Fabrication of Photonic Bandgap Structures

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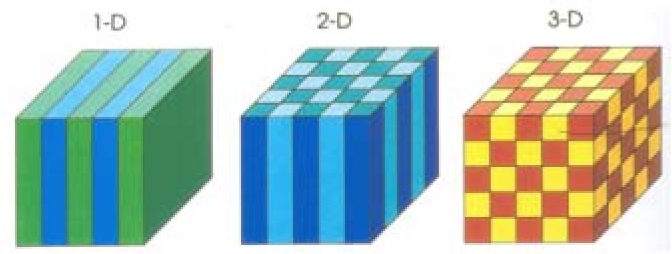
Outline

- Photonic Bandgap (PBG) concept and applications
- Fabrication of 2D PBG structure
- 3D PBG structures and fabrication techniques
- Conclusions

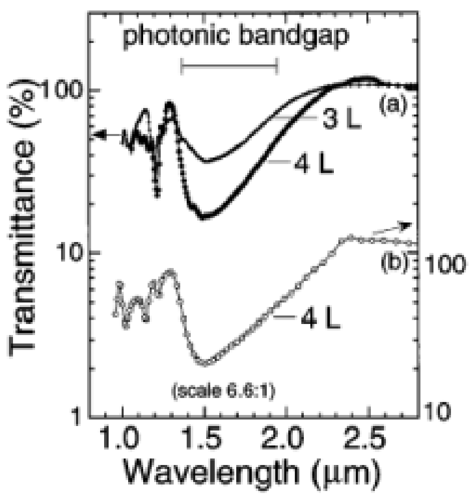
Photonic Bandgap Structures

Photonic Band Gap structures are periodic dielectric structures that forbid propagation of Electromagnetic waves in a certain frequency range

- First postulated by E. Yablonovitch in 1987
- Analogous to semiconductor bandgap
- PBG structures can be classified into 1 dimensional (used in DFB lasers and Fiber Bragg Gratings), 2 or 3-dimensional
- The bandgap is desired to be as large as possible so that it is less sensitive to fabrication-related disorders

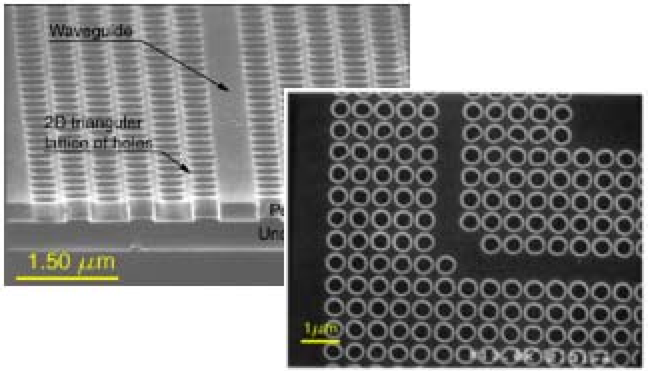


Periodicity of dielectric constants

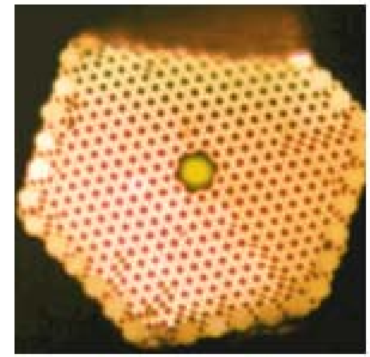


Fleming *et al.*

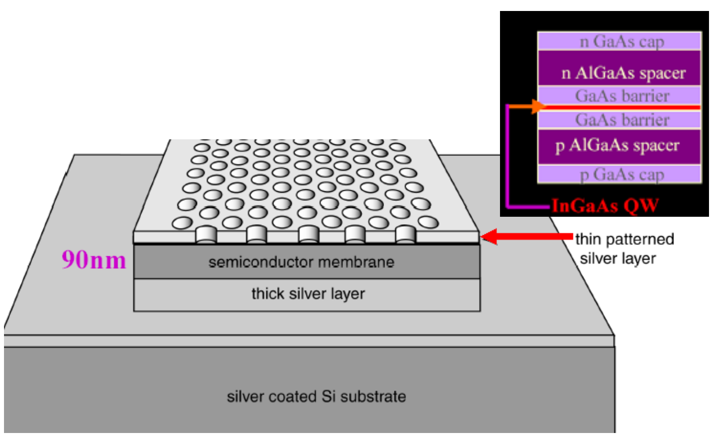
Application of PBG Structures



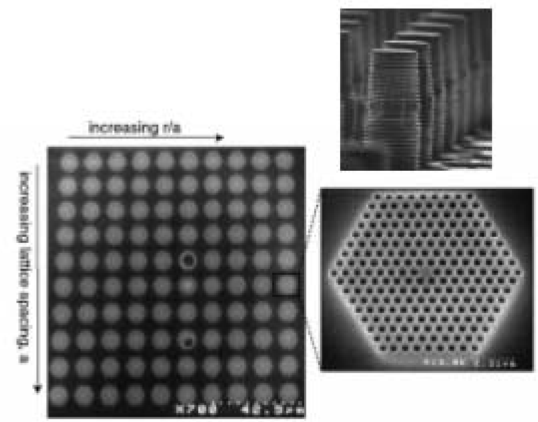
Highly miniaturized optical interconnects



Photonic Crystal Fibers (Holey Fibers)

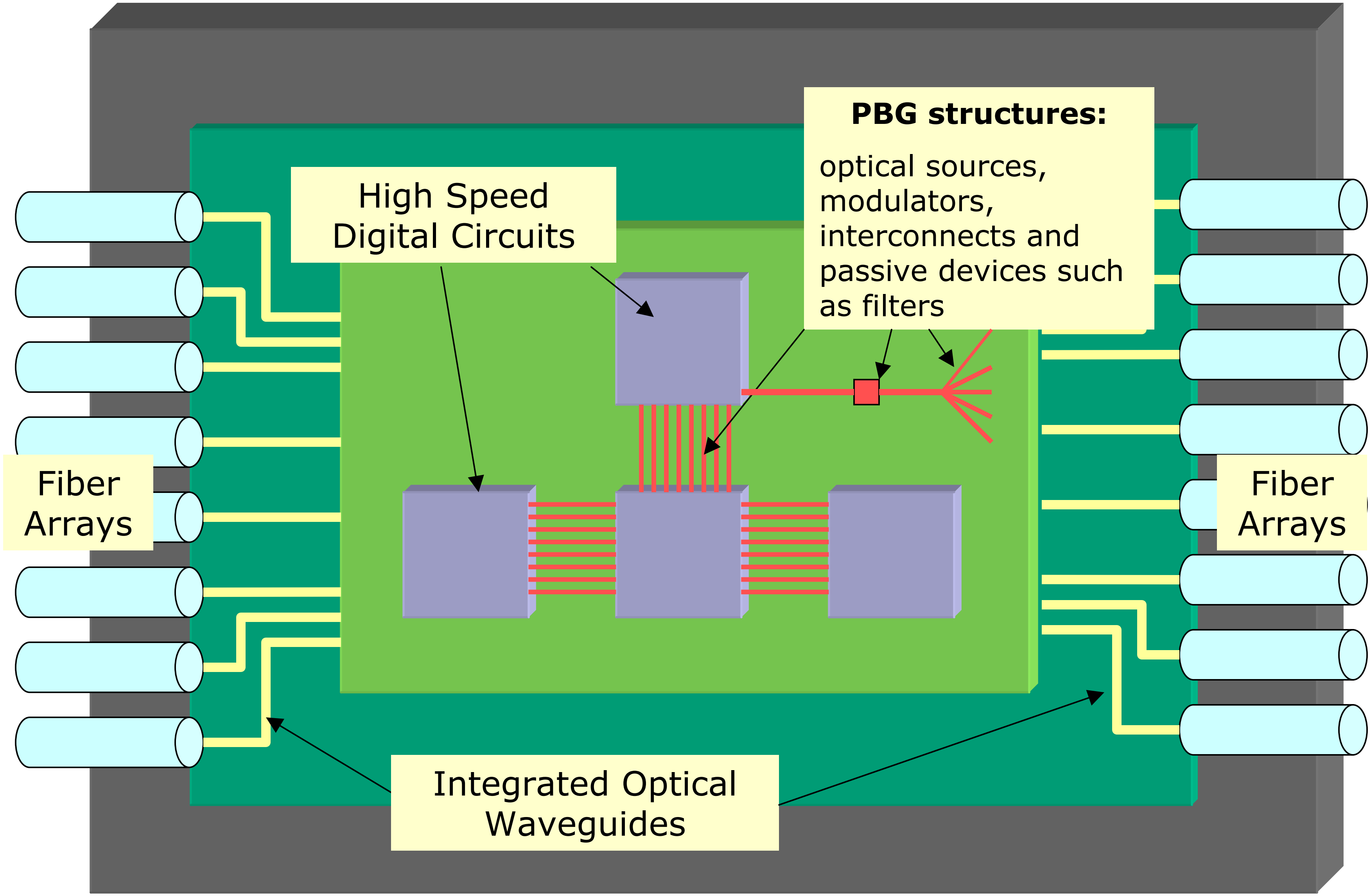


Surface Plasmon LED

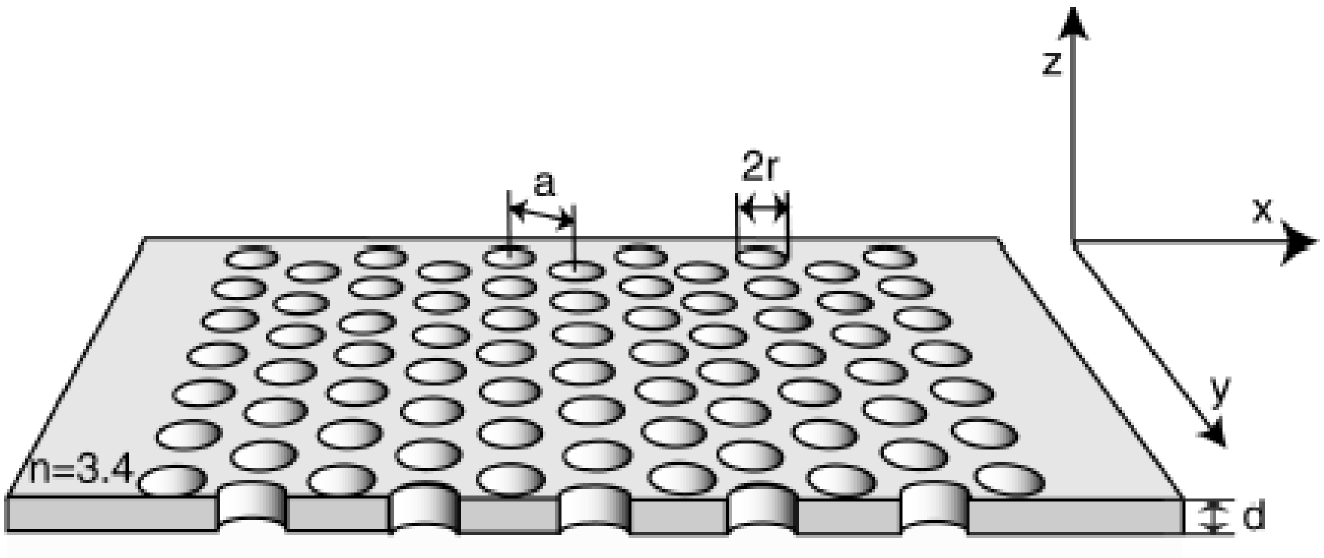


“Thresholdless” Nano-Cavity Lasers

Miniaturization of Opto-Digital Circuits



Typical Dimensions of PBG Structures

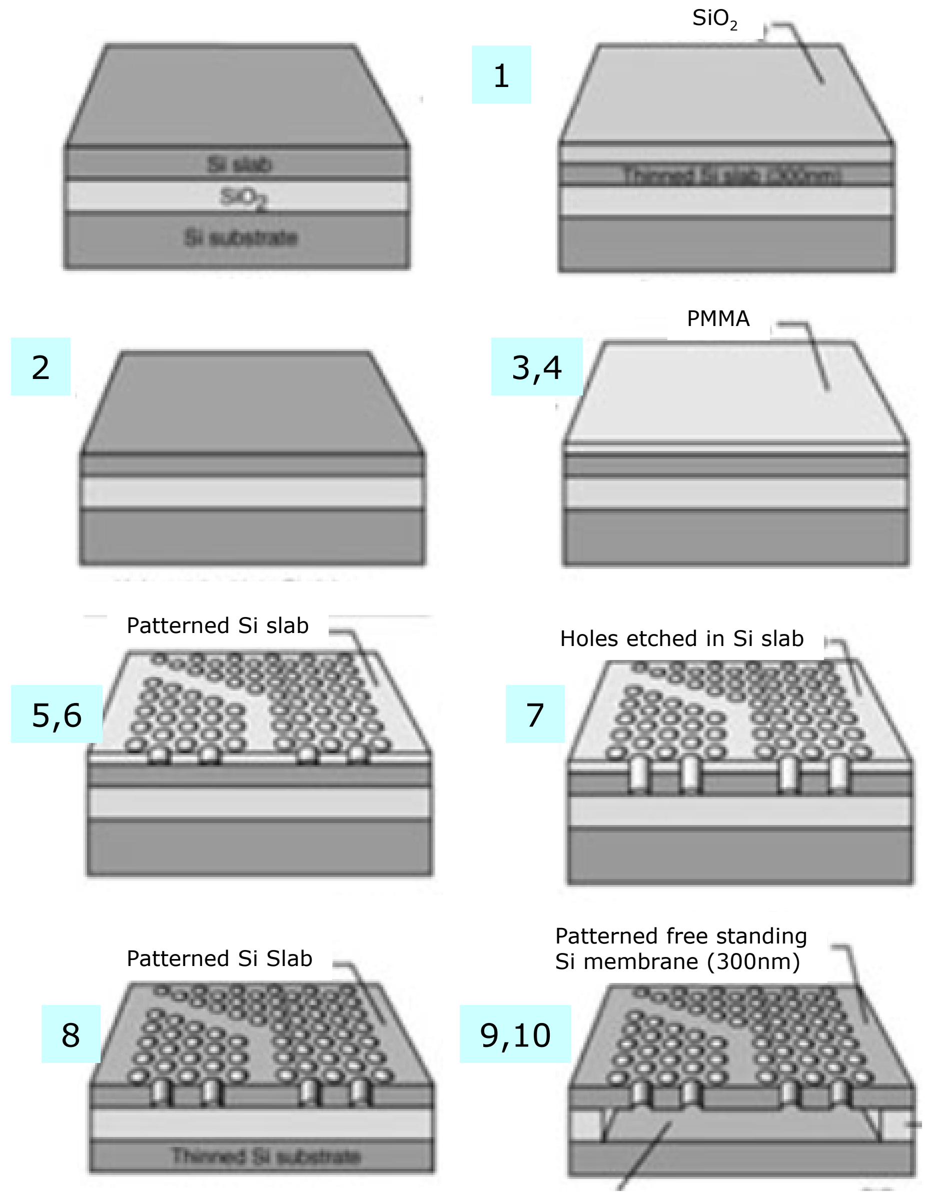


Some numbers (for triangular lattice) : a=500nm; r=200nm; d=280nm

2-Dimensional PBG Structures

SOI-based PBG WG Fabrication Procedure

1. Oxide deposition
2. Hydrofloric acid dissolution to obtain desired thickness
3. Spin coat PMMA
4. Bake at 150degres at 45min
5. E-Beam Lithography [30kV]
6. Develop PMMA in 2-ethoxyethanal and and methanol for 30sec
7. Transfer pattern using Chemically Assisted Ion Beam Etching [1250V Ar+ beam with XeF2]
8. Remove PMMA
9. Wafer thinning and cleaving
10. Undercutting using hydrofloric acid



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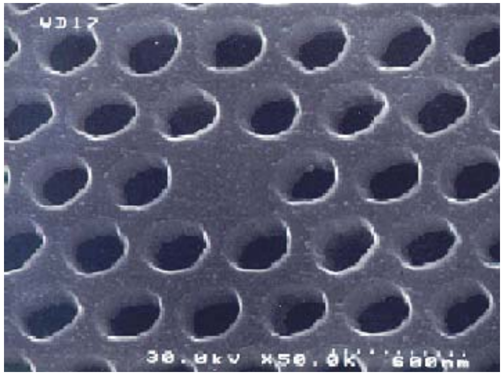
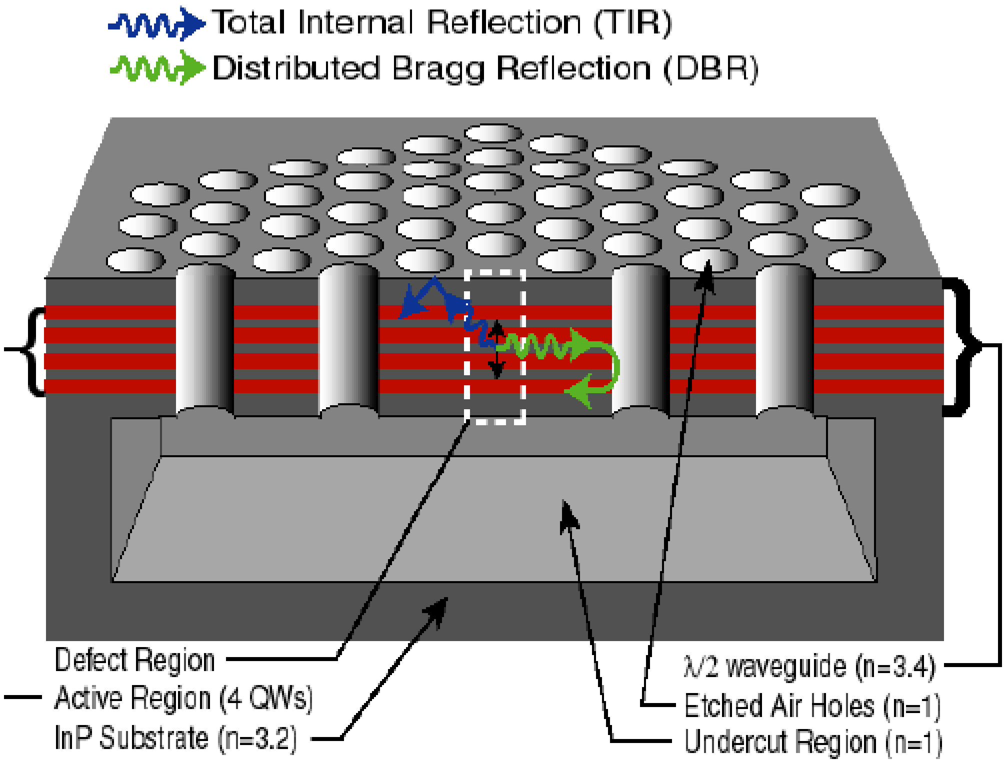
Photonic Nanocavity Laser

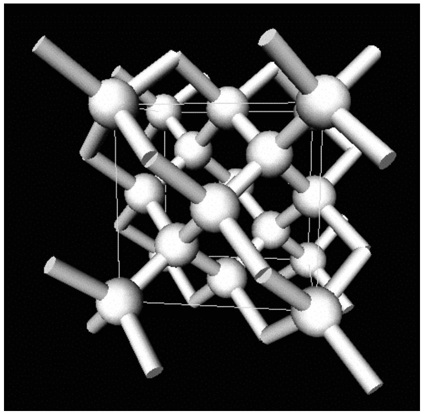




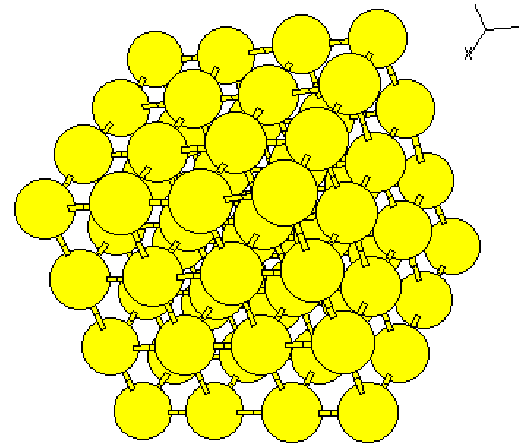
Light is localized through index guiding in the vertical direction and this results in significant radiation losses when the translational symmetry is broken

3-Dimensional PBG Structures

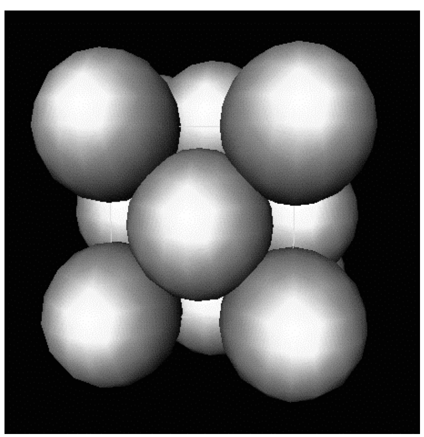
Crystal Structures with 3D Bandgap



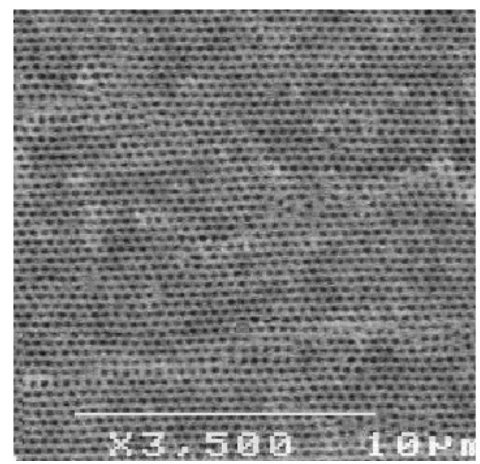
Diamond



A7 - Rhombohedral Graphite



FCC



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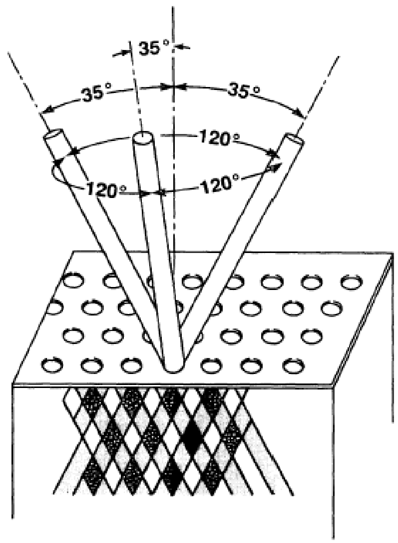
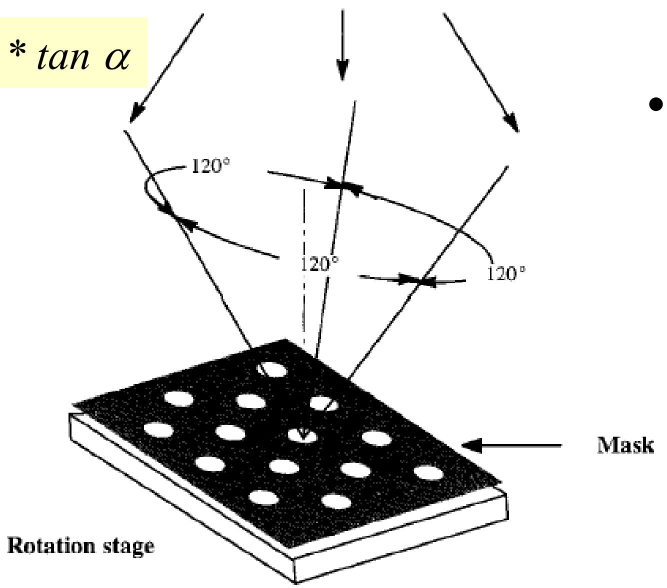
Inverse Opal Structure

3D PMMA Template using X-Ray Lithography



X-rays exposure directions

$d = t * \tan \alpha$

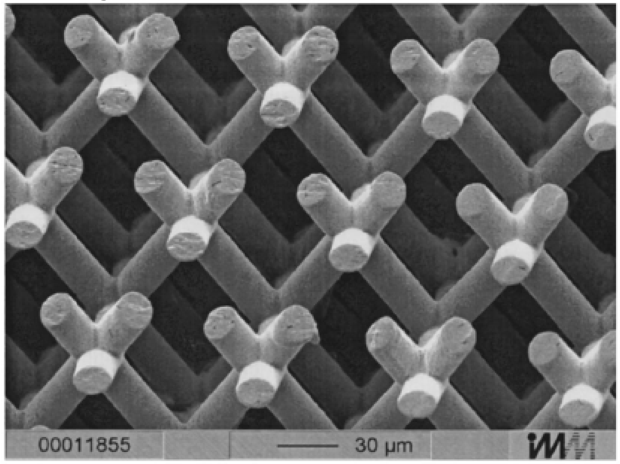


- The first man-made PBG structure with complete photonic bandgap was experimentally demonstrated (using microwaves) in 1991
- XRL is ideal for generating the complex 3D structure due to its large depth of focus
- Soft contact printing used is used: mask is 20-40um away from PMMA resist (6um thick)
- Both mask and sample is rotated 120deg after each exposure
- The PMMA is developed and used as a template for various infilling materials:
  - Dielectric: Silicon Carbon Nitride, Titanium Dioxide
  - Metal: Copper

Cuisin *et al.*

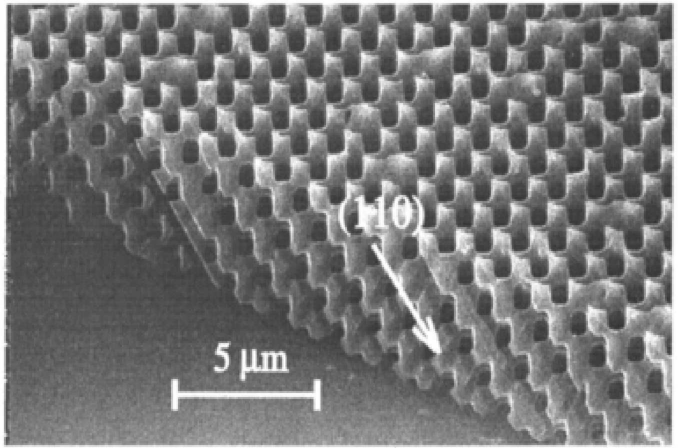
3D Dielectric and Metallic PBG Structures

G Feiertag *et al.*

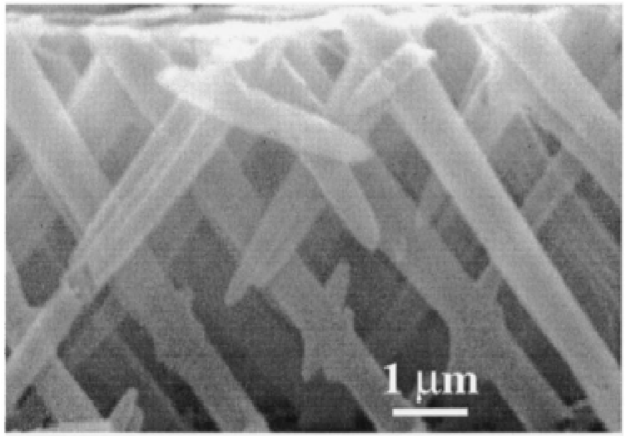


3D structure from negative tone resist

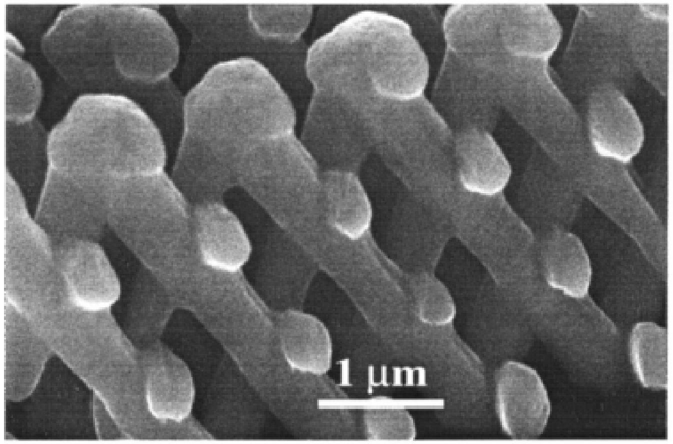
Cuisin *et al.*



Completed PMMA template



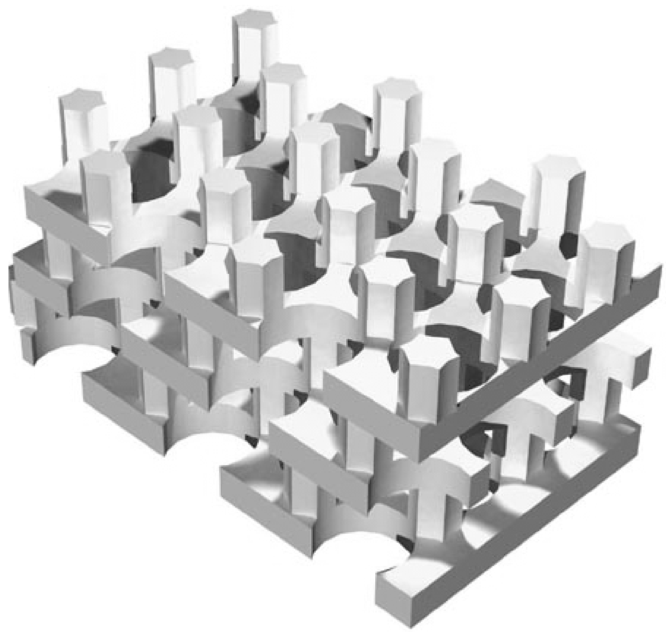
TiO_2 used as filler

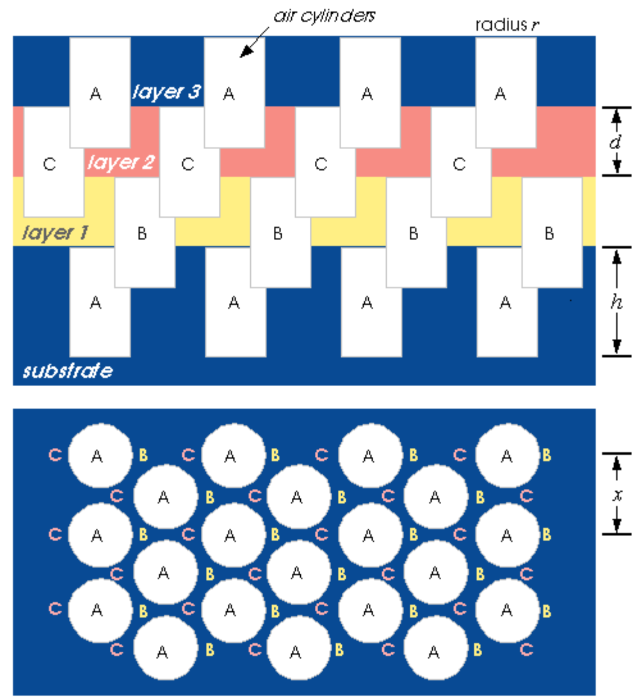


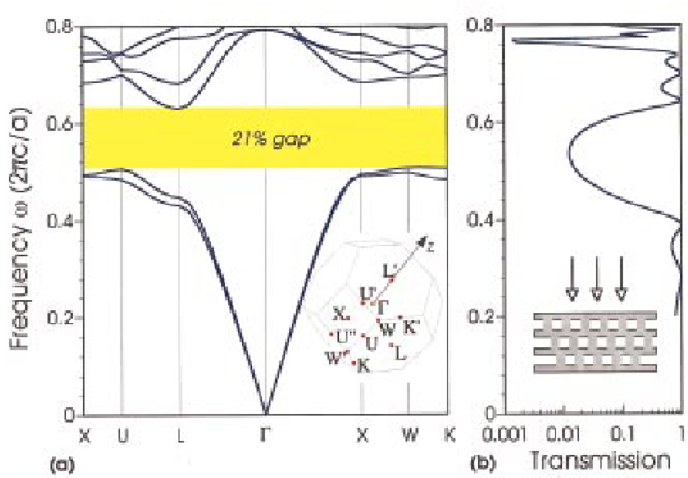
Electrodeposited copper used as filler

Shrinkage and small filling factor of the filler material resulted in non-uniform structures

Layer-by-Layer Fabrication





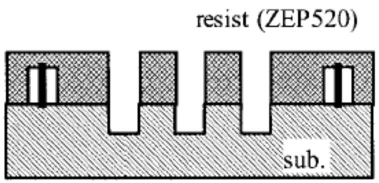


- 3D structure with omnidirectional bandgap
- Precise control of each layer and incorporation of defects and photonic devices is possible
- Alignment of layers is challenging due to requirements for offsetting holes laterally

S.G. Johnson *et al.*

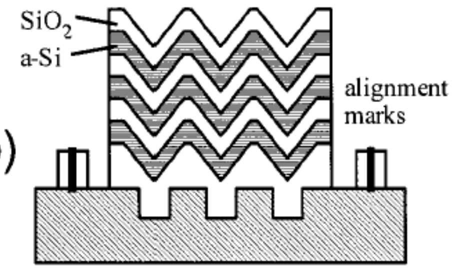
Drilled Alternating Layer of 3D Crystals: DALPC

(a)



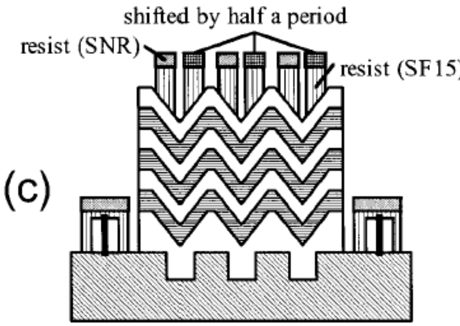
Periodic grooves are patterned by EBL and etched using RIE

(b)



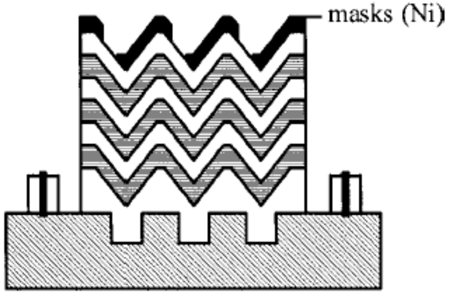
RF bias sputtering of Si/SiO_2 layers

(c)



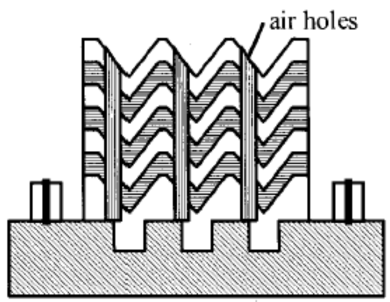
Patterning of SNR/PMGI bilayer for liftoff. 2nd EBL is performed. After developing the SNR resist the pattern is transferred to the PMGI by O_2 RIE

(d)

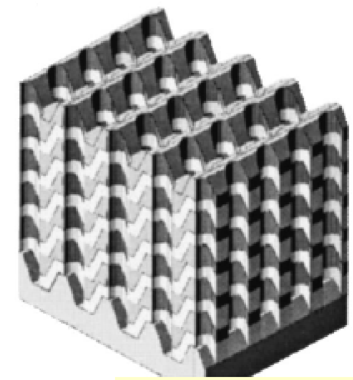


Ni Film is evaporated and unnecessary Ni is lifted off with underlying PMGI

(e)



Air holes are drilled with electron cyclotron resonance (ECR) etching



Completed structure

To obtain corrugated pattern, balance between sputter deposition, sputter etching and re-deposition is crucial

Kuramonchi *et al.*

Fabricated DALPC Samples

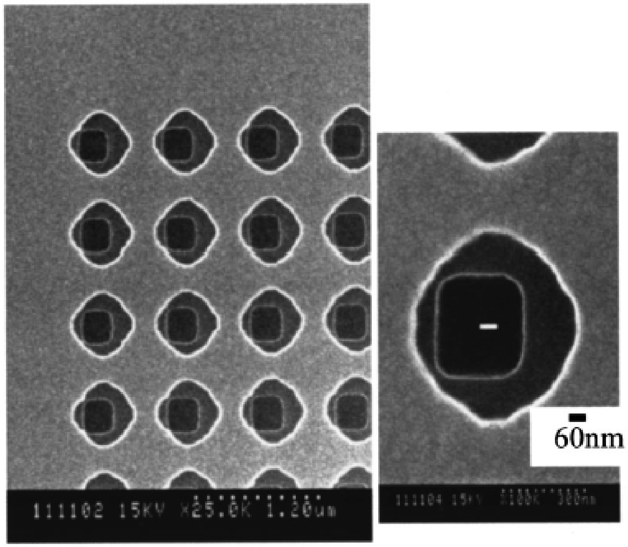


FIG. 4. SEM images of doubly patterned holes. The shift between two patterns corresponds to the alignment error in the EB exposing machine.

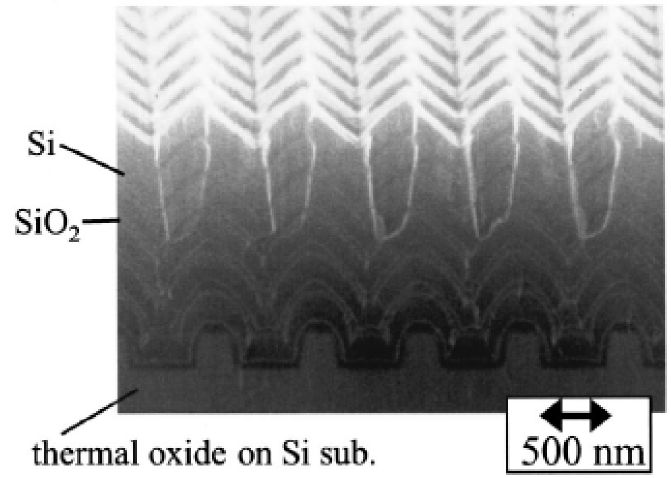
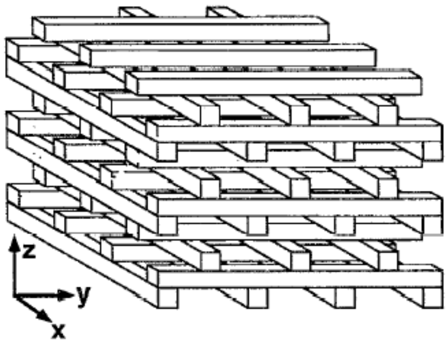


FIG. 7. Cross-sectional SEM image of a Si/SiO_2 DALPC sample after drilling by fluoride-based ECR etching.

- Shift in pattern caused by the alignment error of EB machine (alignment errors of 50-90nm by using the alignment mark patterns)
- The ECR plasma etching process is carried out with SF6-CF_4-CO_2 gas (at pressures below 0.2mTorr)
- As a result of the low pressure, a 30W 400kHz RF bias is enough to accelerate ions for etching SiO_2 without increasing Fluorine radicals that will undercut Si
- Si undercut is also strongly suppressed by sidewall polymerization

Kuramonchi *et al.*

The WoodPile Structure and its Evolution



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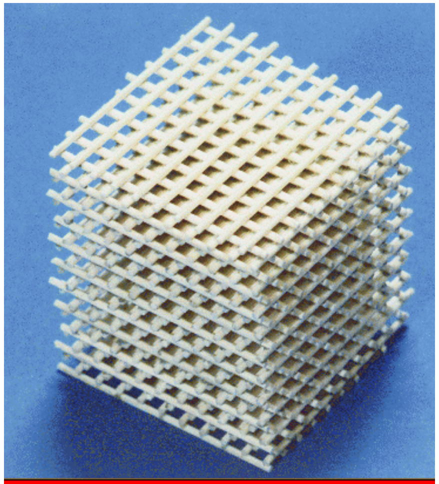
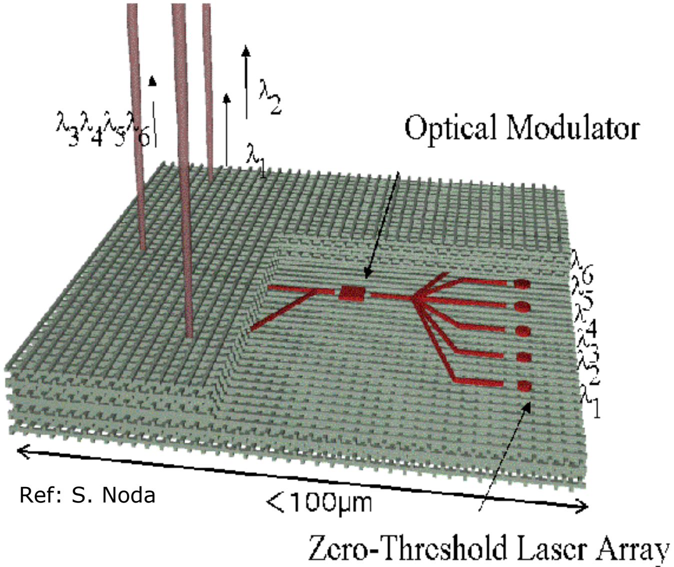


Photonic Band Gap structure obtained by stacking Alumina rods. The gap is between 12 and 14 GHz.

Ozbay *et. al*



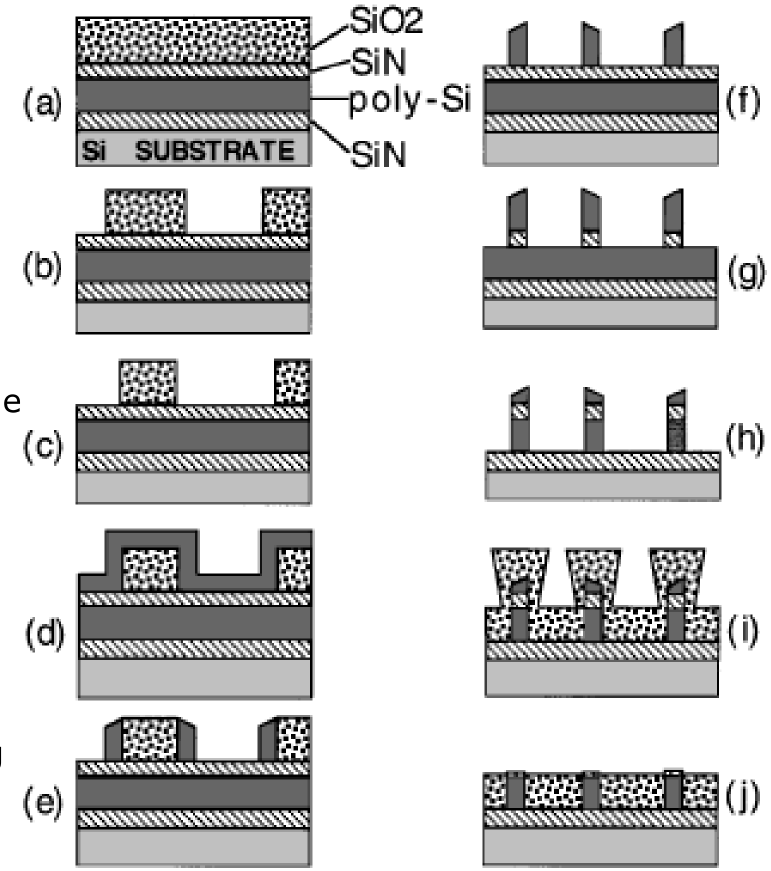
Ref: S. Noda

Woodpile structure first Proposed in 1994. FCC lattice

Alumina rods stacked and glued together; measurements are performed in mm-wave frequencies

Integration of optical interconnects and active devices in same structure

Fabrication of WoodPile Structure



Resist patterned (b)

Remove oxide using wet etch (c)

Poly-Si formed (d)

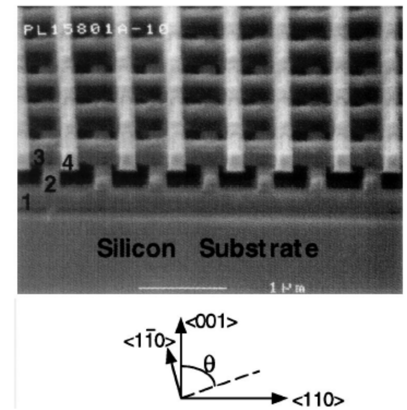
Etch Si using Plasma (e)

Fillets formed, sacrificial oxide removed (f)

Fillet used as mask For etching SiN and poly-Si (g, h)

Grow SiO_2 (i)

Planarize using CMP (j)

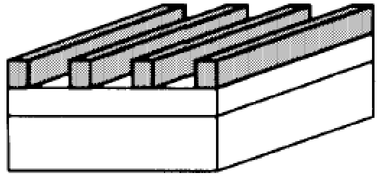


Final structure after oxide removal using HF

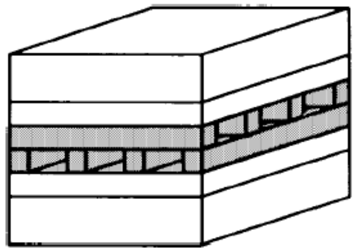
J. G. Fleming *et al.*

Alternate Fabrication Method

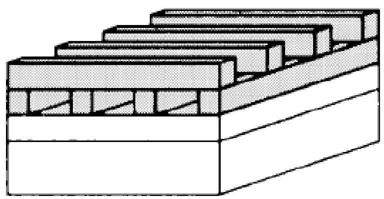
1. Patterning of stripes



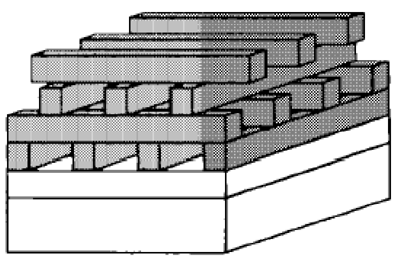
2. Wafer stacked and fused in H_2 environment

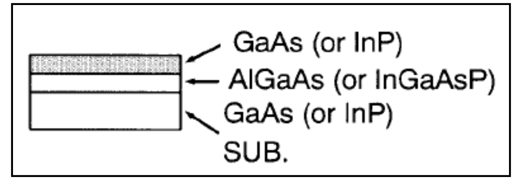


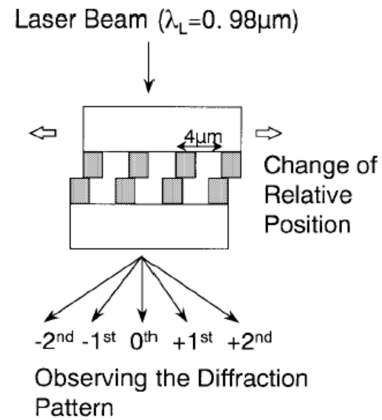
3. One of the substrate and its etch stop layer chemically etched

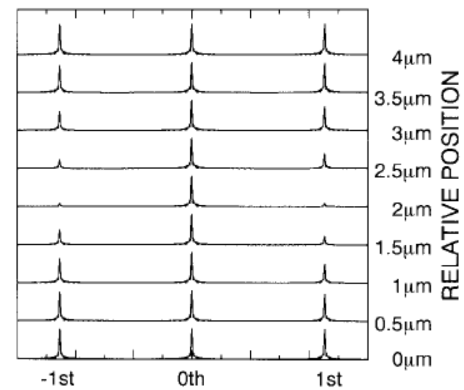


4. Processes 2 & 3 repeated for every subsequent layer









- Layers are aligned using diffraction patterns formed by the gratings
- Samples with 8 layers operating in 1.3-1.55um region have been demonstrated

S. Noda *et al.*

Conclusions

- Various high resolution microelectronic fabrication techniques were successfully used to produce 2D and 3D PBG structures which have been experimentally verified to possess photonic bandgaps in the infrared region

- Fabrication challenges and requirements:
  - Lattice constants comparable to wavelength of propagating light
  - High demand on uniformity and regularity of lattice structure
  - High anisotropy and selectivity requirements for high aspect ratio drilling
  - Layer-to-layer alignment must be very precise
  - Incorporation of active devices and defects into the structure

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