Self-Assembled Opal and Inverse Opal as Photonic Bandgap Structures with Waveguide Defect

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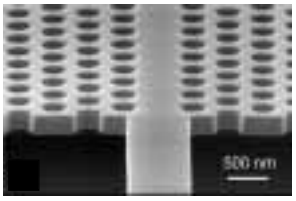
Outline

- **Introduction**
- **Self-assembled Silica Opals**
- **Rib-type Waveguides**
- **Opal Clad Waveguides**
- **Future Work**
- **Summary**

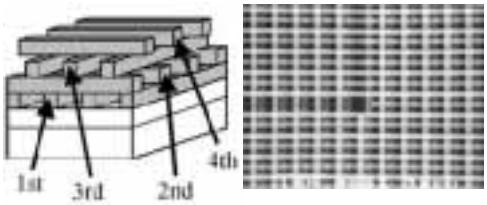
Introduction

- **Photonic bandgap structures**
  - periodical refractive index changes
  - control EM waves
  - filters, sharp bending guides, low threshold lasers



S.J. McNab et al., Optics Express, 2003

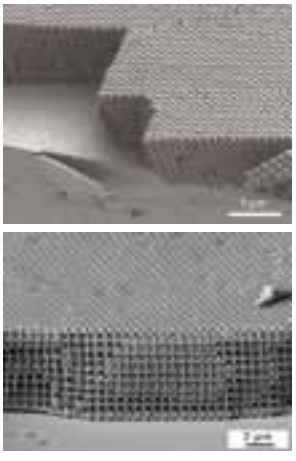
- **Nanofabrication techniques**
  - 2-D slab type structure
  - 3-D layer-by-layer structure
  - complicated and high cost



S. Noda et al., Science, 2000

Introduction

- **Self-assembly photonic crystals**
  - simpler and low cost
  - opals: pseudo- photonic bandgap
  - inverse opals: full photonic bandgap, index contrast ratio (>2.8)
- **Buried waveguides in opals/inverse opals**
  - various applications in integrated optics
  - fiber communication wavelength

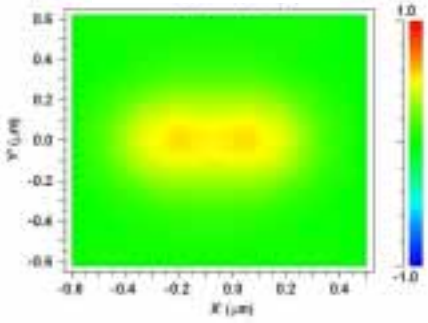


Y.A. Vlasov et al., Nature, 2001

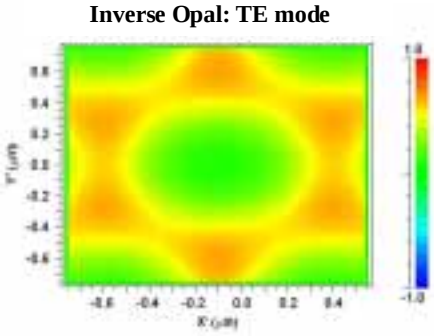
Introduction

- **Near Field Intensity**

Opal: TE mode

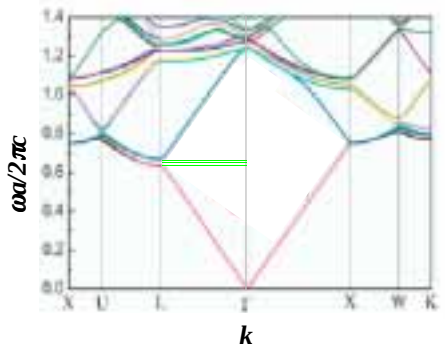


Inverse Opal: TE mode



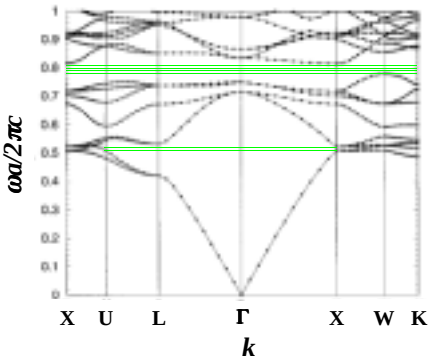
Introduction

- **Opal: pseudo-PBG**



C. López, Adv. Mater., 2003

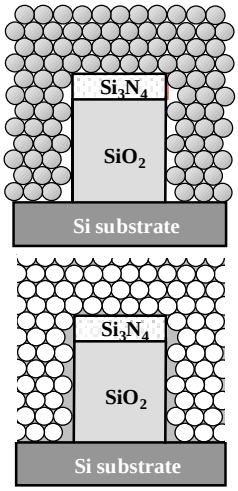
- **Inverse Opal: Full PBG**



K. Busch et al., Phys. Rev. E, 1998

Introduction

- **Opal/inverse opal clad waveguides**
  - Si_3N_4 guide & SiO_2 supporting layer
  - silica spheres with D @ 710nm
  - self-assembled opal clad waveguides:
    pseudo-photonic bandgap
  - inverse opal clad waveguides (in process):
    full photonic waveguides,
    infiltration of amorphous Si by CVD,
    etching silica spheres by HF

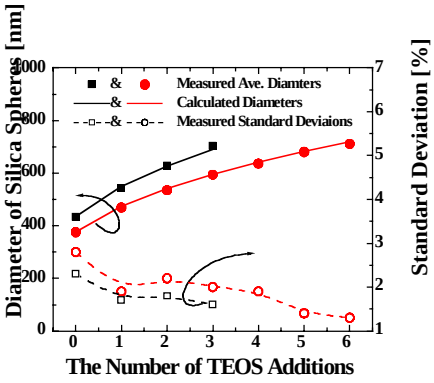


Synthesis of Silica Spheres

- **High quality silica spheres**
  - required diameters (D @ 710nm @ λ = 1550 nm)
  - narrow size distribution (< 2%)
  - no aggregation and adhesions
- **Stöber-Fink-Bohn method**
  - hydrolysis and condensation of TEOS
  - uniform size: ~ 400 nm

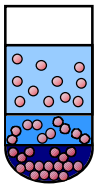
Synthesis of Silica Spheres

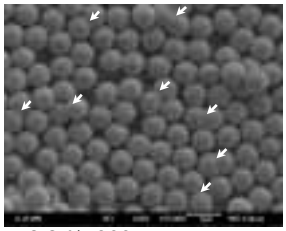
- **Seeding Technique**
  - large and monodisperse spheres
  - seeds synthesis by Stöber-Fink-Bohn method
  - sequential additions of TEOS
  - 703 nm ±1.6 %, 711 nm ±1.3 %
  - aggregations & adhesions

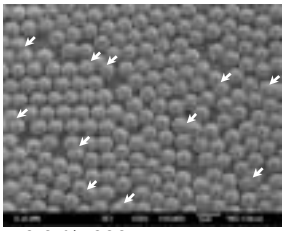


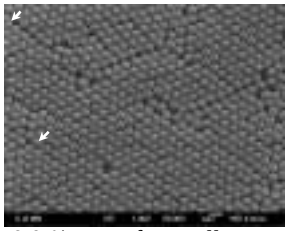
Synthesis of silica spheres

- **Synthesis & preparation with low defects**
  - **slow magnetic agitation method**
    reducing collisions of spheres
  - **centrifuge collection method**
    relative differences of sedimentation velocity, fast and effective



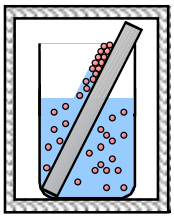

8.8 %, 900 rpm agitation

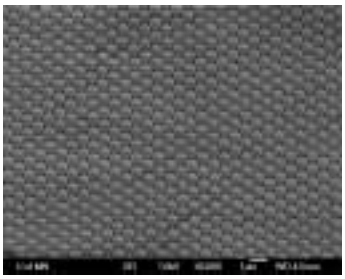

3.0 %, 300 rpm agitation


0.3 %, centrifuge collection

Self-Assembly with Silica Spheres

- **Coating technique**
  - capillary force at the meniscus
  - convection by heating (~ 60°C)
  - special enclosure: stable meniscus
  - declination angle of 60°
  - no longitudinal and lateral line defects
- **Coating on planar substrate**
  - Face centered cubic closed-packed structure
  - uniform coating: 1 cm by 3 cm





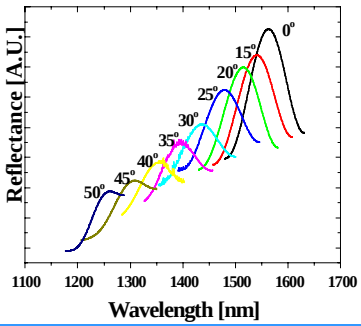
Characterization of Opals

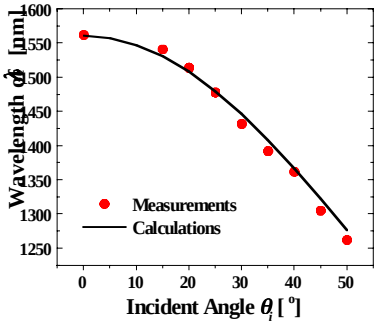
- **FTIR reflectance measurements**
  - incident angle (θ_i) variations
  - (111) direction (θ_i = 0): dominant

$$\lambda_0 = \frac{2d_{hkl}}{m_B}\sqrt{n_{eff}^2 - n_{air}^2 \sin^2\theta_i}$$

m_B: order of Bragg reflection

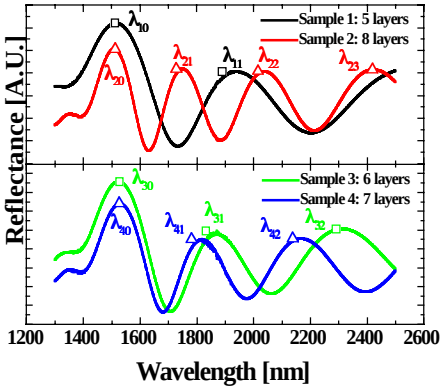
d_{hkl}: inter-planar spacing

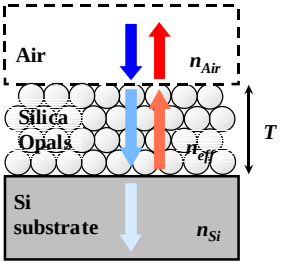




Characterization of Opals

- **Reflectance spectrum:** $\theta_i = 0^o$





$$\lambda_{pq} = \frac{2n_{eff}T}{m} = \frac{2n_{eff}Nd_{hkl}}{N-q}$$

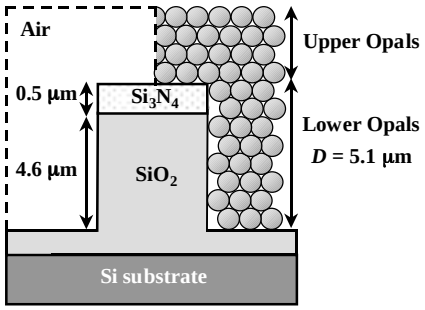
N: # of opal layers

m, q: positive integers (or zero)

p: sample #

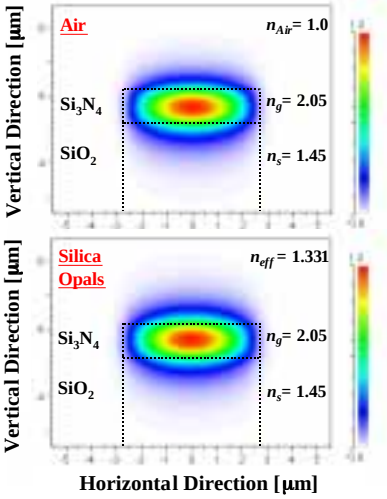
Design of Rib-Type Waveguides

- **Rib-type Waveguide**
  - high index contrast waveguide
  - Si_3N_4 guide layer (0.5 μm)
  - SiO_2 buffer layer (>4 μm):
    to reduce leakage into substrate
- **Etch depth: D = 5.1 μm**
  - matching upper & lower opals
  - planar coating



Simulation of Rib-Type Waveguides

- **Simulation results**
  - imaginary distance beam propagation method
  - single mode: W < 5.5 μm
- **Guides with n_{air} and n_{eff} of opals**
  - opal cladding:
    - decreased index contrast ratio,
    - larger mode size
  - lossy

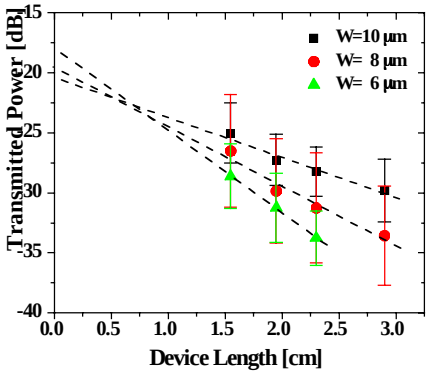


Fabrication of Rib-Type Waveguides

- **Depositions**
  - SiO_2 (thermal growth) & Si_3N_4 (PECVD)
- **RIE Dry etch**
  - CH_4 & CHF_3 gases
  - metal mask: aluminum
  - long process time: rough surface
  - scattering loss
- **Chemical Polish**
  - buffered HF, H_3PO_4

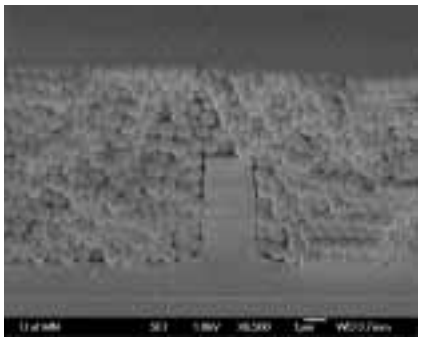
Loss Measurements of Rib-Type Waveguides

- **Cutback method: propagation loss**
  - 1465 nm laser
  - multimode waveguide:
    - 10 μm wide: 3.4 dB/cm,
    - 8 μm wide: 5.0 dB/cm,
    - 6 μm wide: 6.9 dB/cm
  - scattering loss
- **Fabry-Perot method**
  - not successful

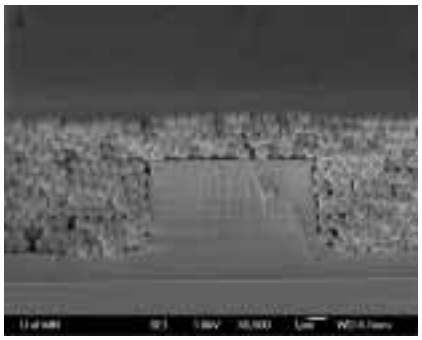


Opal Clad Waveguides

- **Uniform self-assembled opals on non-planar structures**



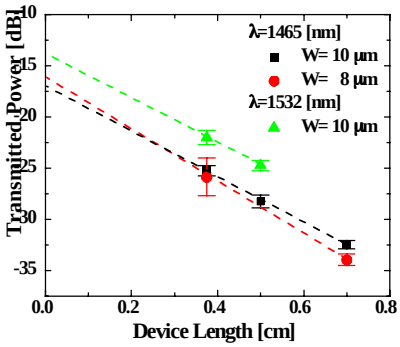
3 μm wide waveguides



10 μm wide waveguides

Measurements of Opal Clad Waveguides

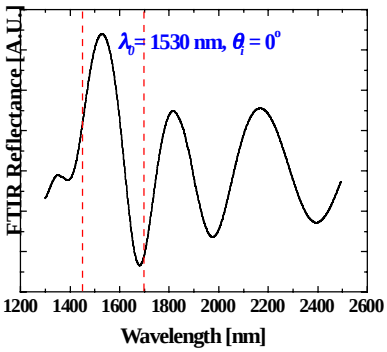
- **Loss measurements**
  - cutback method
  - multimode waveguide
    - 10 μm wide: 22dB/cm @ 1465nm,
    - 8 μm wide: 25dB/cm @ 1465nm,
    - 10 μm wide: 22dB/cm @ 1532nm
  - increased propagation loss
    - decreased index contrast ratio,
    - silica opals: scattering source

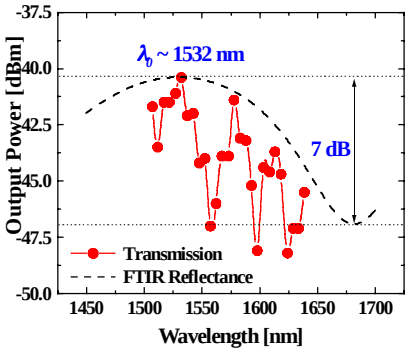


- **3-D Inverse opal clad waveguides: full photonic bandgap**

Measurements of Opal Clad Waveguides

- **Transmission spectrum of 10 μm wide opal clad waveguides**
  - resonance oscillation from thin upper opal layers



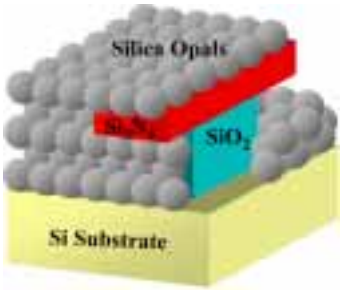


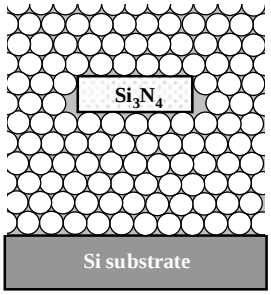
Future Work

- **3-D opal/inverse opal clad waveguides**

  - air-bridge structures

  - including complete 3-D photonic crystal structure



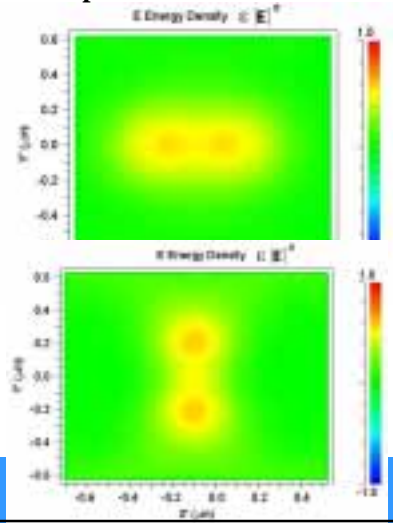


Summary

- **Self-assembled Silica Opals by High Quality Spheres**
- **Rib-type Waveguides**
- **Self-assembled Opal Clad Waveguides: pseudo-photonic bandgap**
- **3-D Inverse Opal Clad Waveguides: full photonic bandgap**

Introduction

- **Opal: TE and TM mode**



- **Inverse Opal: TE**