Highly Tunable Photonic Band Gap in Inverse Non-Close-Packed Shell Structures

Davy P. Gaillot, Elton Graugnard, Jeffrey S. King and Christopher J. Summers

School of Materials Science and Engineering

Georgia Institute of Technology

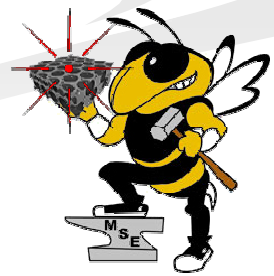
Atlanta, Georgia 30332-0245

IEEE/LEOS 18th Annual Meeting

Sydney, Australia

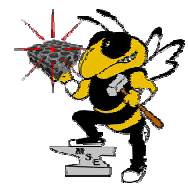
25th October, 2005

Georgia Institute of Technology



Outline

- **Challenges for 3D PC**
- **Background**
  - **Inverse Shell Opals**
    - Optical Properties & Limitations
- **Inverse Non-Close-Packed Opals**
  - **Conformal Sacrificial Layer/Backfill Thru ALD**
    - Experimental Achievement
  - **Structures Modeling**
    - PBG Mechanisms
    - PBG Width & Refractive Index Requirement (RIR)
    - PBG Tunability (Width & Location)
- **Conclusions**

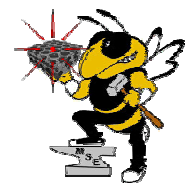


Challenges

- **Design 3D Photonic Crystal with:**
  - Largest complete PBG possible for a given material
  - Lowest refractive index requirement (RIR)
  - PBG tunability over a wide spectral region
  - Easy implementation into electro-optic devices

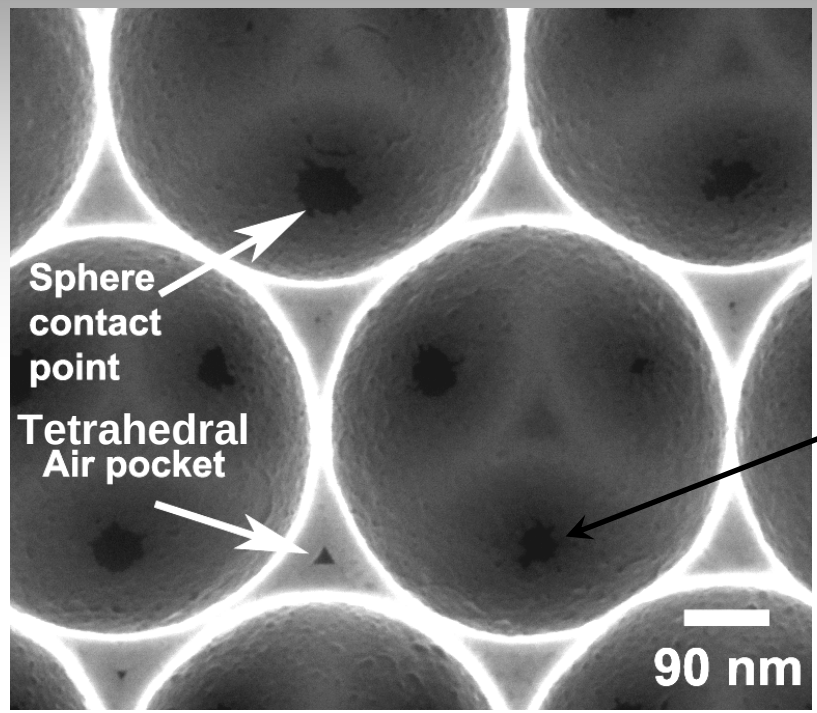
- **The fabrication process should be:**
  - Reasonably simple to implement & reproduce
    - Bottom-up (Self-assembly) - Top-down (ALD/CVD)
  - Low-cost, Reliable & Applicable to large scale devices

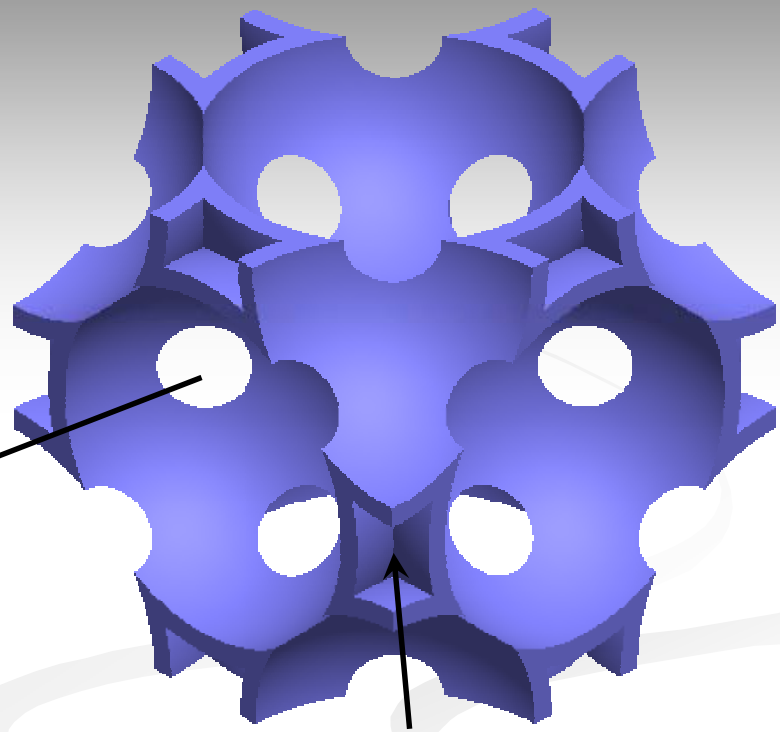
- **Applications for 3D luminescent devices:**
  - Phosphors, QD in Micro-Cavities



Inverse Shell Opals

[111]

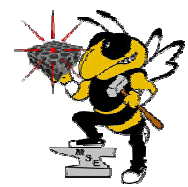




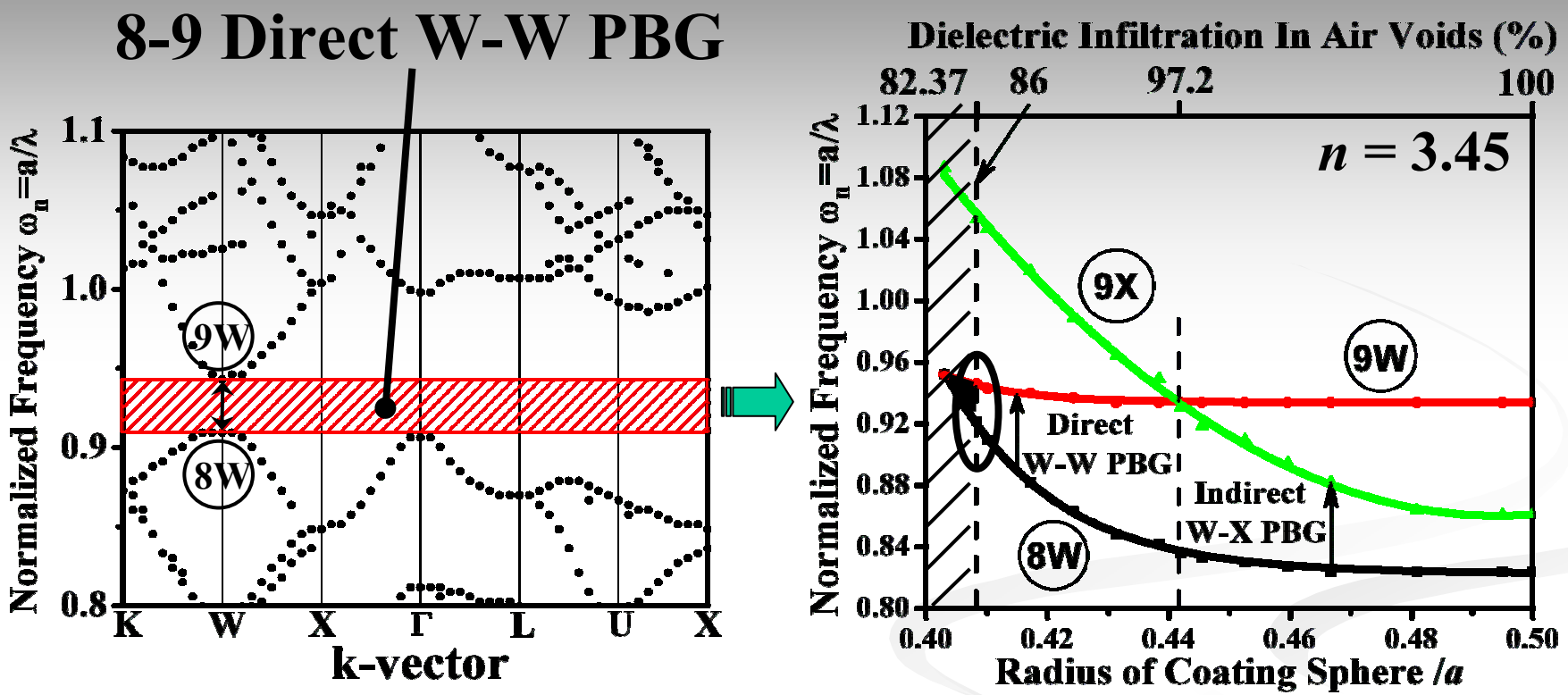
Octahedral air pocket

Inverted anatase TiO_2 opal in air (2.65/1)

- **ALD/CVD conformal infiltration steps**
  - **0.05nm/cycle for TiO_2**
- **Fcc structure prevents dielectric volume fraction >86% of interstitial air volume.**
  - **Trapped octahedral/tetrahedral air pockets within backbone**



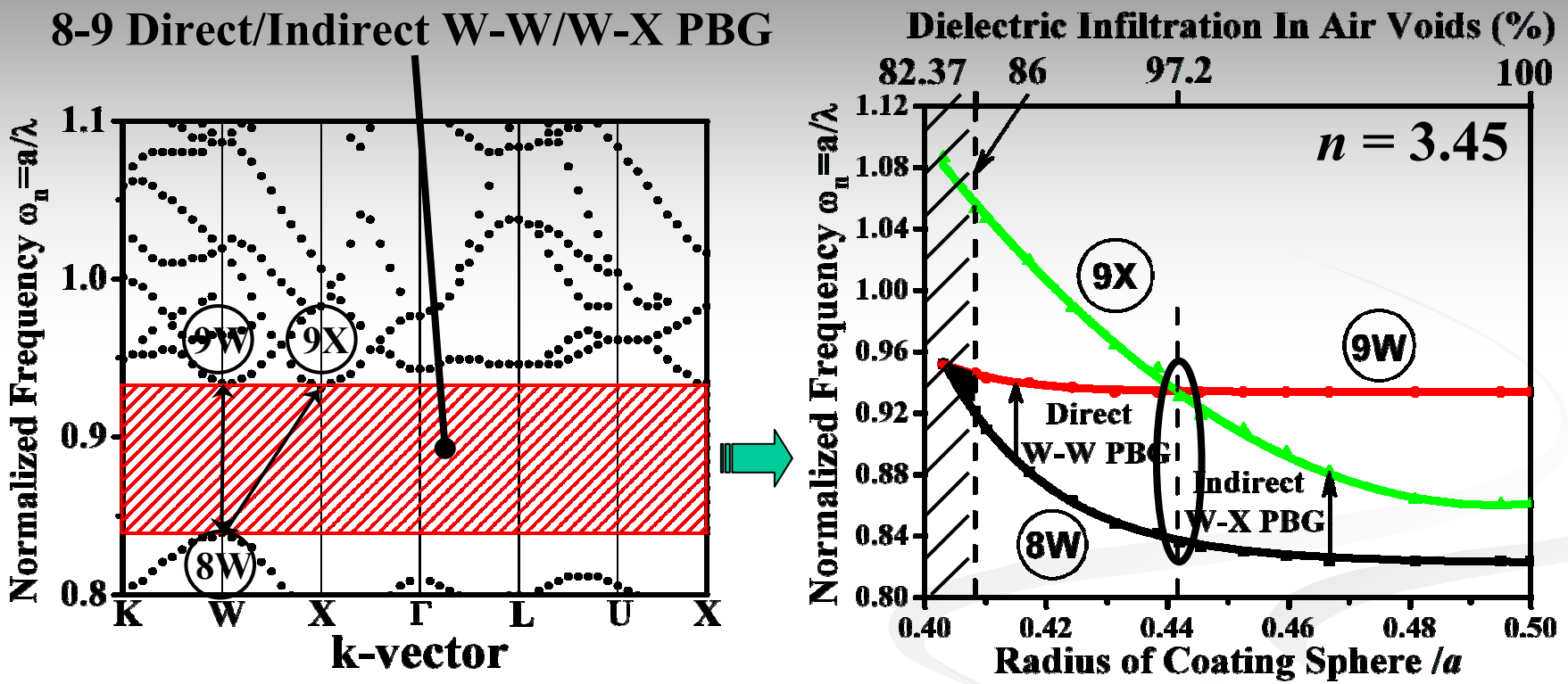
PBG Mechanisms & Limitations*



- Narrow complete PBGs (n = 3.45)
- High refractive index contrast required (n > 3.3)
- Dielectric volume fraction limited (0 to ~22%)
- Choice of high index, transparent materials is limited

*Gaillot *et al.*, Phys. Rev. B (in press)

PBG Mechanisms & Limitations*

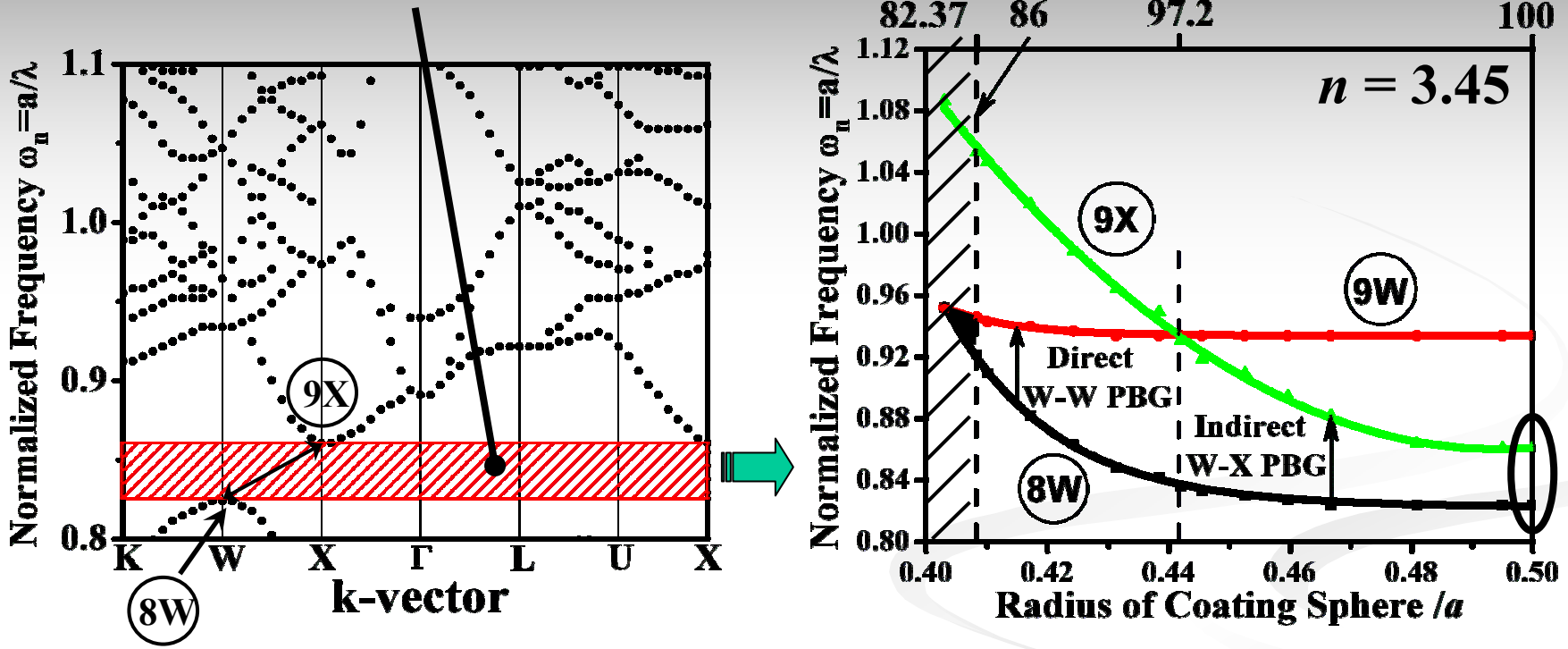


- Narrow complete PBGs (n = 3.45)
- High refractive index contrast required (n > 3.3)
- Dielectric volume fraction limited (0 to ~22%)
- Choice of high index, transparent materials is limited

*Gaillot *et al.*, Phys. Rev. B (in press)

PBG Mechanisms & Limitations*

8-9 Indirect W-X PBG

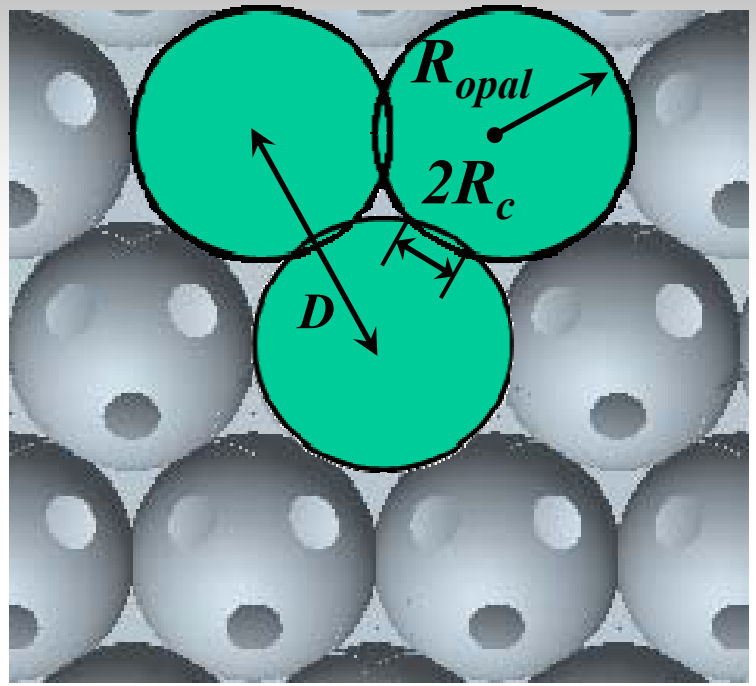


- Narrow complete PBGs (n = 3.45)
- High refractive index contrast required (n > 3.3)
- Dielectric volume fraction limited (0 to ~22%)
- Choice of high index, transparent materials is limited

*Gaillot *et al.*, Phys. Rev. B (in press)

Inverse Shell Opals & Inverse Non-Close-Packed Structures

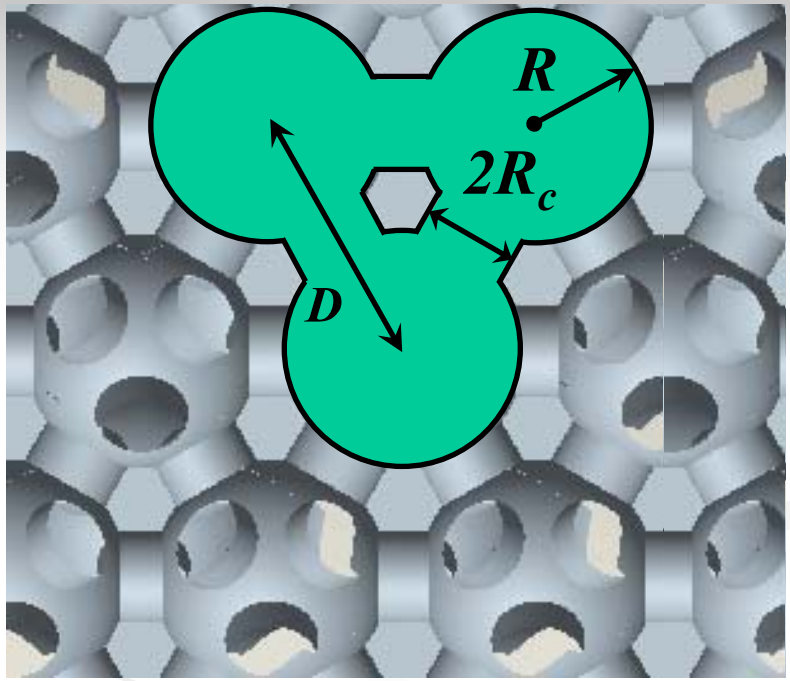
Inverse Shell Opal



- **Air pores formed after template sintering & conformal infiltration**
- **Limited enhancement of PBG properties**
- **Studied theoretically & experimentally**

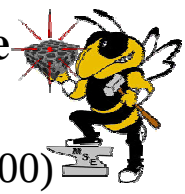
[111]

Inverse Non-Close-Packed

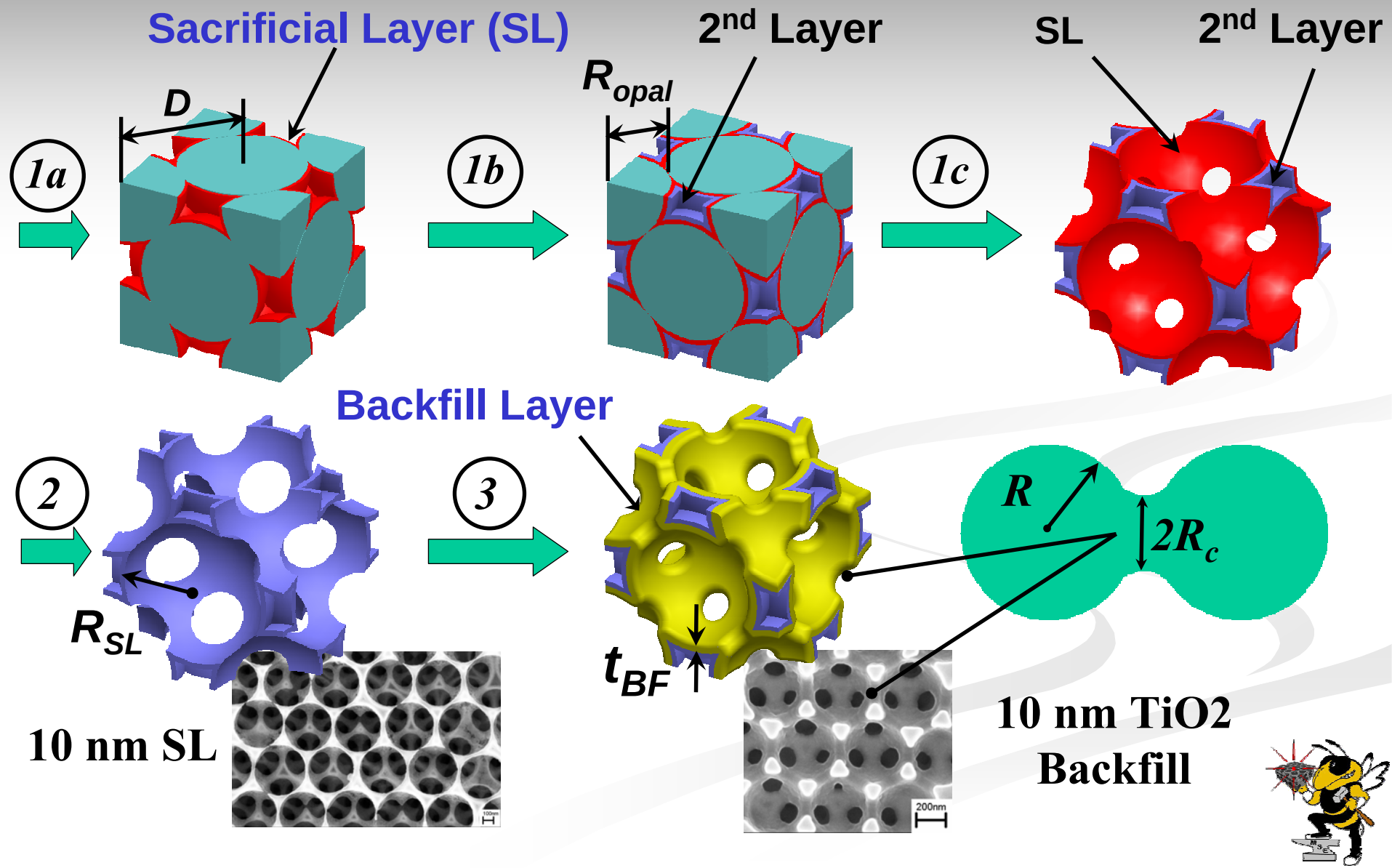


- **NCP spheres interconnected w/ tubular channels**
- **Large enhancement of PBG properties**
- **Studied theoretically**
- **How to make and control these structures ?**

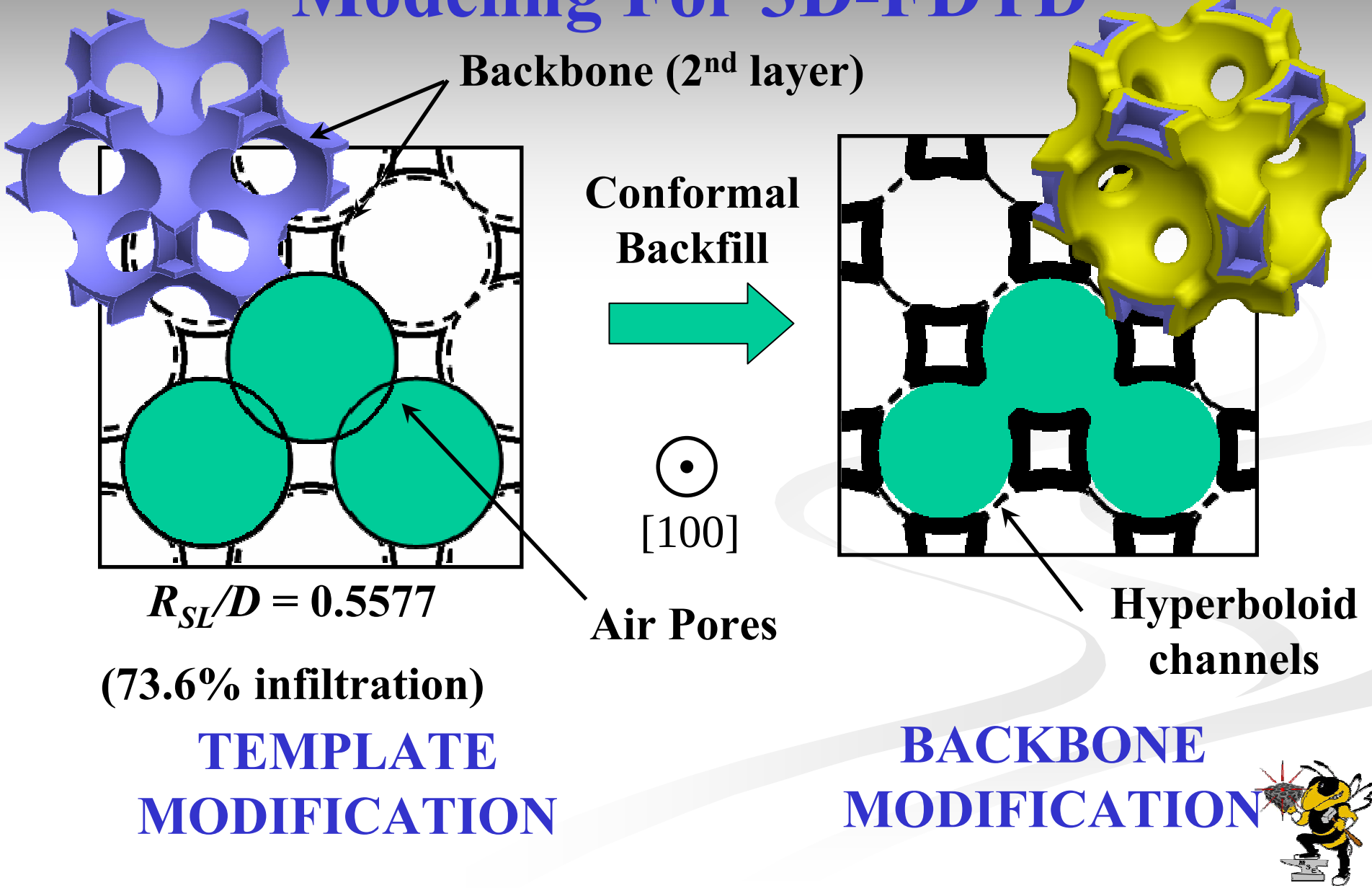
*Busch & John, Phys. Rev. E **58**, 3896 (1998)
*John & Busch, J. Light. Technol. **17**, 1931 (1999)
*Doosje *et al.*, J. Opt. Soc. Am. B **17**, 600 (2000)



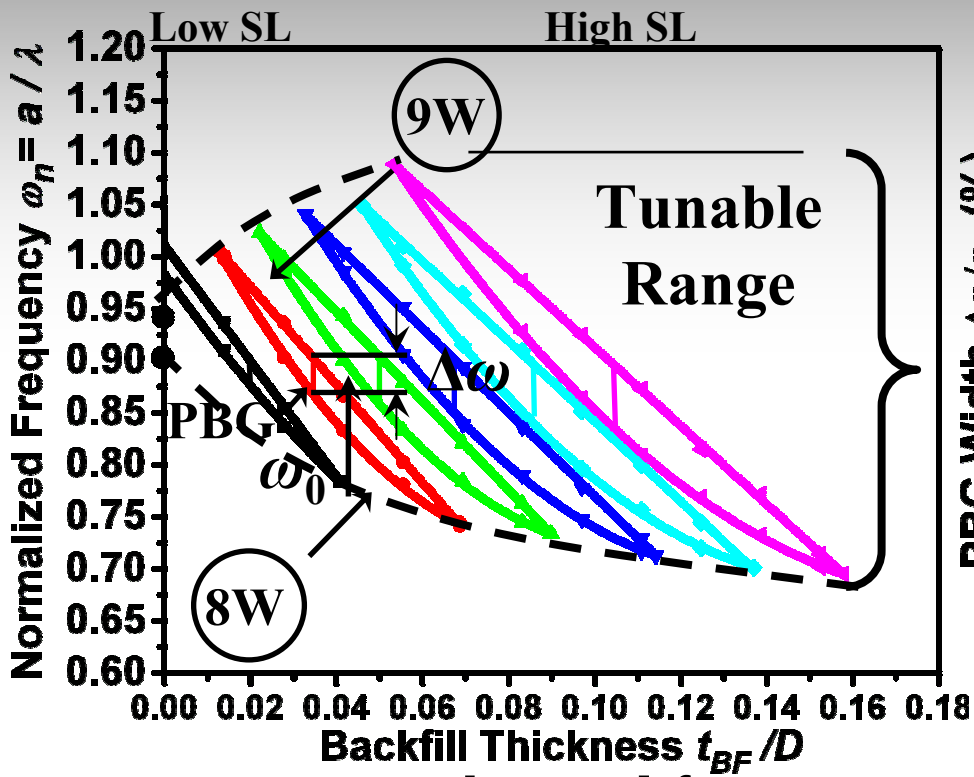
Inverse Non-Close-Packed Structure: Sacrificial Layer Technique*

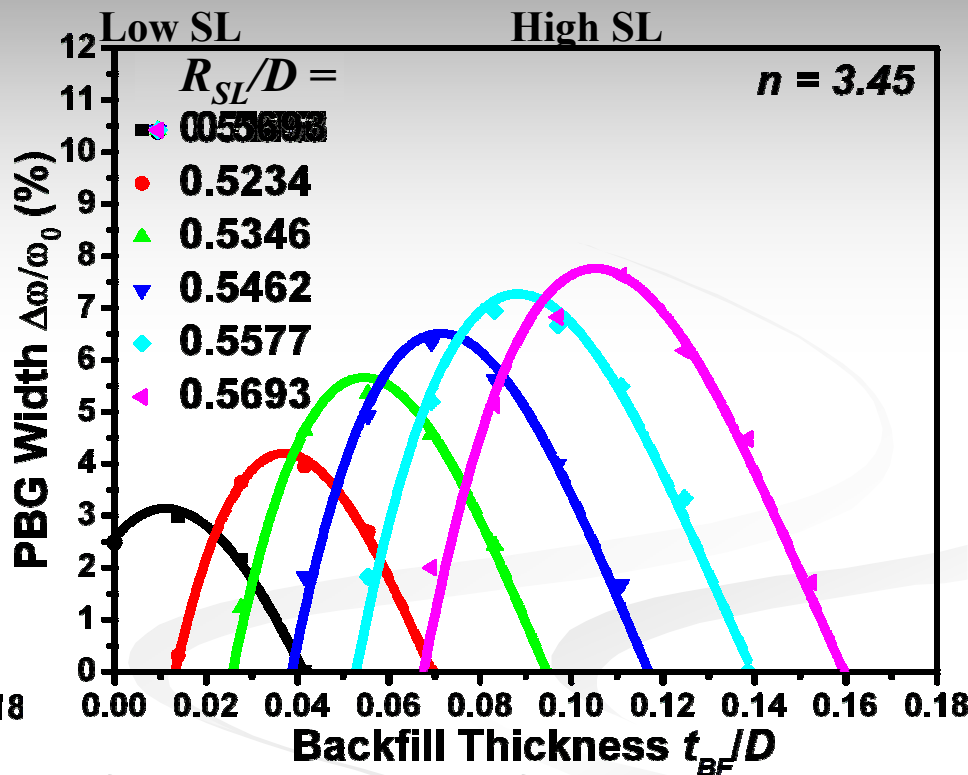


Inverse NCP Shell Opals Modeling For 3D-FDTD

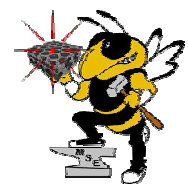


Photonic Band Diagrams For Inverse Non-Close-Packed Shell Structures

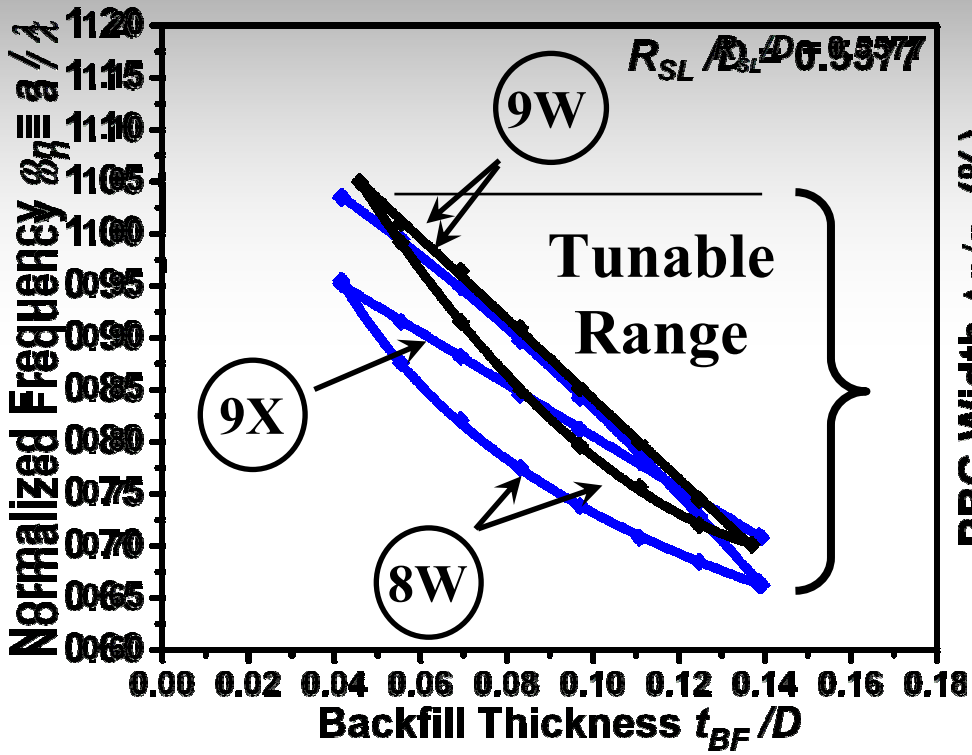


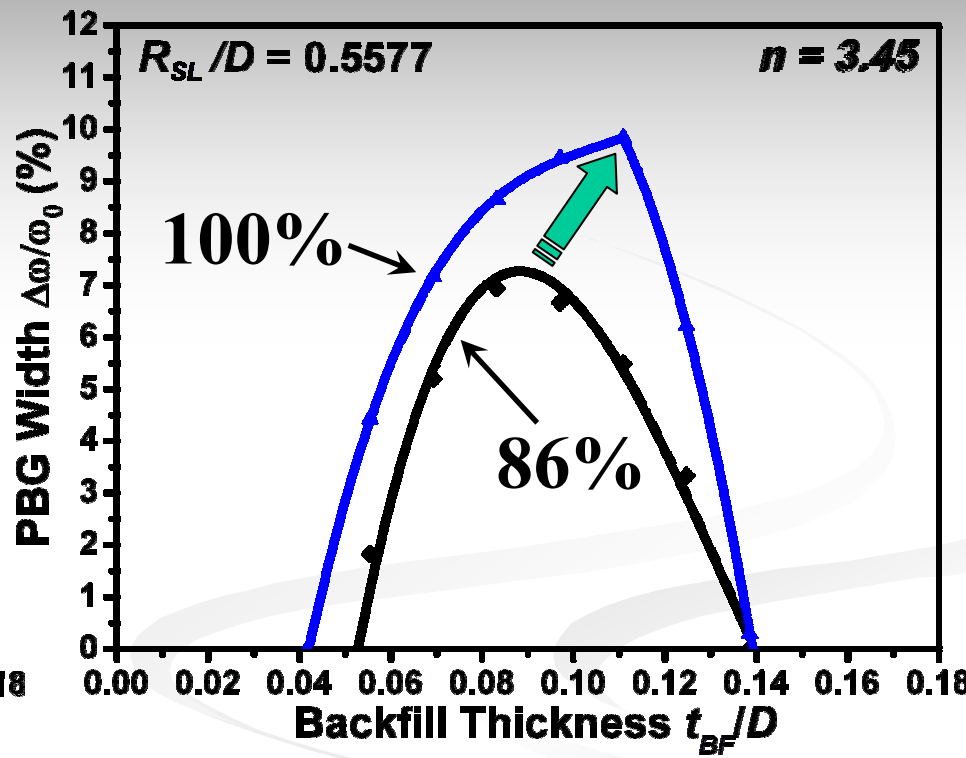


- Large PBG obtained for many sacrificial layer/backfill values
- PBG width & location tuned with backfill infiltration thickness
- **Thinnest backbone template yields**
  - **Maximum PBG width**
  - **Largest PBG tunability (width & location)**

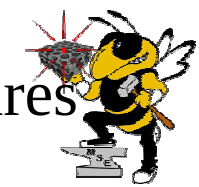


Photonic Band Diagrams: 86% Vs. 100% Infiltrated Inverse NCP Structures

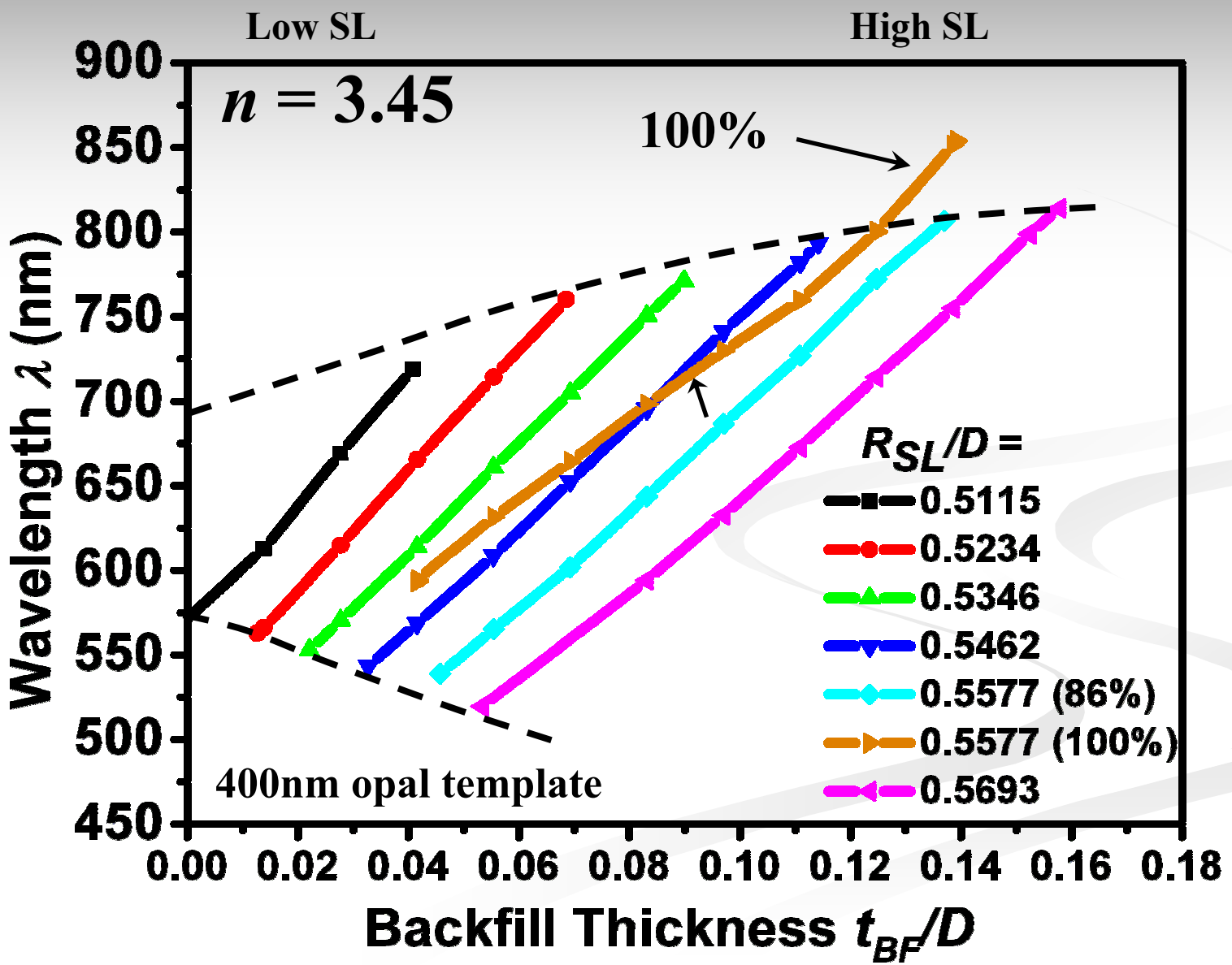




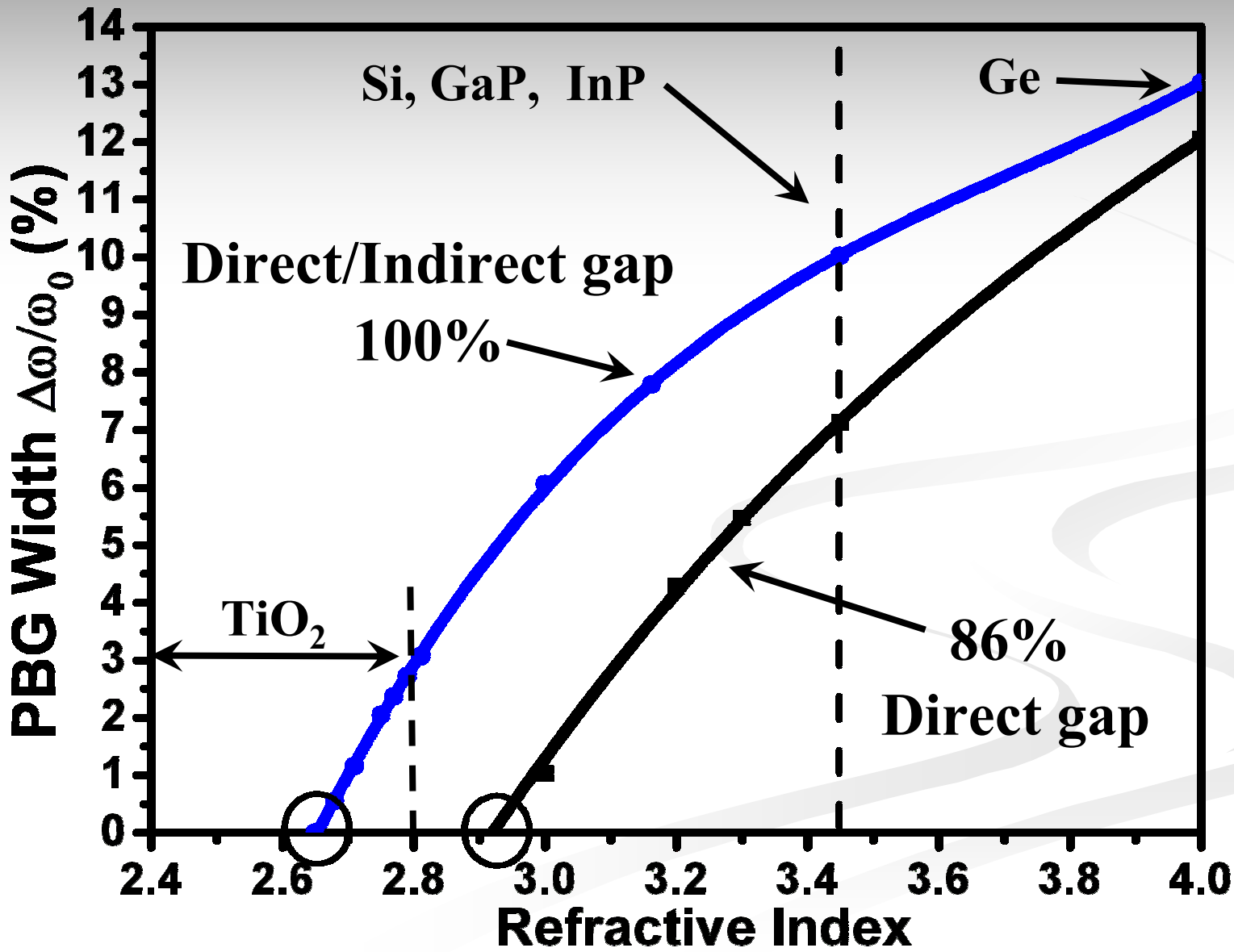
- **100% infiltrated structure yields**
  - PBG behavior driven by two mechanisms
  - Higher PBG width value
  - Similar tunability range compared w/ 86% infiltrated structures



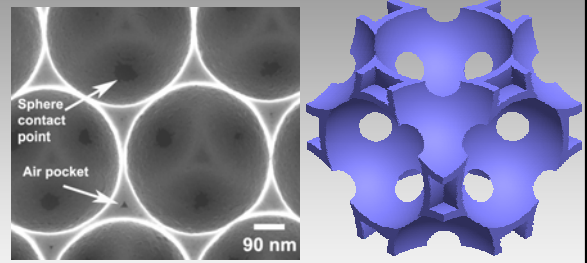
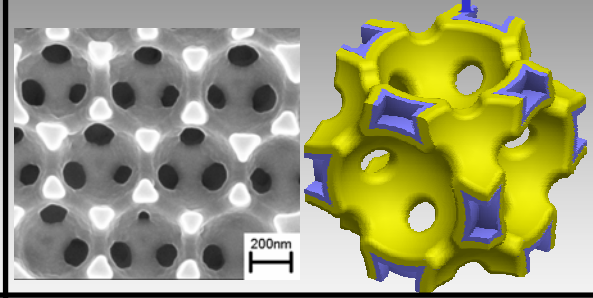
Wavelength Tunability Vs. Conformal Backfill

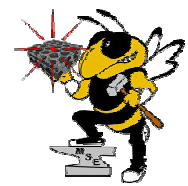


Dependence of PBG on Refractive Index For Best Structures



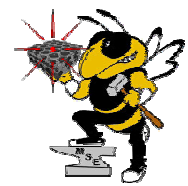
Summary

		Inverse Opals	Inverse NCP Opals
			
PBG Width (%) for n=3.45	86%	~2.5	~7.5
	100%	~4.5	~10
RIR	86%	>3.3	>2.9
	100%	>3.0	>2.6
PBG Tunability		Limited • Template size • Sintering • Material • Infiltration %	High • Template size • Material • SL thickness • Infiltration % • Backfill thick.



Conclusions

- **Conformal SL/Backfill technique offers:**
  - **High structural control of the template**
    - **Air pores tunability & open structure: R_{SL}**
    - **High degree of overlap w/o change in lattice constant**
  - **High structural control of the backbone template**
    - **High filling fraction with conformal backfill: t_{BF}**
  - **LOW-COST, RELIABLE & LARGE-SCALE UNIFORMITY**
- **Complete PBG properties framework introduced**
  - **Largest PBG width & smallest RIR**
  - **Highest PBG tunability (width & location)**
- **100% infiltrated structures yield better PBG properties**



Acknowledgements

- **Supported under MURI project by Army Research Office under contract DAAA19-01-1-0603**

- **IEEE/LEOS Student Travel Grant Committee**

Thank You!!!!!!