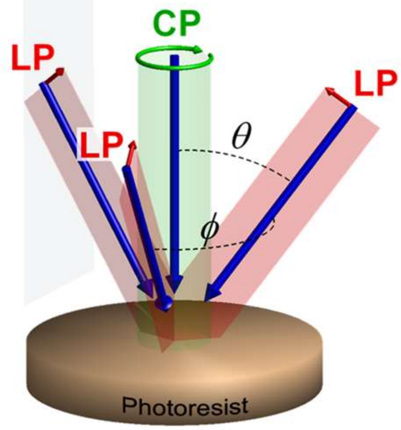
Example

The famous "umbrella" configuration to fabricate photonic crystals with FCC symmetry.

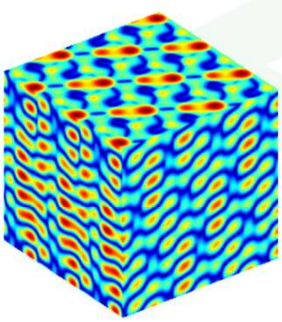
$$\theta = 38.94^\circ \qquad \phi = 120^\circ$$

The three side beams are linearly polarized in their planes of incidence. This makes them very nearly orthogonally polarized. The three gratings induced by the interference of these beams will have very low visibility.

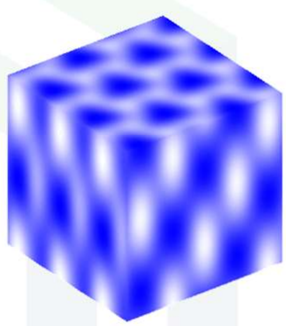
The center beam is circularly polarized and interferes well with the side beams. The three gratings induced by their interference will have high visibility.



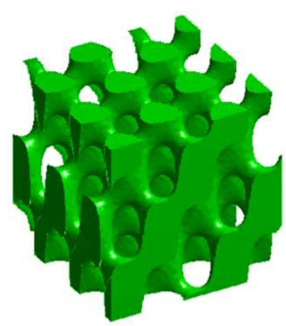
The Resulting FCC Lattice



Electric Field



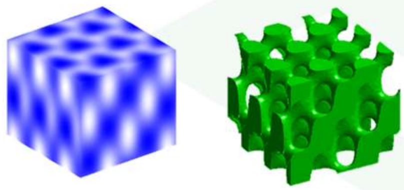
Aerial Image



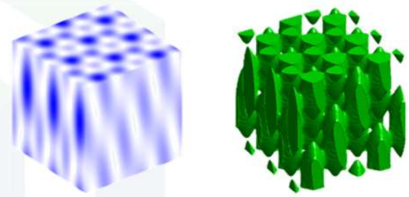
FCC Lattice

Impact of Polarization

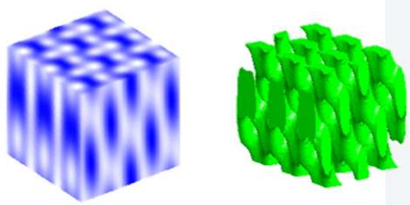
Famous Umbrella Configuration



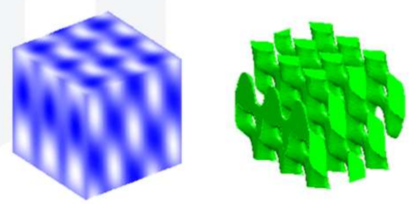
All Beams with Circular Polarization



All Beams with TE Polarization



All Beams with TM Polarization

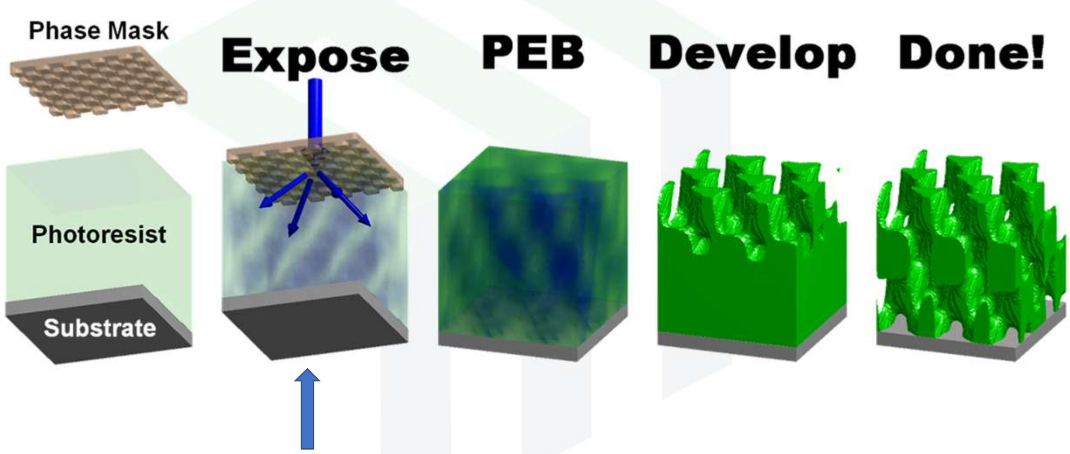


Final Notes on Beam Synthesis

- This beam synthesis procedure described here is unique in that more degrees of freedom have been identified than ever before.
  - Calculation of $\vec{K}_A$, $\vec{K}_B$, and $\vec{K}_C$ from $\vec{T}_1$, $\vec{T}_2$, and $\vec{T}_3$.
  - Relation between wave vectors and grating vectors.
  - Beam reorientation.
  - Beam polarization.
- Exploit this freedom to produce a beam configuration that is realizable for you.

Near-Field Nano-Patterning

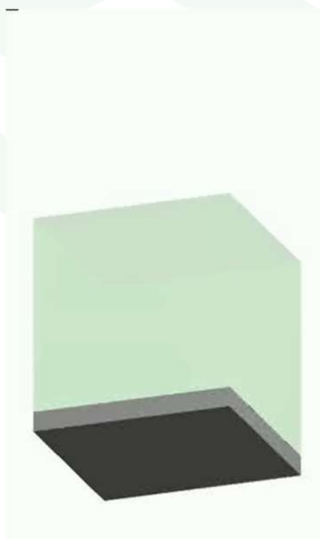
What is Near-Field Nano-Patterning?



We must search for a beam configuration where all four beams are from the top.

The added degrees of freedom are VERY helpful for this!!

Animation of NFNP



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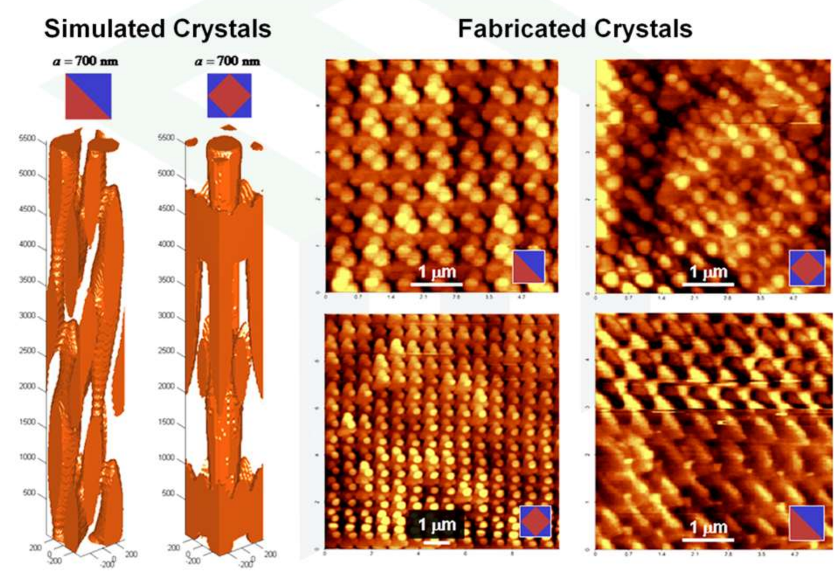
First-Ever 3D Photonic Crystals Formed by NFNP



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Benefits and Key Points of NFNP

- A diffraction grating is designed that provides the desired four beams. This is not easy!
  - Grating symmetry is selected based on the angle of beams.
  - Grating pattern is designed to balance diffraction efficiencies and control polarization.
  - More modes diffracted than just the desired four.
  - Must maximum diffraction into the four desired beams and suppress the others.
  - Must try to control polarization to optimize the interference.
- The source of the four beams (the grating) is in direct physical contact with the photoresist so NFNP is highly immune to mechanical vibrations.
- The path length difference between beams is only 10's of microns so the requirement on coherence is very low. Lamps can be used to perform holography.