The Science and Technology of Photonic Crystals

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(Harnessing Light at Nano-Scales)
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Integrated photonics
Micro-photonics
Si-photonics
Energy-saving devices
CONTENT

(I) Motivation (4)

(II) Definition and Introduction (12)

(III) Two Applications
(I) 20th Century: Modern Electronic Revolution

- Semiconductor Si
- Transistor
- Integrated Circuit (IC)
  - Integrated Micro-System Nano-System

Applications
- Computer
- Satellite
- Missile

Science & Technology
- Bell Lab
- IBM
(II) 21 Century: Information Age

• Optical signal processing. (broadband, routing, switching, delivering)

• Photonic Chip
• Optical Semiconductor (photonic crystal)
How can we use less? Energy-saving devices.
Energy crisis?

*But the world is full of energy!*

"energy conversion devices"

--- the key scientific challenge

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Biomass power plant

Anderson, Cal (50MW) (fm TM Lu)

India: solar electric water pump

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Sun
(I) Motivation

(II) Definition and Introduction

(III) Two Applications
“If only it were possible to make dielectric materials in which electromagnetic waves cannot propagate at certain frequencies, all kinds of almost-magical things would be possible.”

---John Maddox


Photonic Crystal:
- New structural material
- Light
Photonic Crystal is an Optical Semiconductor.
(It has the power to control light on-chip)

The first silicon photonic crystal made in 1998. (on-chip control of light)
The first transistor made in 1948. (on-chip control of electrons)
(II) Definition of Photonic Crystal

Si

SiO₂

Silicon Crystal Structure

Photonic Crystal Structure

Issues:
Fabrication
3D topology
Symmetry
μm and nm scale
3D Silicon Photonic Crystals
(a diamond lattice symmetry)

Silicon Substrate

(Nature Sep. 1998)
(1) Photonic Crystal and Crystal Symmetry
(1) For the Past Five Years, There Has Been Rapid Advances in The Realization of 3D Lattices.
Three Classes of Photonic Crystals

1D

1D hole-array built on a SOI substrate.

2D

2D hole array built from GaAs on Al-oxide.

3D

3D diamond lattice built on a Si substrate.
Formation of Bands and Gaps in a Photonic Crystal

- in free space;
- Photonic DOS continuous;
- linear (speed of light).

- in a photonic crystal;
- Photonic DOS discontinuous;
- clean gap of insulating photonic states.
(2) We Have Also Come to Realized The Full Potential of The Unique Photonic-Crystal Dispersion. - mold the flow of light on-chip -

\[ e^{i(\omega t - kx)} \]

**Complete photonic band-gap**

**Frequency, \( \omega \), \( c/a \)**

**Wavevector, \( k \)**

- **Prism, polarizer, rotator**
- **Guide, bend; op. interconnect**
- **Band-edge**
- **Dispersive dispersion**
- **Birefringent dispersion**
- **An-isotropic dispersion**
(3) Micro-Photonics and Nano-Photonics
(characteristic feature size)

Gap wavelength: $\lambda \sim 10 \ \mu m$
Rod-to-Rod spacing: $a = 4.3 \ \mu m$
Width of Rod: $w = 1.2 \ \mu m$
Nano-Structutural Photonics

Operating Wavelength (nm)

Minimum Feature Size (nm)

Near Infrared (1.55 μm)
Blue
Ultra-violet
EUV

op communication
blue/green LED
UV and EUV optics
Photonic Crystal
(New material for controlling light)

• 3D mirror
• On-chip integration
  • Micro-photonics
  • Nano-photonics
Applications

1. “Dielectric” photonic-crystal Information Technology (5)

2. “Metallic” photonic-crystal Energy
Photonic Lattice is a New Material That Could Lead to a Wide Range of Technological Breakthroughs.

*Communication Chip*

*Efficient* Light Source*

*Efficient* Electricity Generation*

E&M Response
passive
active

New Material Revolution via Nano-Structuring!
(1) Integrated Optics Application:
(Control the Flow of Light; Cavity Lasers)

Op Interconnect
• guide
• bend
• cross
• splitter
• etc
Experimental Realization of Guide, Bend, Splitter and Cavity Laser

Micro-Cavity (Q~300-1000)

90-degree Bend

Light-in

Light-out

Linear Guide (no data yet)

120-degree Splitter

Nano Lasers

Bragg Fiber

(A. Scherer, Caltech)
The First Realization of 3D Silicon Photonic Crystal Operating at Communication Wavelengths, $\lambda \sim 1.55\mu m$

180nm 6-inch wafer uniform

Optics Letters 24, 49 (1999).
What’s Next:

At optical wavelengths:
Guides
Bends
Splitters
Filters
Switches
Losses
In-coupling (fiber)
Out-coupling (fiber)
Optical network
3D “Metallic” Photonic-Crystal (the third kind)

Full 6-Inch Wafer

(2, 0.5, 0.35, 0.18, 0.10 μm)
The Operating Principle of These Light Emitters Are Different.

(1) Light Emitting Diode

(2) Incandescent Lamp
The Photonic-Crystal Emitter Is Perhaps The Third One.

(3) Photonic-Crystal Emitter

Spon. Thermal Emission

Engineered DOS

Photonic Band Gap

Light Emission

(EM Vacuum)
40% Electric-to-optical efficiency
Variable Emission-\( \lambda \)
Compact (~Watts/cm\(^2\))

“Device’s micro/nano-structure does matter!”
(3) Lighting Application: An Incandescent Lamp Is Fundamentally Inefficient, Due To Its Broad Emission.

Visible

Power Density (W/cm²)

Wavelength (µm)  

T=3000K

T=2500K

T=2000K

BB Radiation: Broad band

Eye-response: Narrow band

Wien Law: \( \lambda_{peak} \times T \approx 2898[\mu m \cdot °K] \)
By A Proper Length Scaling, The Band-Edge Position Could Be Shifted From 4, 2µm To Visible Wavelengths

\[ \lambda = 4 \text{ and } 1.8 \mu m \text{ (experimental result)} \]
\[ \lambda \sim 400nm \text{ (simulation result with Au)} \]

- Fabrication: feature size ~ 100-150nm. (Multi-layer e-beam/ nano-imprint)
- Material: dielectric constant/ melting point. (material limit)

**New material**
**Small dimension**
INSIDE

Technology
A Light Bulb Went On In His Head
A researcher stumbled on the idea, and a far more energy-efficient bulb may result. B2

Advertising
Nuts About Nascar
Ford focuses on stock-car racing fans, who spend fast and furiously on their vehicles. B2

How to Build Better Light Bulb: Use the Original

‘Tungsten Lattice’ Is Key To Boosting Efficiency Of Edison’s Incandescent

By JOHN J. FIALKA

In a new twist on a 123-year-old idea, scientists at Sandia National Laboratories say they have developed a way to greatly boost the energy efficiency of the commonly used incandescent light bulb.
(4) Portable Electricity: The Successful Realization of a $\lambda \sim 2\mu m$ Emitter Is Important for Thermal Photo-Voltaic (TPV) Power Generation

“A TPV generator converts radiation energy ($Q_r$) into electrical energy ($P$).”

* Compact! Quiet! Efficient! High power!

Basic Principle of a TPV system:

(Scientific American, p. 90-95, September 1998; Physics World, Aug. 9.49, 1998)
For a conventional TPV system, its efficiency and power are limited by the “broad” thermal radiation spectrum.

Modify thermal emission, prevent light leakage at long-\(\lambda\),

\[ \text{Ideal radiation pattern} \quad : \text{Step function} \]

~70% of wasted radiation energy!!

\[ \text{E}_g(\text{GaSb}) \]

\[ \begin{array}{c}
\text{Power Density (W/cm}^2\text{)} \\
\begin{array}{c}
\text{GaSb} \\
\text{Response}
\end{array} \\
\eta \sim 11\%, \\
P \sim 3\text{W/cm}^2
\end{array} \]

\[ \text{BB Cavity Radiator (T=1500K)} \]

\[ \begin{array}{c}
\text{Wavelength (\mu m)} \\
\begin{array}{c}
1 \\
2 \\
3 \\
4 \\
5 \\
6 \\
7 \\
8
\end{array}
\end{array} \]
A PBG Narrow-Band Emitter Is Promising For Enhancing TPV Conversion Efficiency and Power

3D “Tungsten” photonic lattice

\[ Q_r, \text{ Power Density (W/cm}^2) \]

\[
\begin{array}{c}
\text{Wavelength (\text{\mu m})} \\
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8
\end{array}
\]

\[ \text{Eg}, \text{ GaSb PV Cell} \]

\[ \text{suppressed emission} \]

\[ 1.1\text{\mu m} \]

\[ 20 \]

\[ 15 \]

\[ 10 \]

\[ 5 \]

\[ 0 \]

\[ 0 \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ 4 \]

\[ 5 \]

\[ 6 \]

\[ 7 \]

\[ 8 \]

\[ \text{Conversion Efficiency} \]

\[ T \text{ (K)} \]

\[ 900 \]

\[ 1100 \]

\[ 1300 \]

\[ 1500 \]

\[ 1700 \]

\[ 1900 \]

\[ \text{Photonic Crystal} \]

\[ \text{Stru.- W} \]

\[ \text{Er-Oxide} \]

\[ \text{BB} \]

\[ \text{Emitter} \]

\[ \text{Window} \]

\[ \text{GaSb Cell} \]

\[ \text{Reflector} \]

Compact and efficient Infrared light source 
\((\lambda=1-10\mu m; P=100mW-10W)\)

- Lattice Constant \(a_0\) graph
- \(a_0=1.5\mu m\)
- \(a_0=2.8\mu m\)
- \(a_0=5\mu m\)

Compact and efficient \(\lambda=1.5\mu m\) Pump Source 
\((P=1W-10W; Area<0.5\;cm^2)\)

Electricity generation using thermal photovoltaic technology

- GaSb Cell
- Thermal Radiator
- Burner

Near-Visible Light Emission

- \(\lambda=0.5\mu m\)
- \(\lambda=0.35\mu m\)
- \(\lambda=0.18\mu m\)