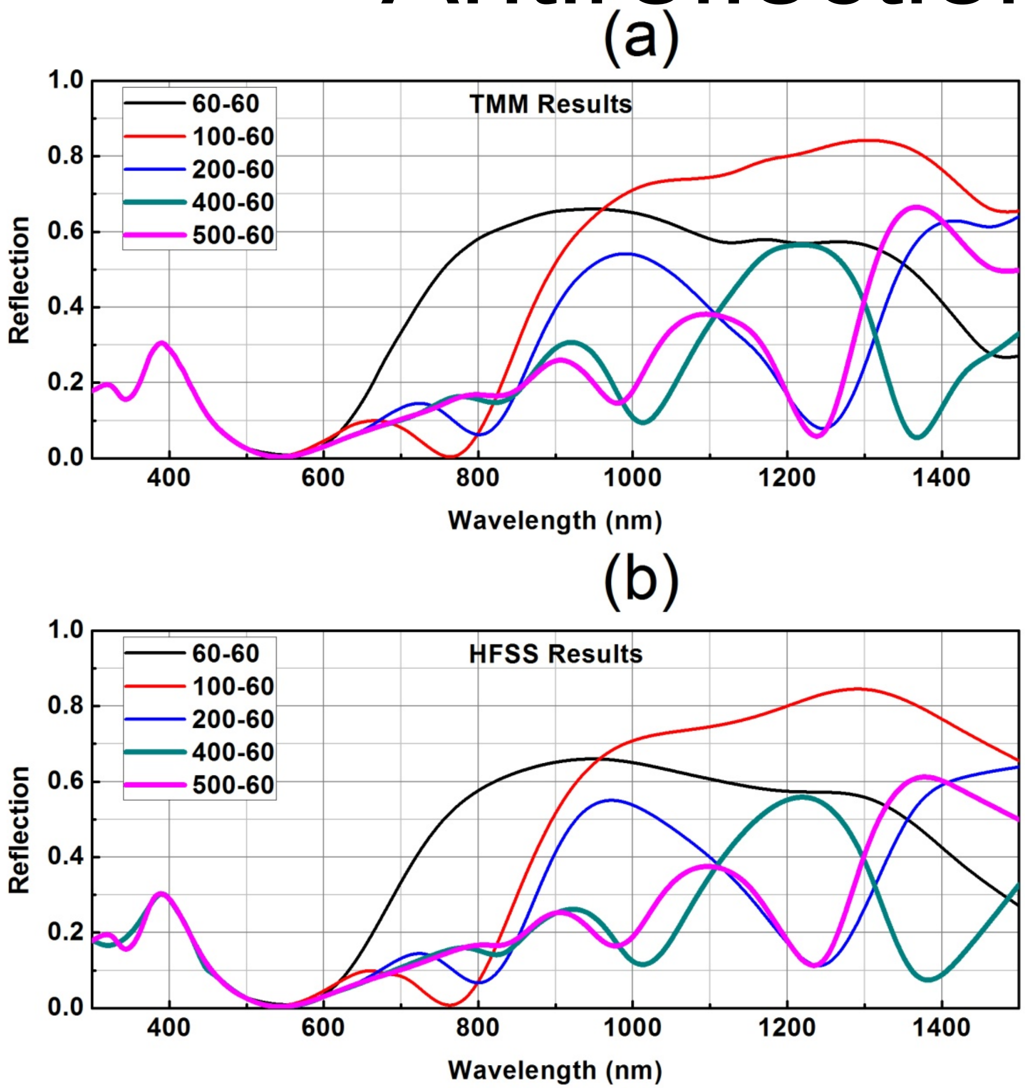
Building College-University
Partnerships for Nanotechnology
Workforce Development

Light Trapping

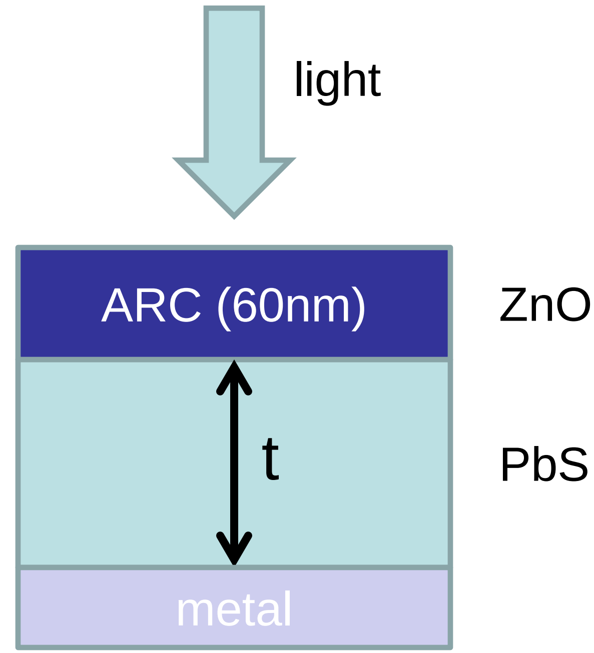
Outline

- Flat solar cells
  - ARC for flat solar cells
  - Manifestations of Fabry Perot Resonances
- Light trapping
  - Advantage of a nanodome
  - Yablonovitch limit
  - Bloch modes
  - Diffraction aided waveguiding
  - Mie resonances
  - Hybridizations
  - Plasmonics
- Examples

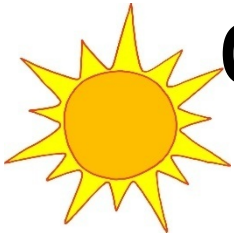
Flat Solar Cells
Antireflection Coating

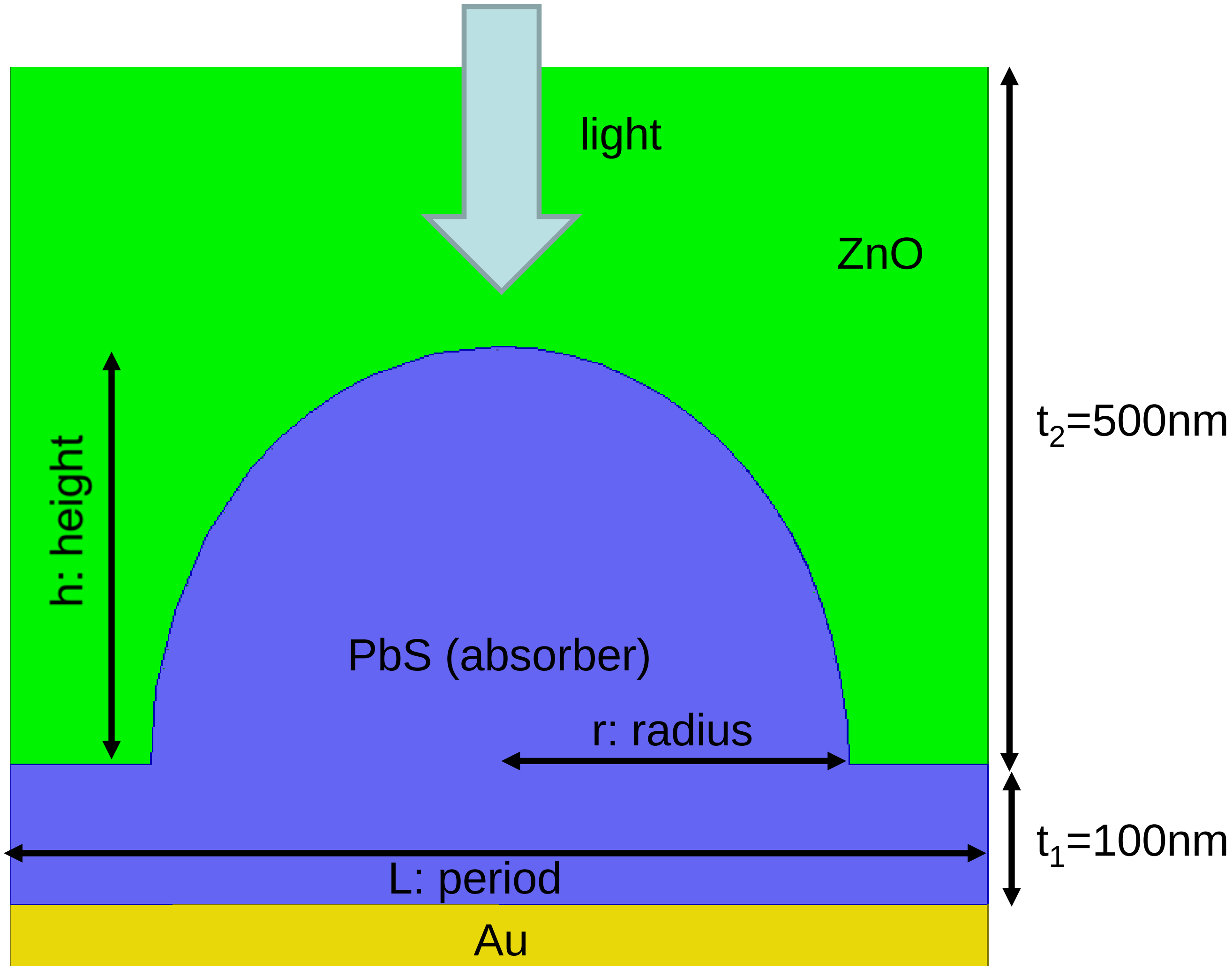


$$\frac{\lambda}{4n} = 60nm \Rightarrow \lambda \approx 500nm$$

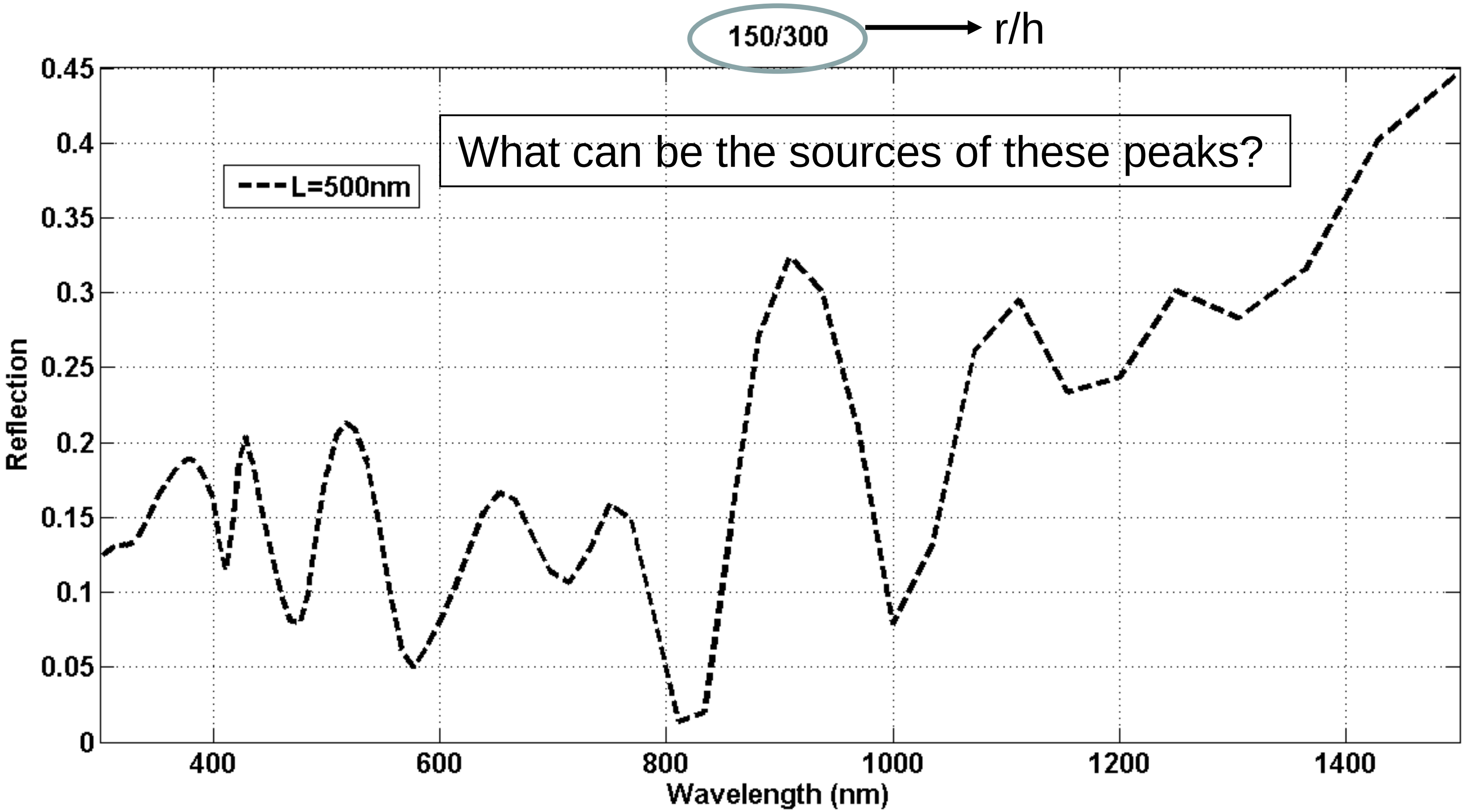


Flat Solar Cells: Manifestations of Fabry Perot Resonances

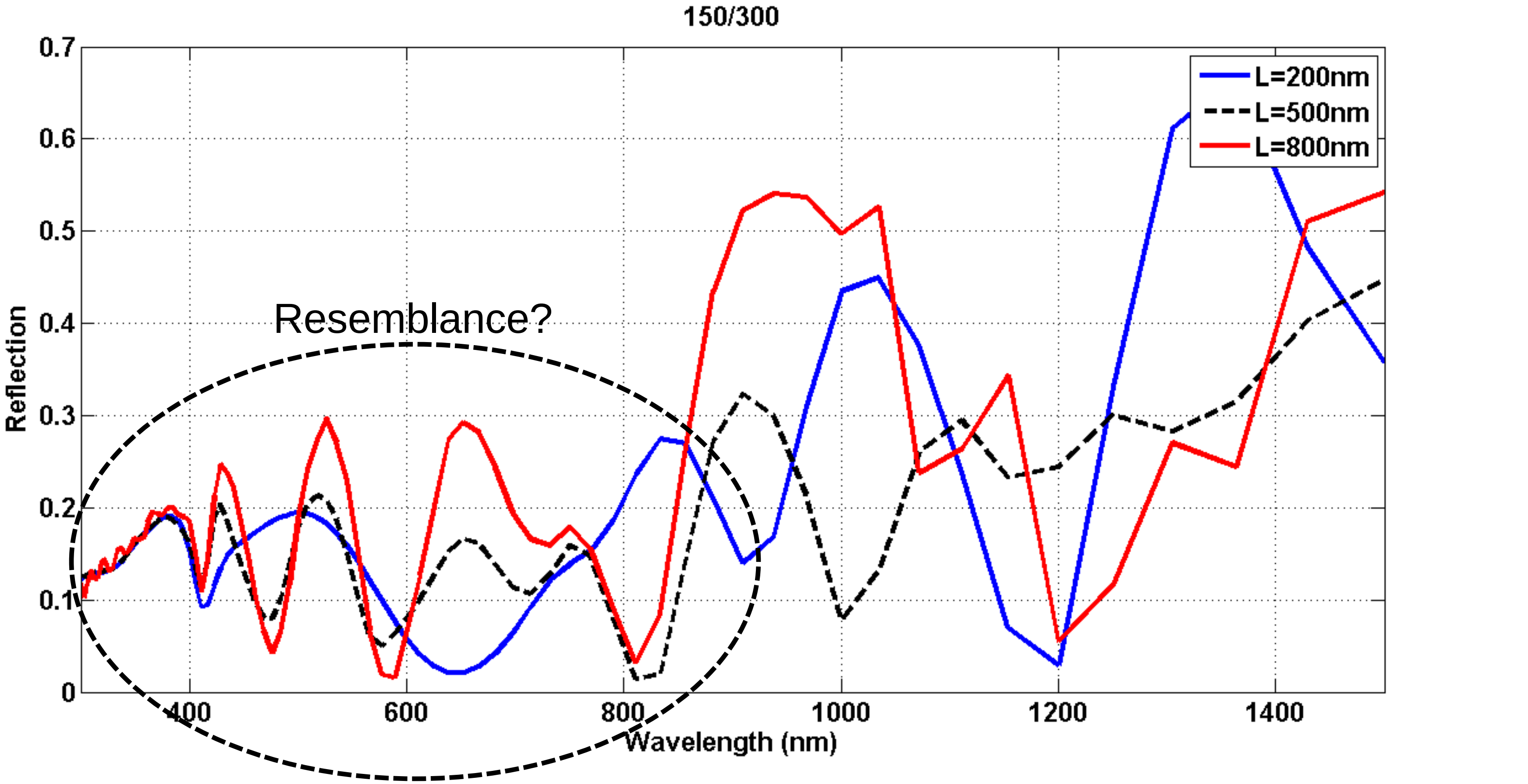




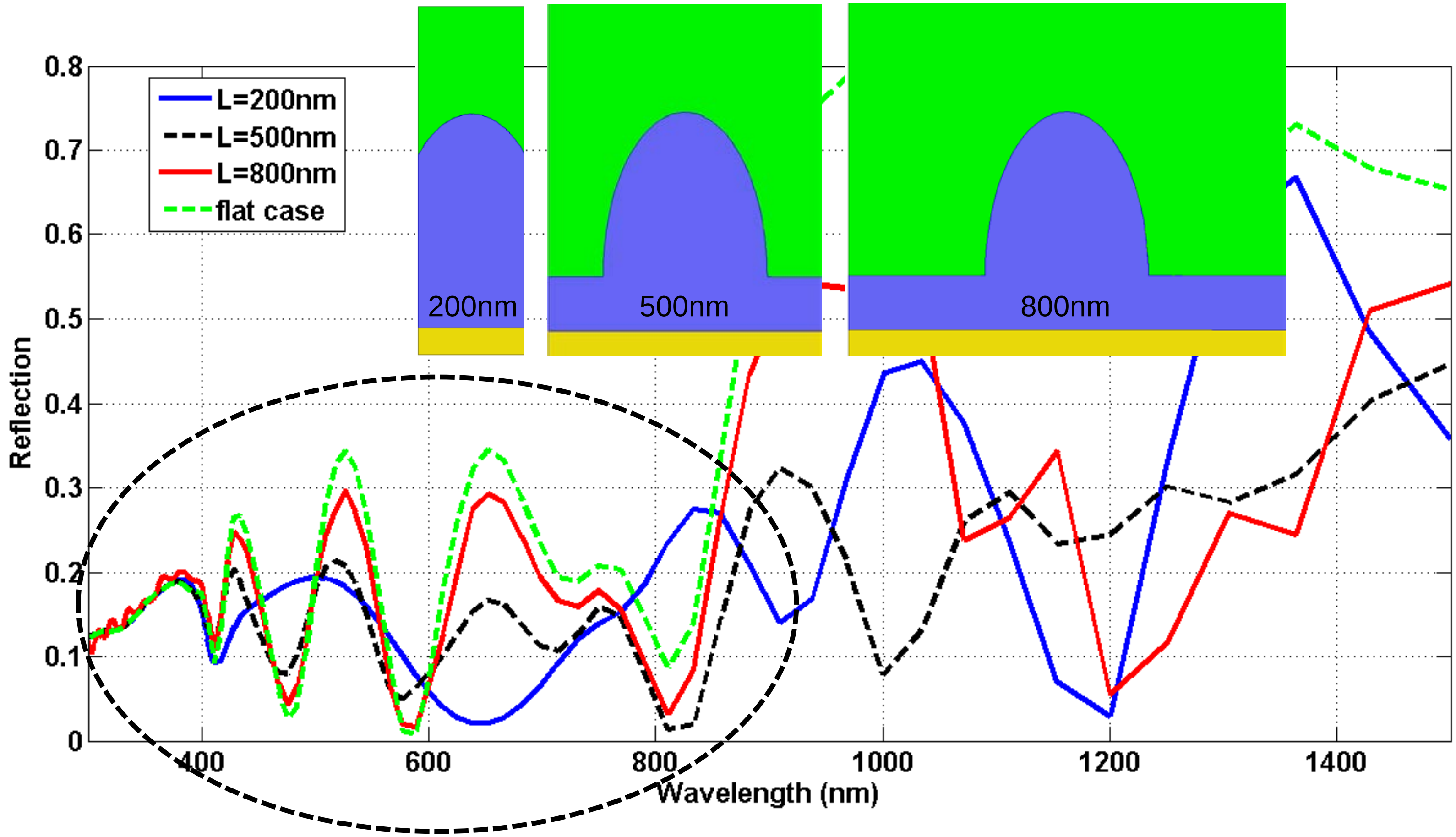
Flat Solar Cells: Manifestations of Fabry Perot Resonances



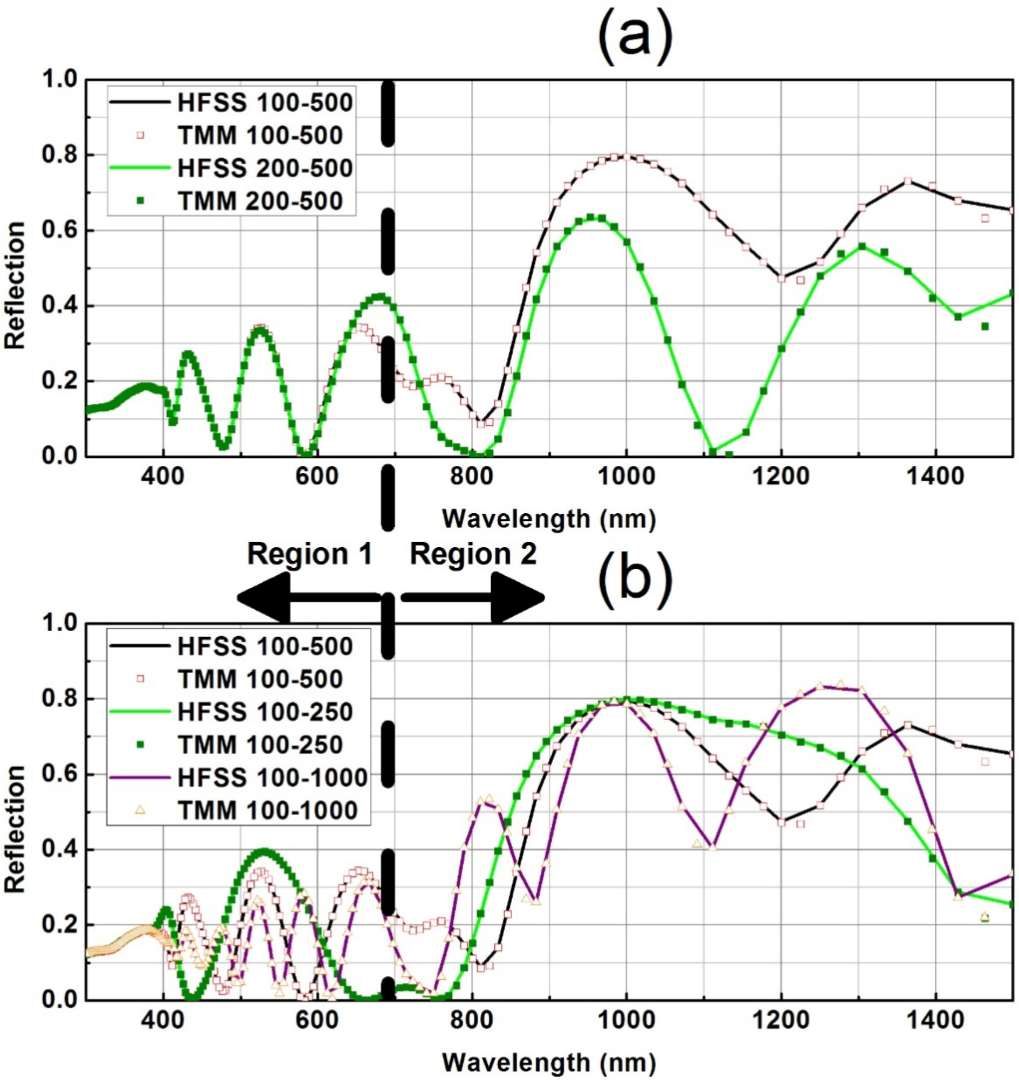
Flat Solar Cells: Manifestations of Fabry Perot Resonances

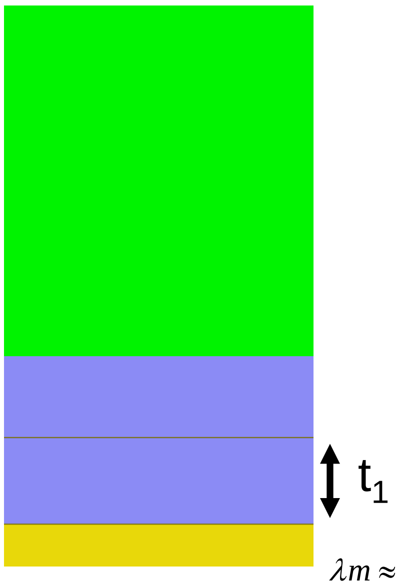


Flat Solar Cells: Manifestations of Fabry Perot Resonances



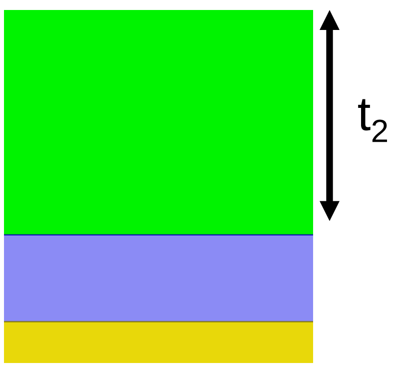
Flat Solar Cells: Manifestations of Fabry Perot Resonances



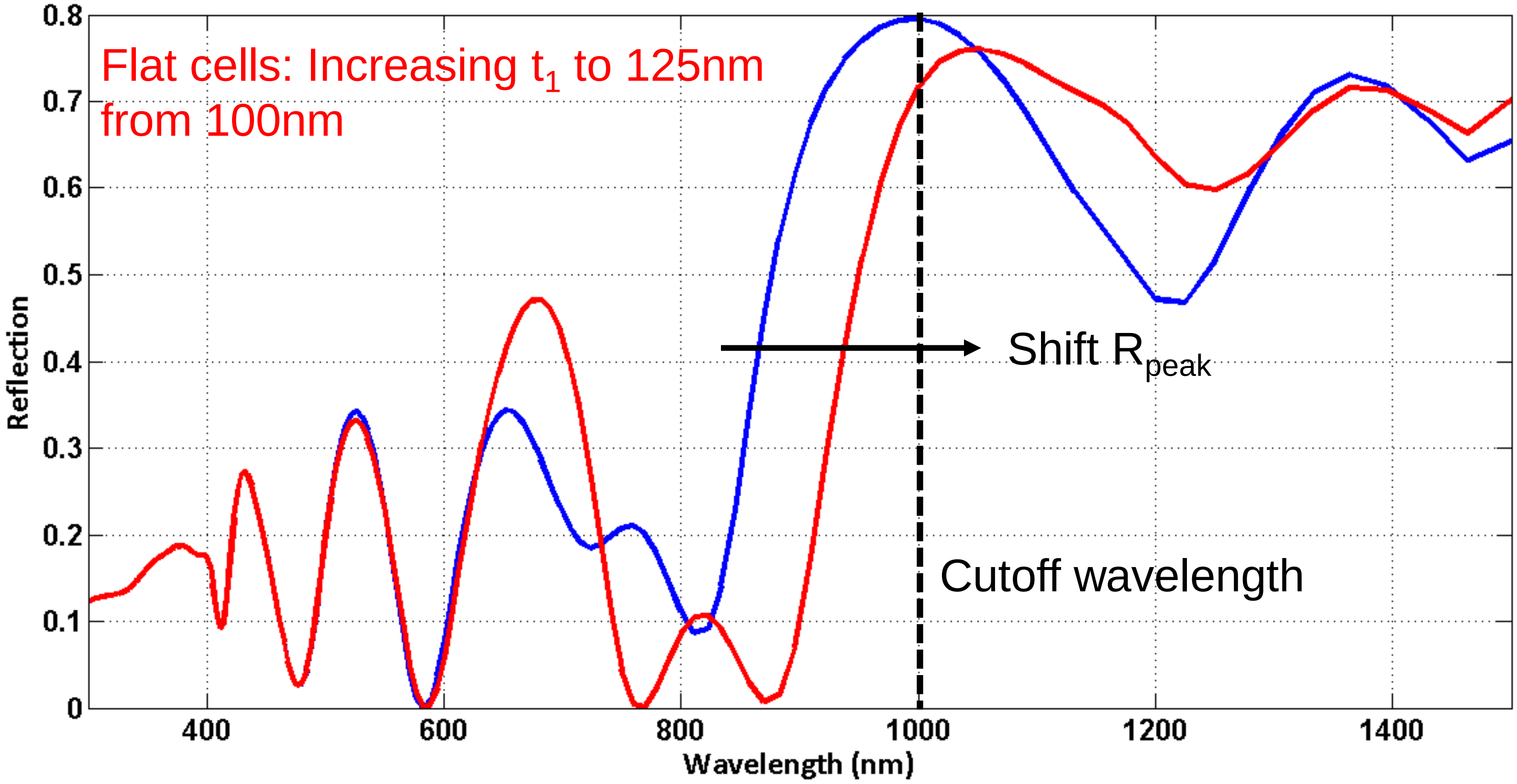


$\lambda m \approx 2n_{ZnO}t_2 \cdots \text{region 1}$

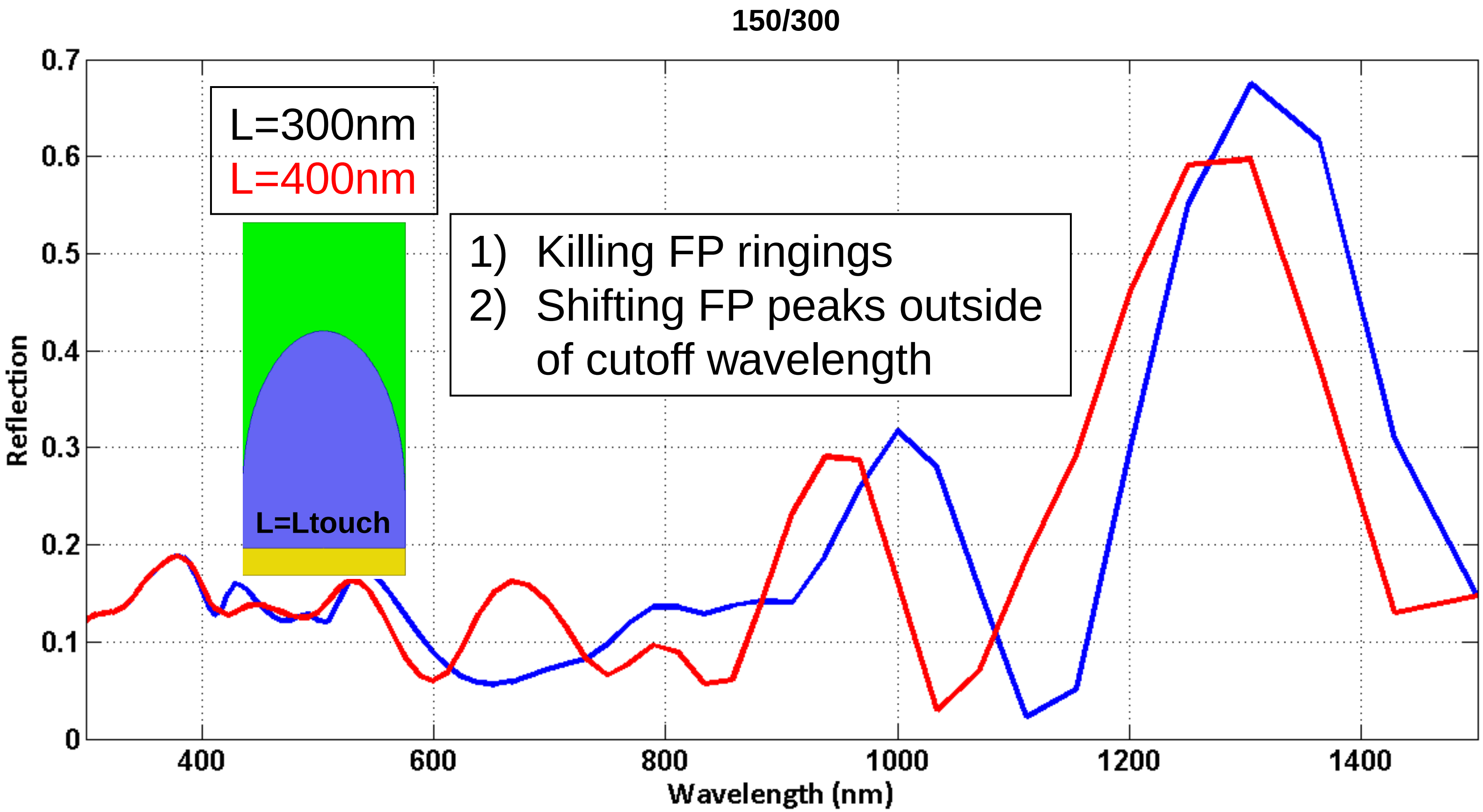
$\lambda m \approx 2(n_{ZnO}t_2 + n_{PbS}t_1) \cdots \text{region 2}$



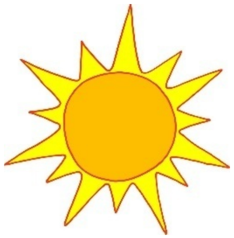
Flat Solar Cells: Manifestations of Fabry Perot Resonances

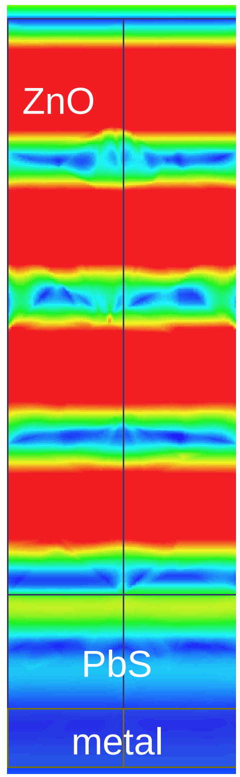


Flat Solar Cells: Manifestations of Fabry Perot Resonances

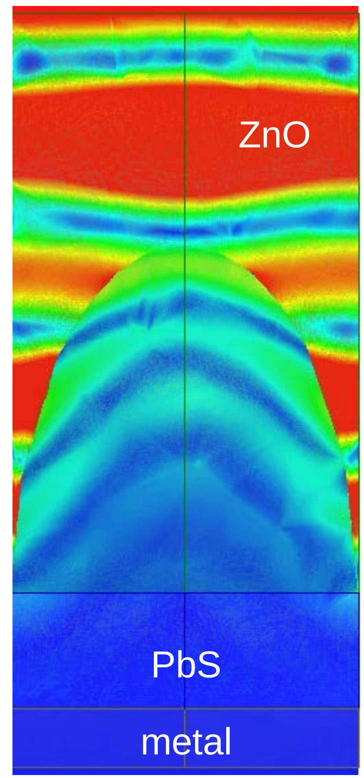


Light trapping: Advantage of a nanodome





Flat layers



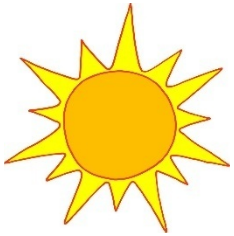
Dome case

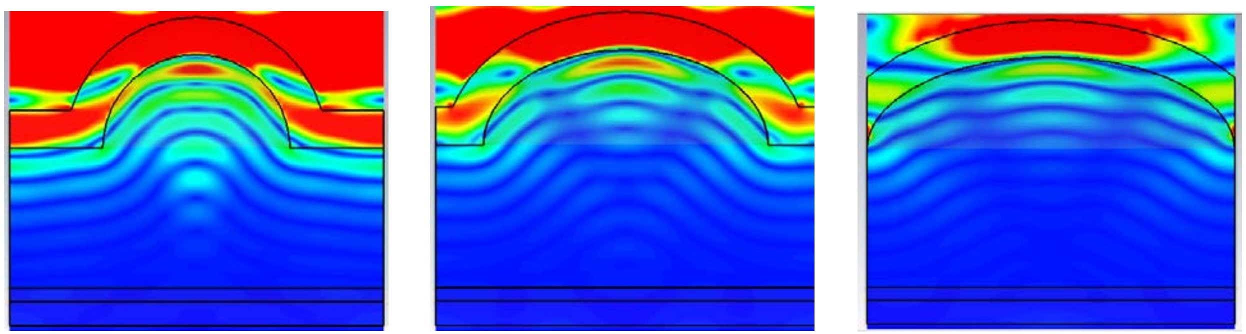
Same effective thickness: a jump from 30 to 37 mA/cm^2

- Increasing optical length, wavefront shaping
- Focusing

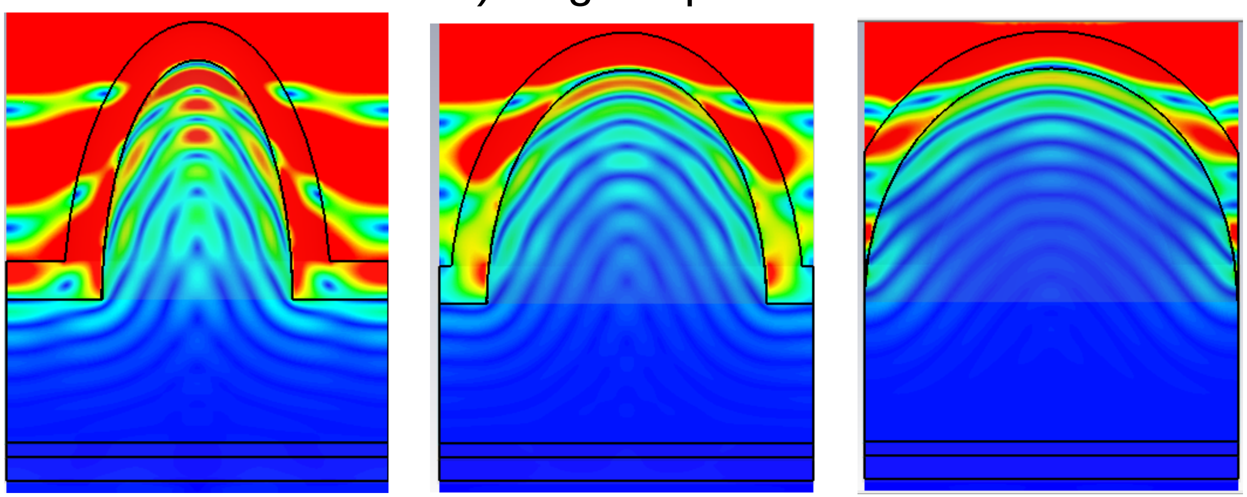
- Increasing the absorber volume

Light trapping: Advantage of a nanodome

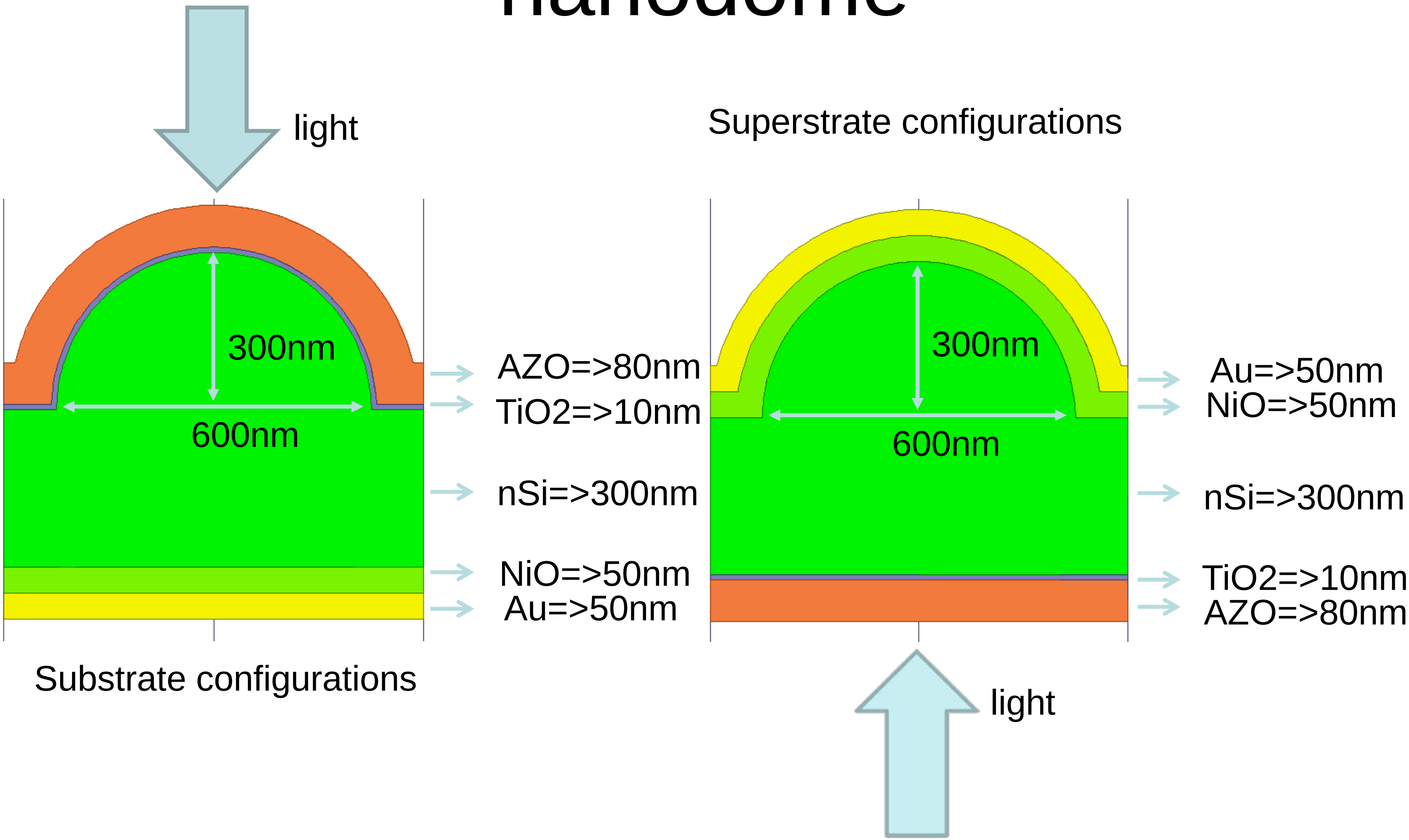




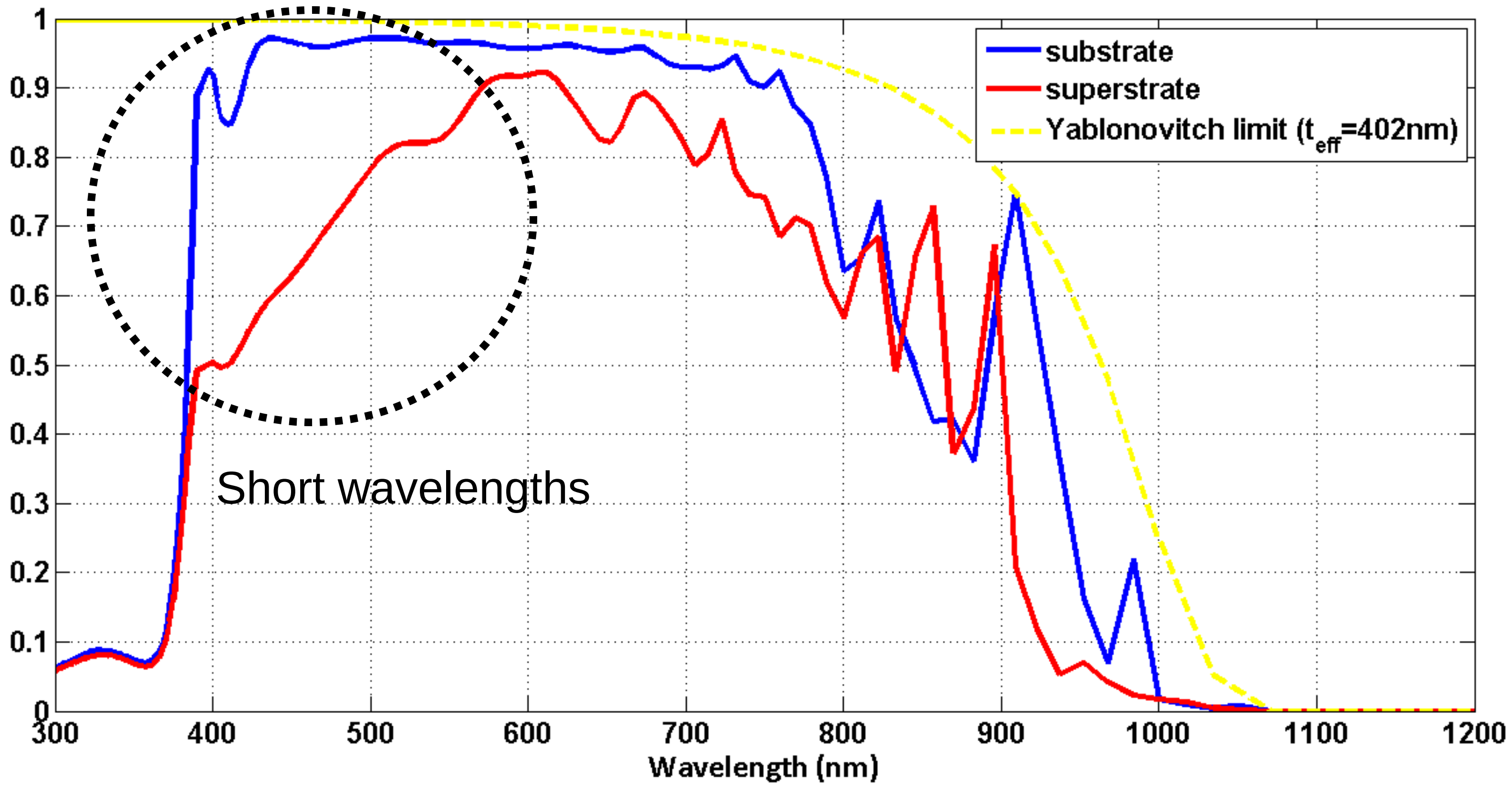
1) L=Ltouch
2) High aspect ratio



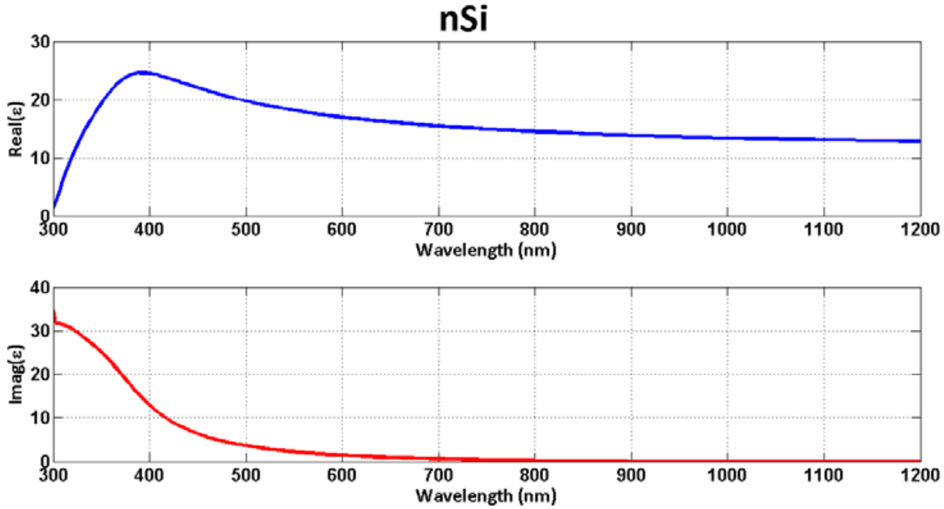
Light trapping: Advantage of a nanodome

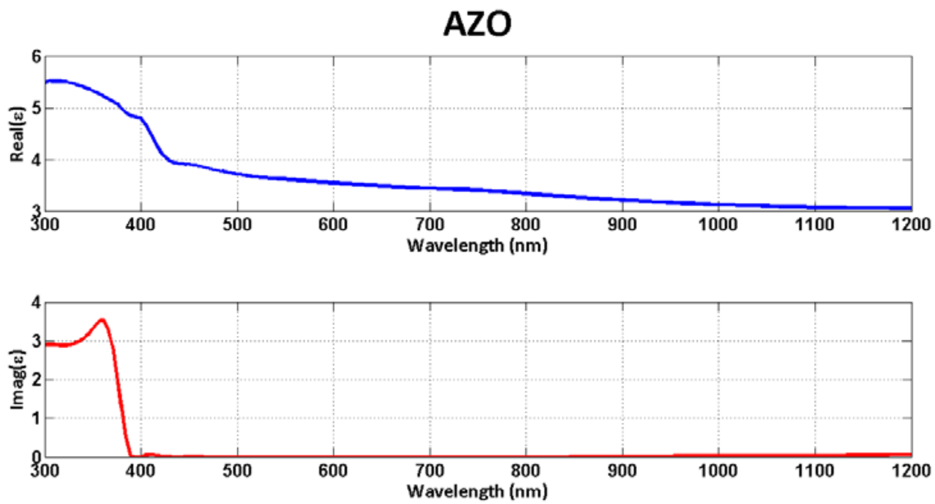


Light trapping: Advantage of a nanodome



Light trapping: Advantage of a nanodome

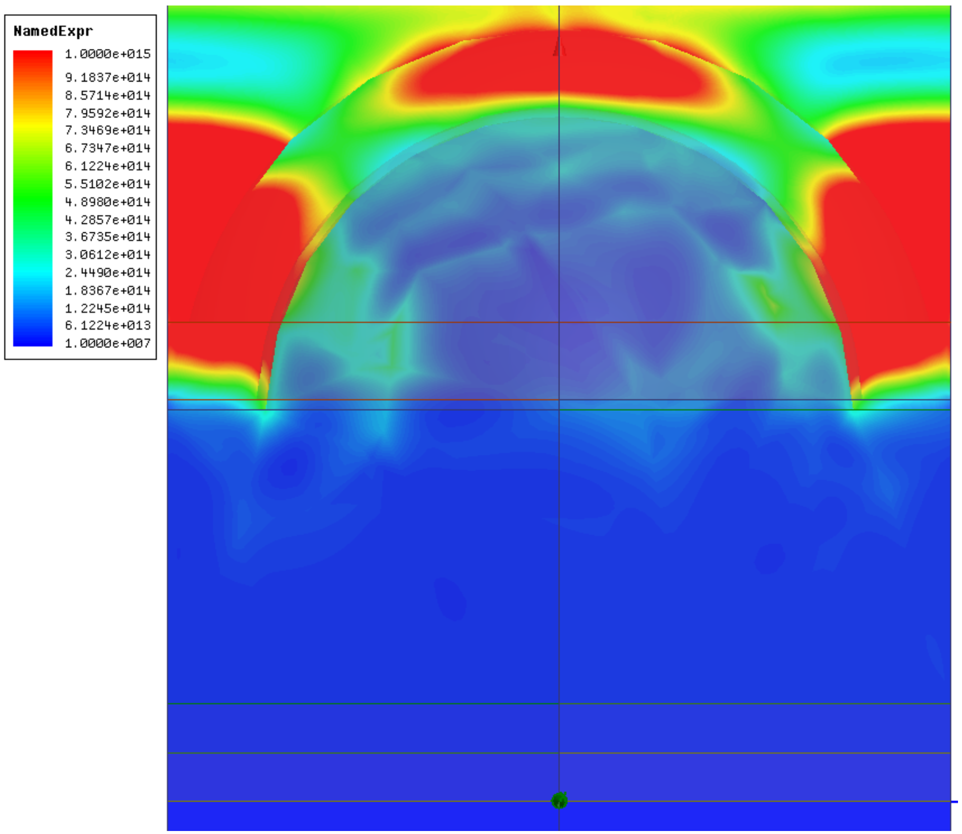


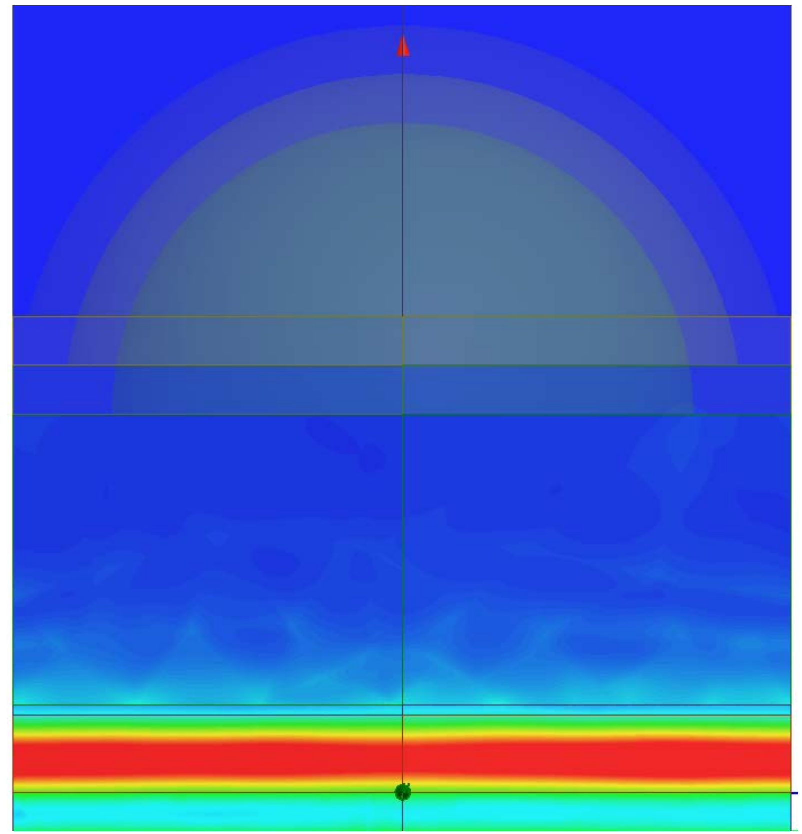


Light trapping: Advantage of a nanodome

(E-field)^2 @ 458nm – 650 THz

Substrate	Superstrate



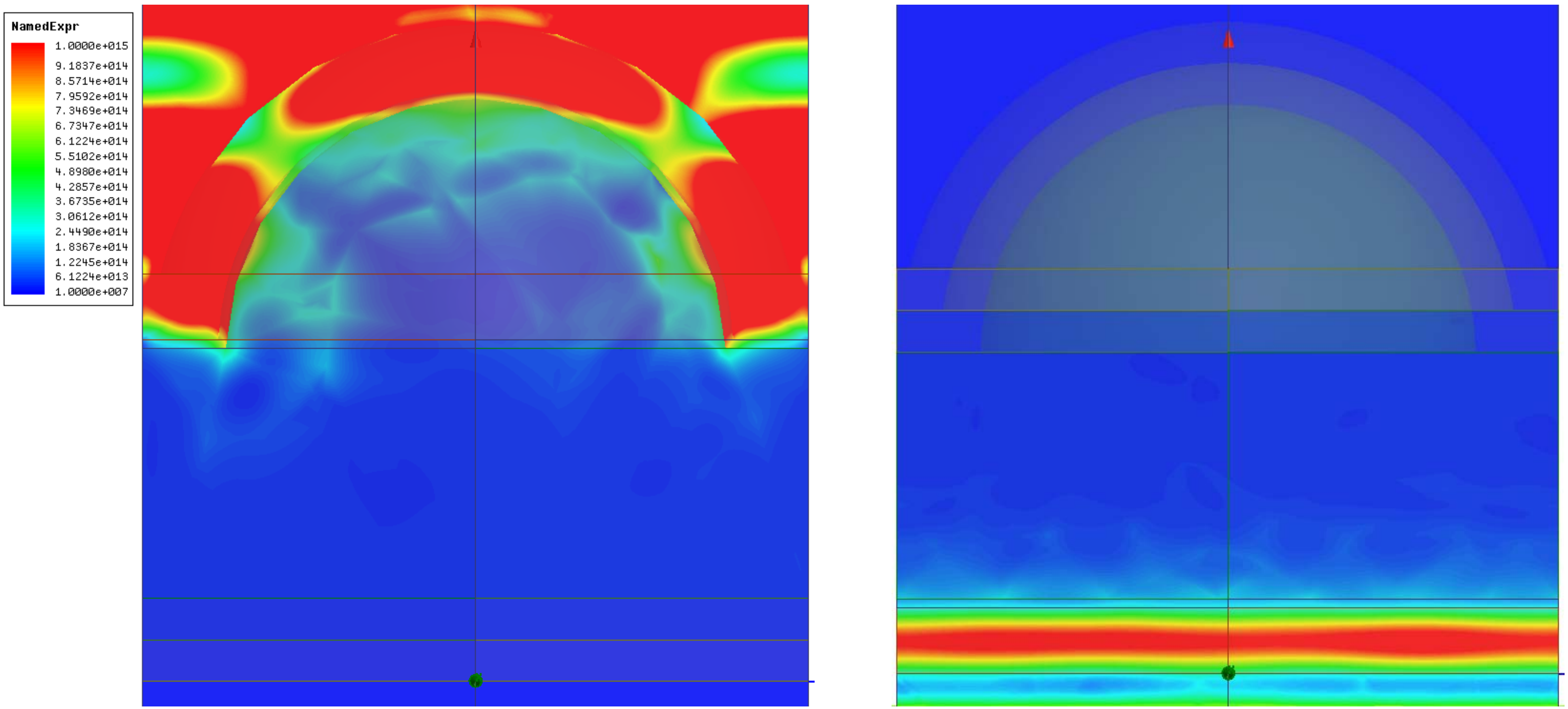


All intensity plots are on the same scale

Light trapping: Advantage of a nanodome

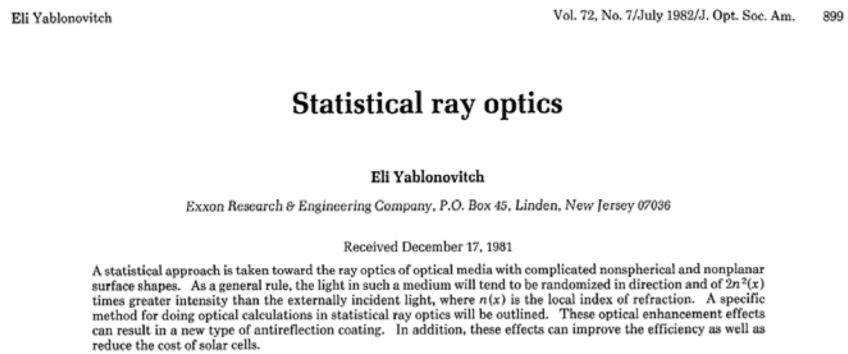
(E-field)^2 @ 434nm – 690 THz

Substrate	Superstrate



All intensity plots are on the same scale

Light trapping: Yablonovitch limit


Eli Yablonovitch Vol. 72, No. 7/July 1982/J. Opt. Soc. Am. 899

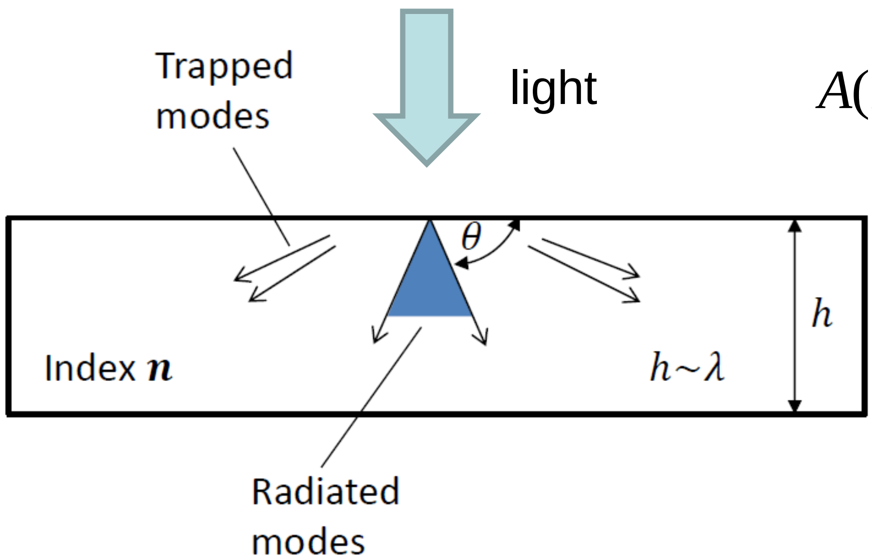
Statistical ray optics

Eli Yablonovitch

Exxon Research & Engineering Company, P.O. Box 45, Linden, New Jersey 07036

Received December 17, 1981

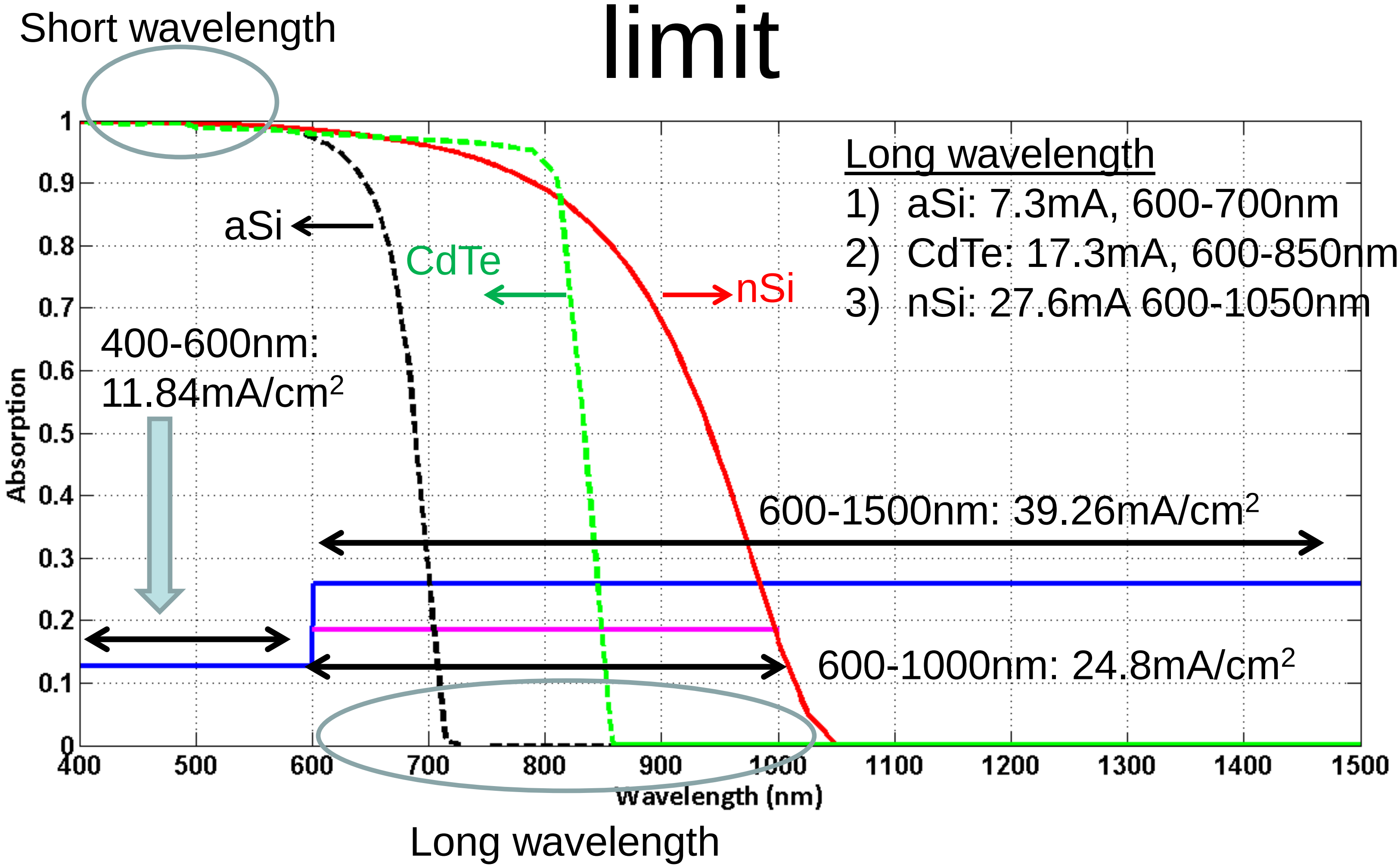
A statistical approach is taken toward the ray optics of optical media with complicated nonspherical and nonplanar surface shapes. As a general rule, the light in such a medium will tend to be randomized in direction and of $2n^2(x)$ times greater intensity than the externally incident light, where $n(x)$ is the local index of refraction. A specific method for doing optical calculations in statistical ray optics will be outlined. These optical enhancement effects can result in a new type of antireflection coating. In addition, these effects can improve the efficiency as well as reduce the cost of solar cells.



$$A(\lambda, h) = \frac{4n^2\alpha h}{4n^2\alpha h + 1}$$

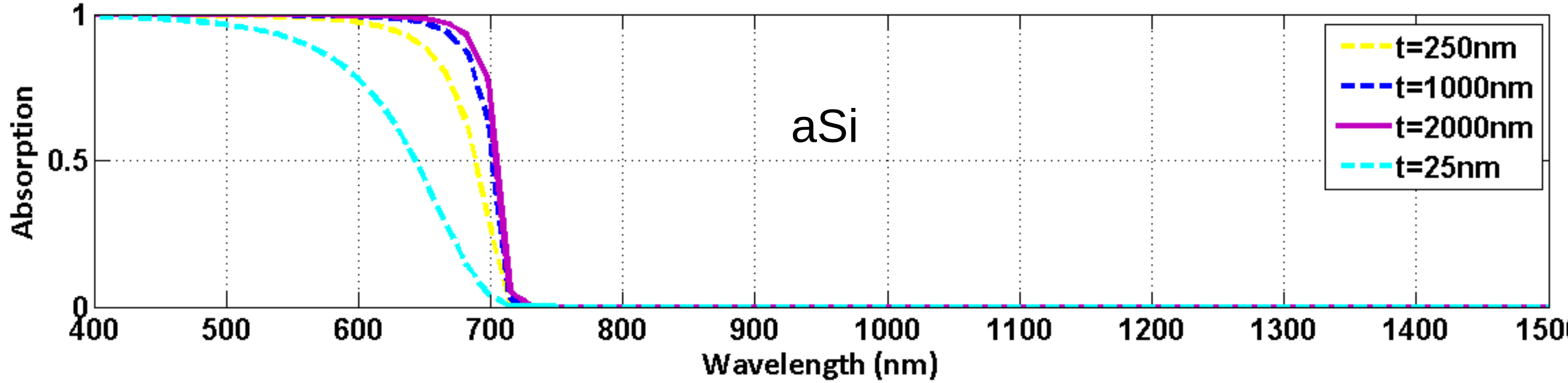
Paper: E. Yablonovitch, J. Opt. Soc. Am. vol. 72, 899, 1982

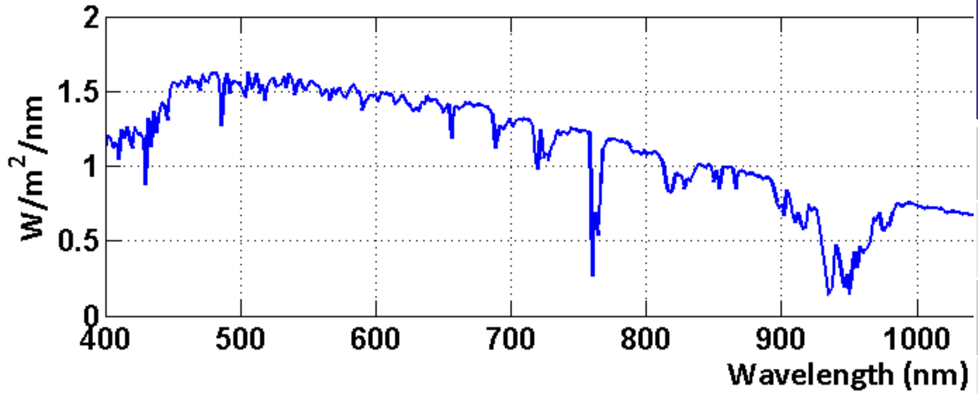
Light trapping: Yablonovitch limit



Yablonovitch limited absorption curves for h=250nm

Light trapping: Yablonovitch limit

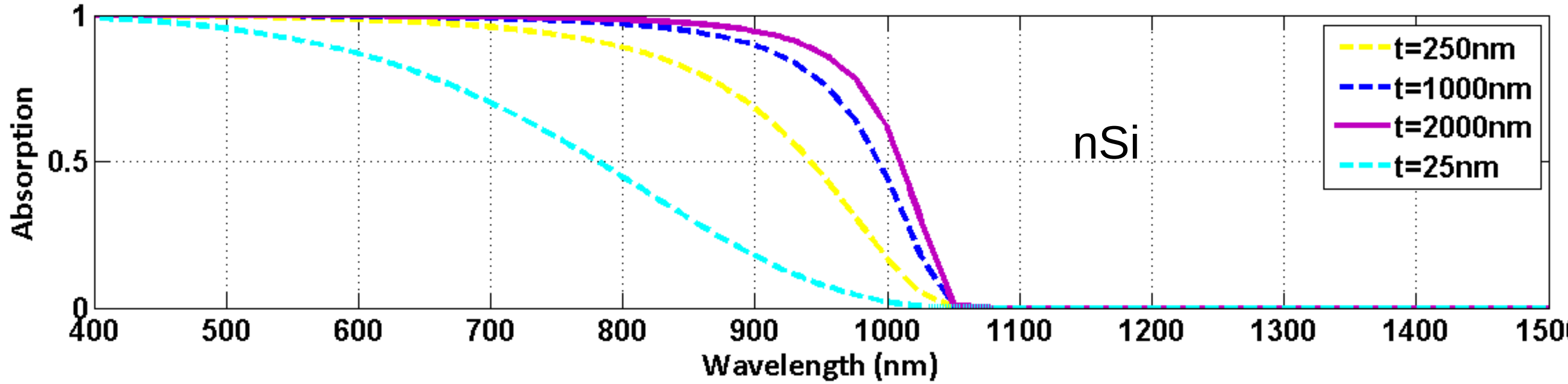


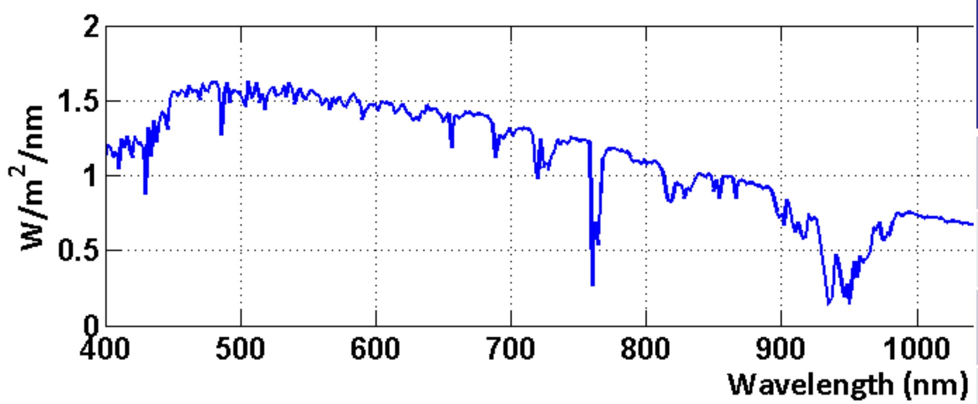


Absorber thickness	Jsc (mA/cm²)
25nm	14.01
250nm	17.61
500nm	18.24
1000nm	18.73
2000nm	19.07

Mostly governed by short wavelength response

Light trapping: Yablonovitch limit

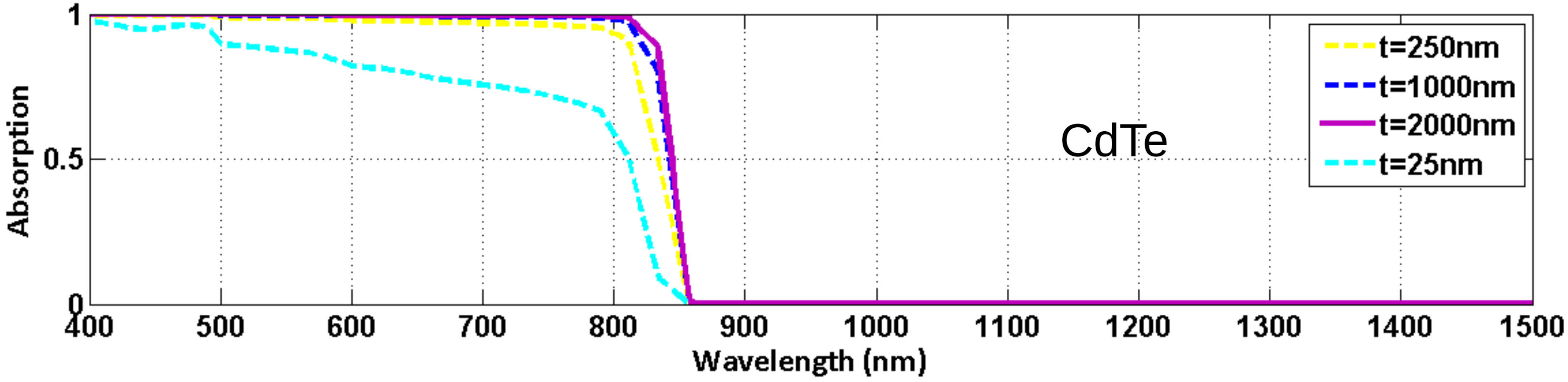


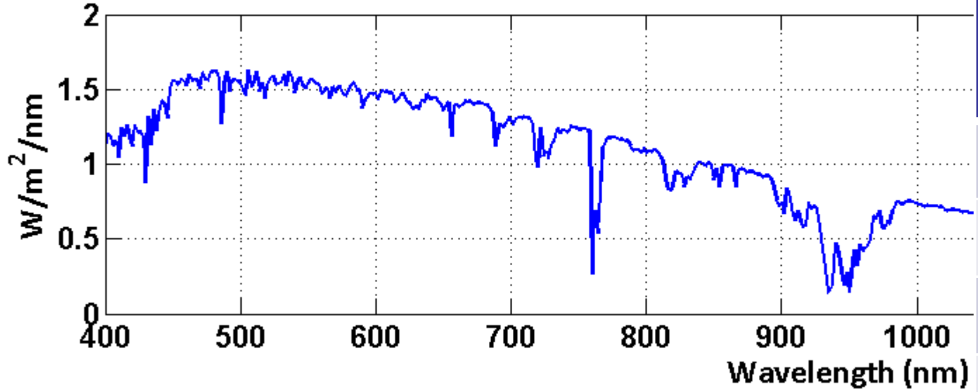


Absorber thickness	Jsc (mA/cm²)
25nm	23.1
250nm	32.32
500nm	34
1000nm	35.33
2000nm	36.37

Mostly governed by long wavelength response

Light trapping: Yablonovitch limit





Absorber thickness	Jsc (mA/cm^2)
25nm	22.12
250nm	27.36
500nm	27.93
1000nm	28.31
2000nm	28.54

Governed by short wavelength response

Light trapping: Bloch modes

(a)

Slab modes

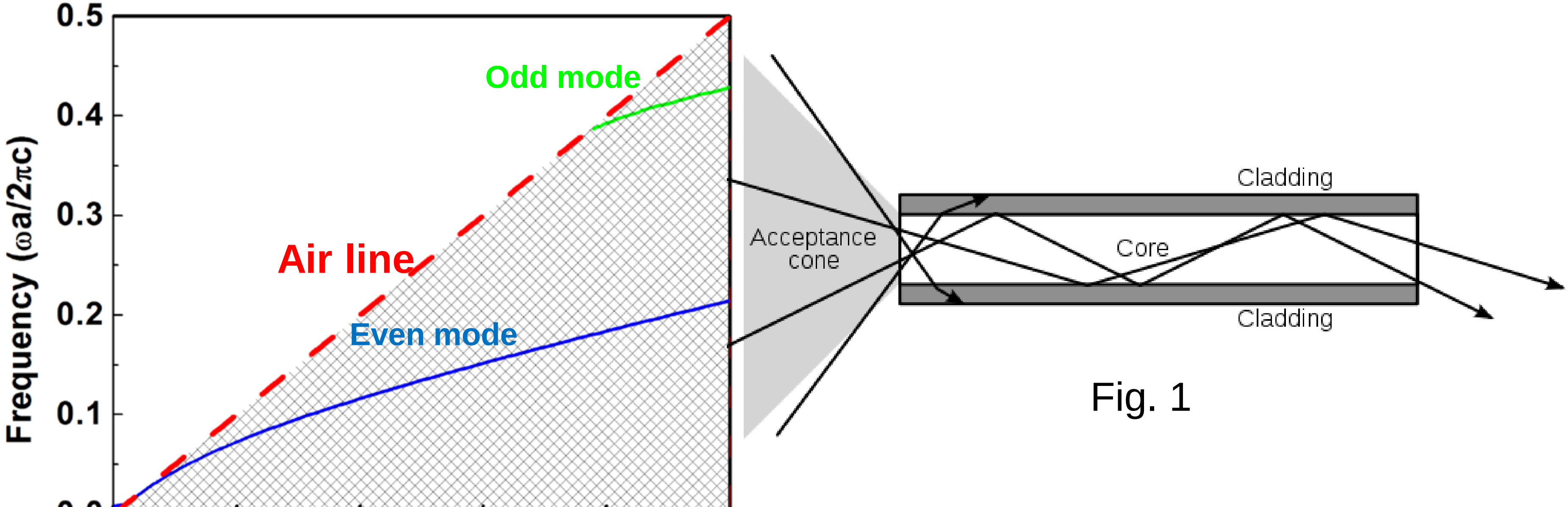
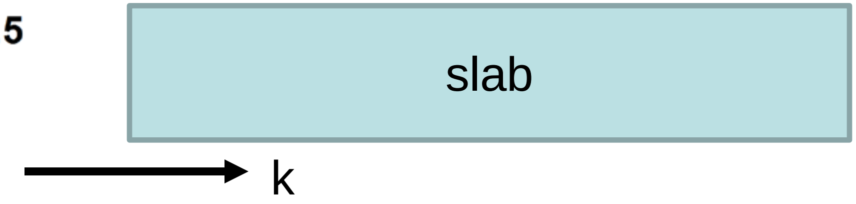
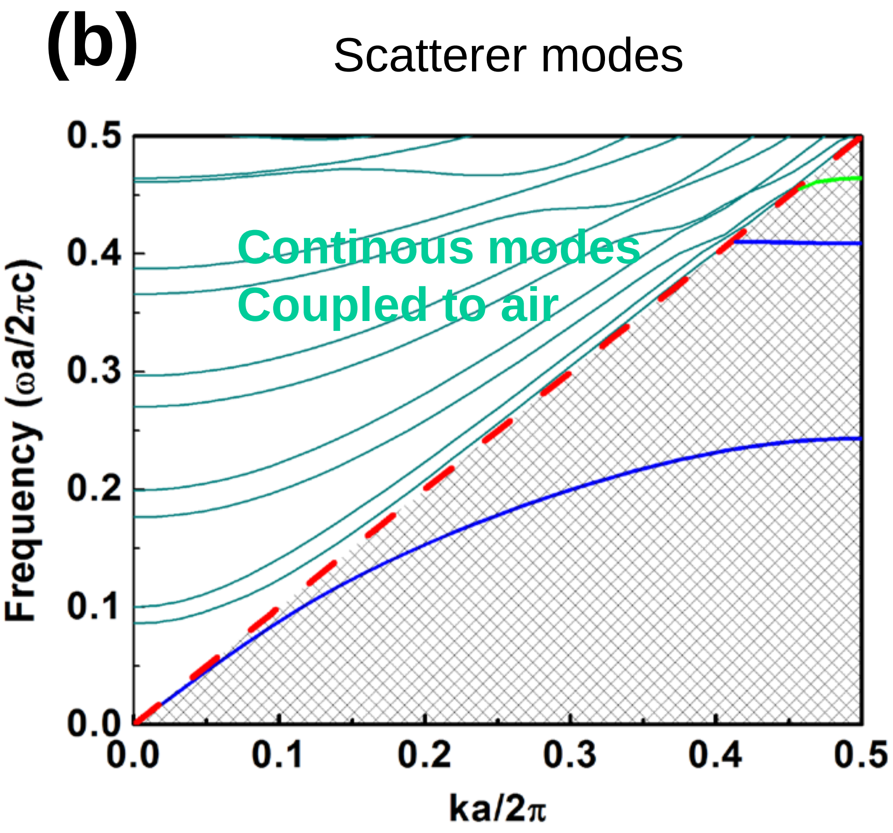


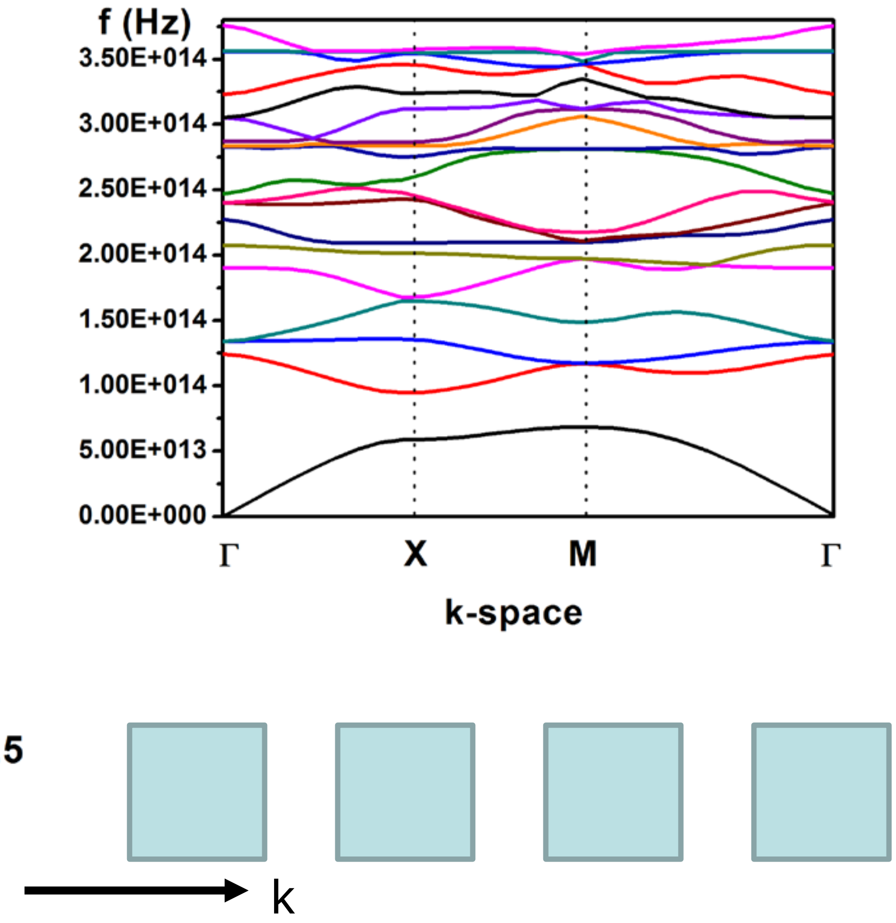
Fig. 1



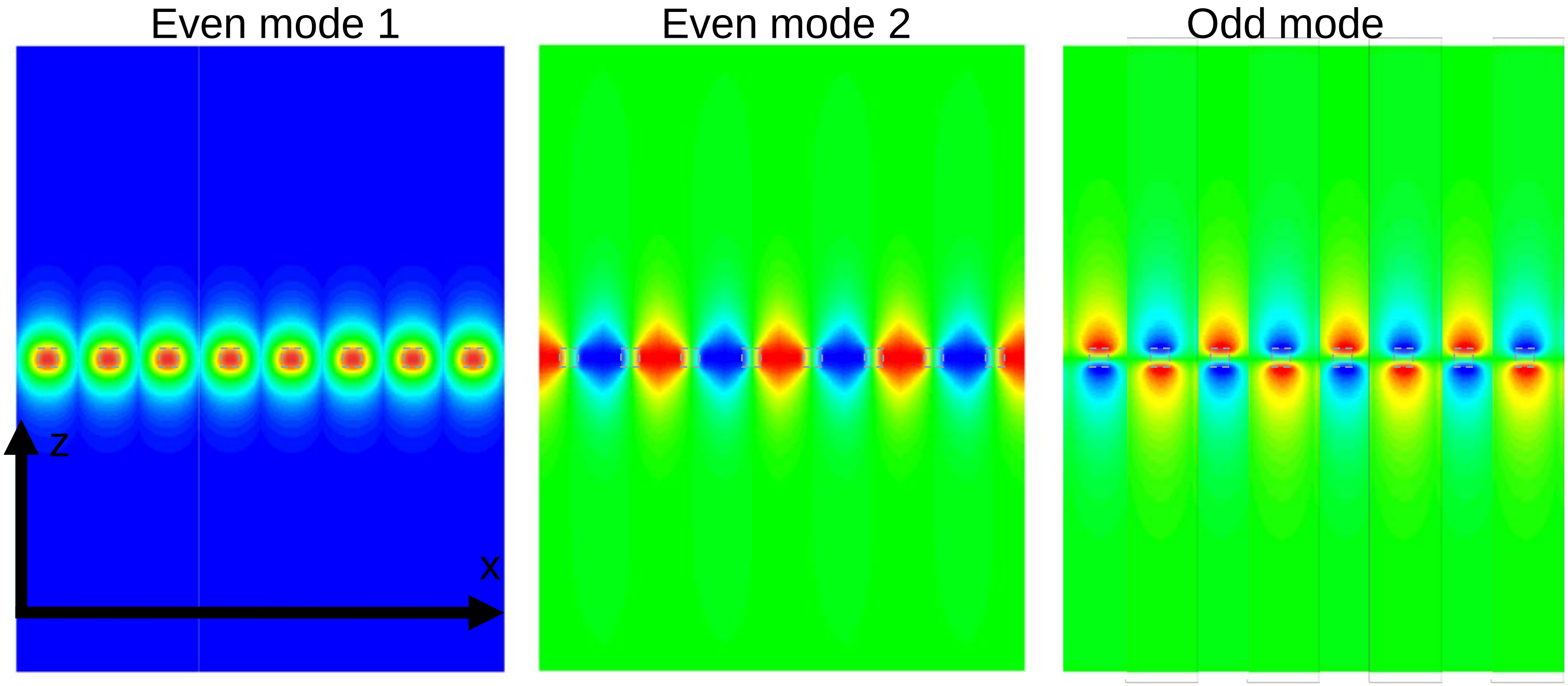
- Fig. 1 taken from: http://photonicswiki.org/index.php?title=File:Optical-fibre.svg

Light trapping: Bloch modes

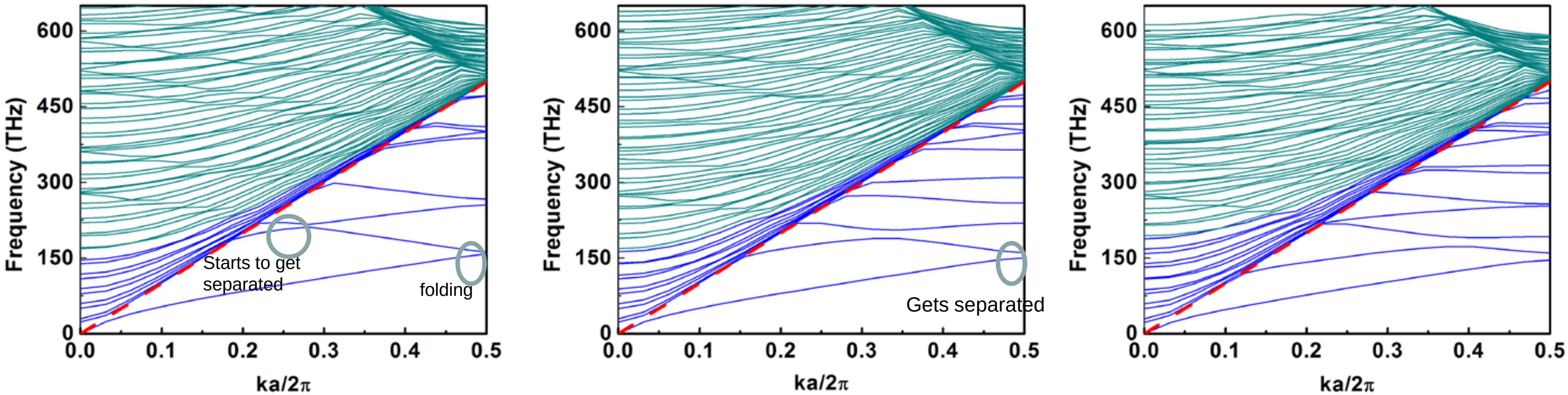




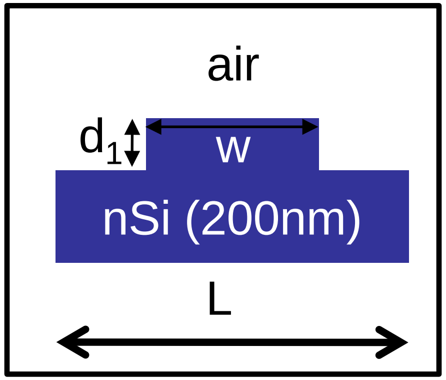
Light trapping: Bloch modes



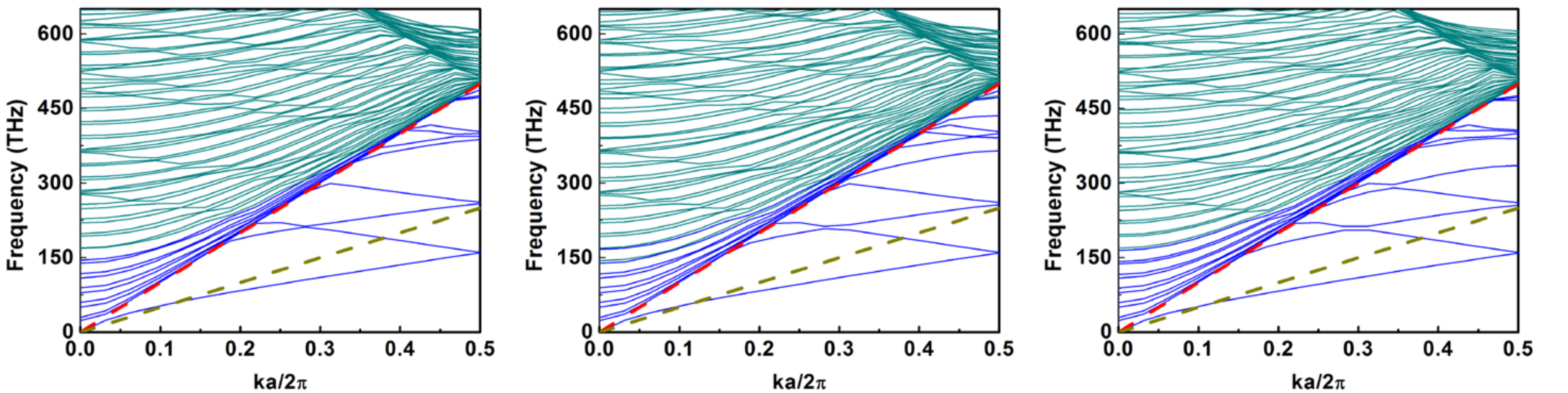
Light trapping: Bloch modes



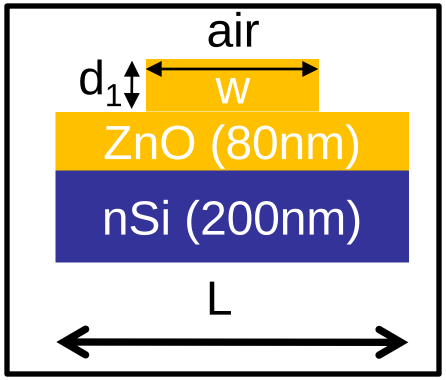
L=300nm, w= 150nm, d2=200nm, d1=20nm (left), d1=100nm (middle), d1=200nm (right)



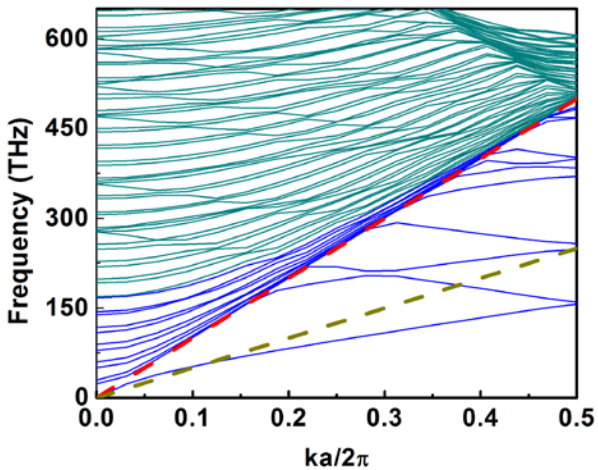
Light trapping: Bloch modes

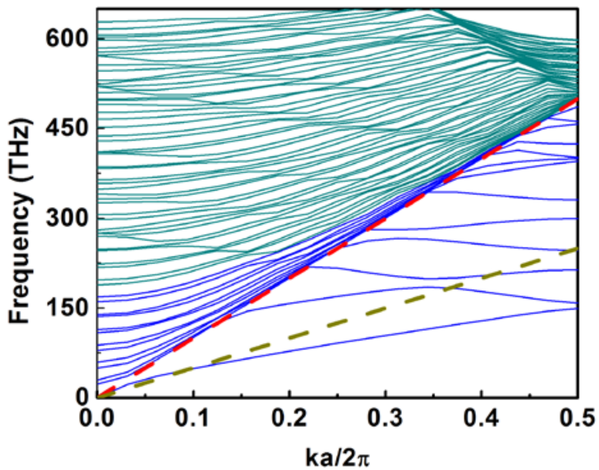


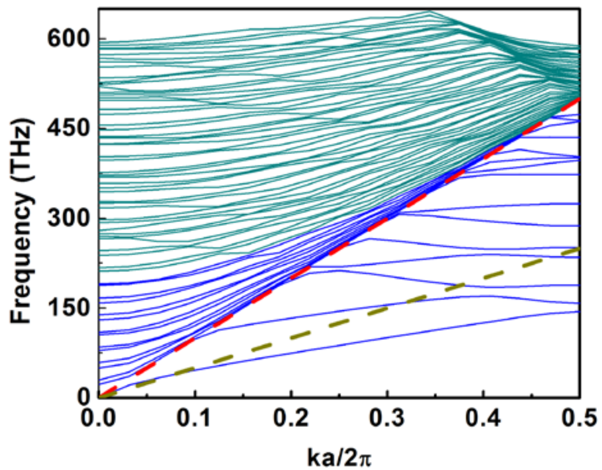
L=300nm, w= 150nm, d2=200nm, d1=20nm (left), d1=100nm (middle), d1=200nm (right)



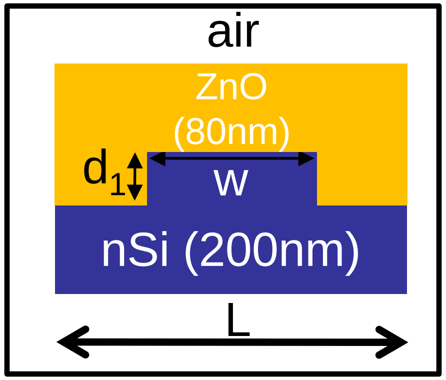
Light trapping: Bloch modes



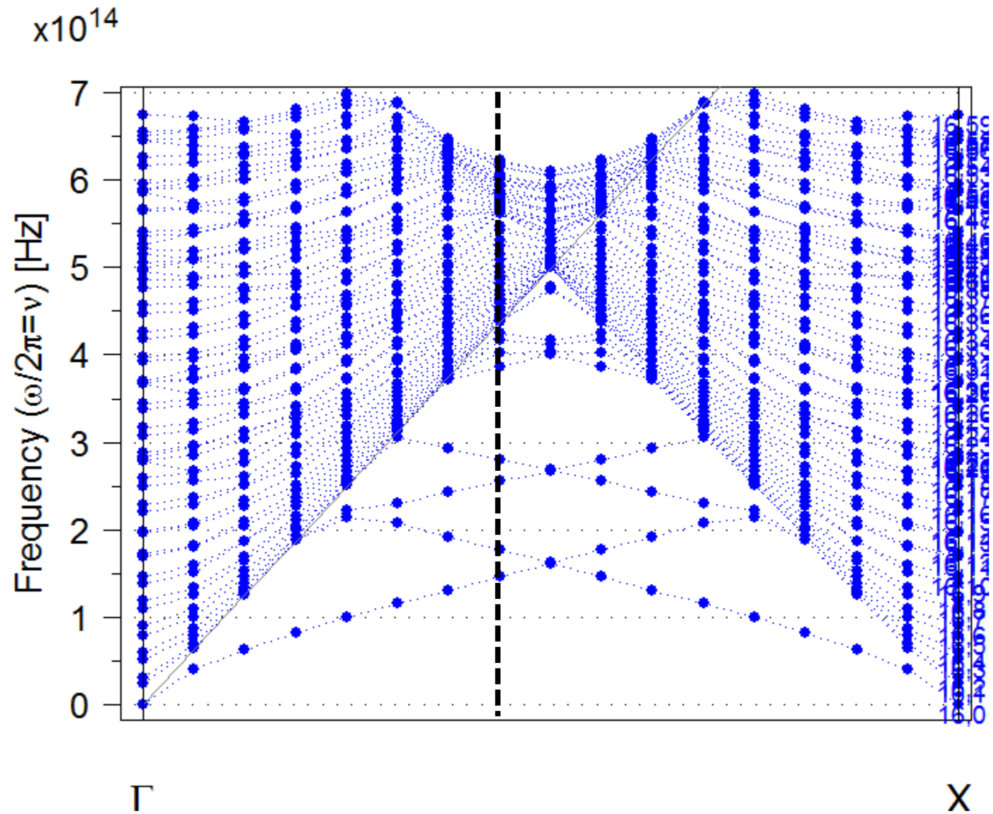


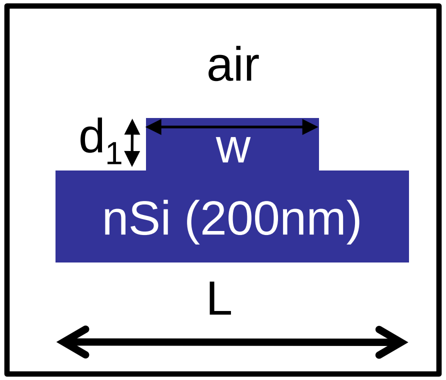


L=300nm, w= 150nm, d2=200nm, d1=20nm (left), d1=100nm (middle), d1=200nm (right)

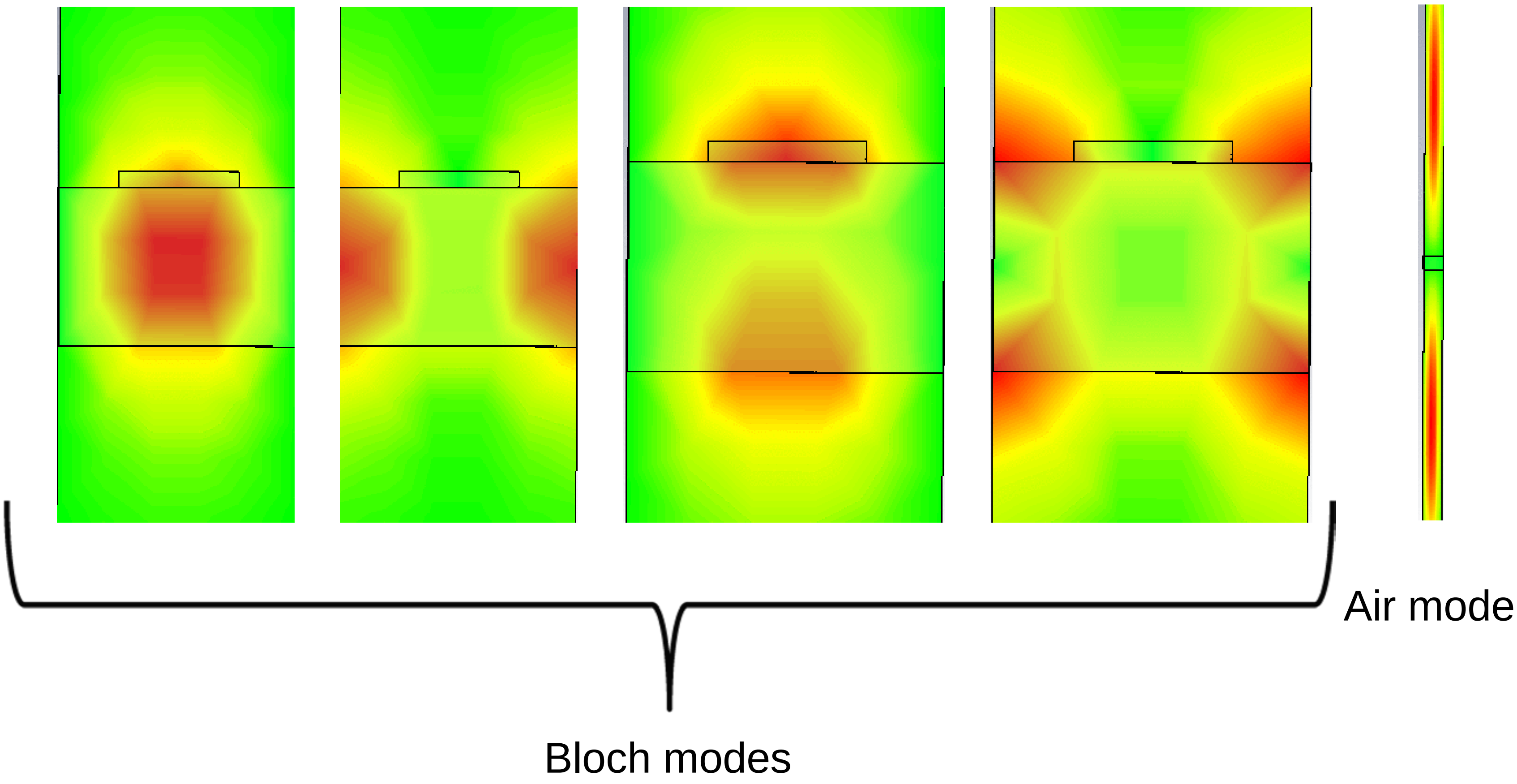


Light trapping: Bloch modes





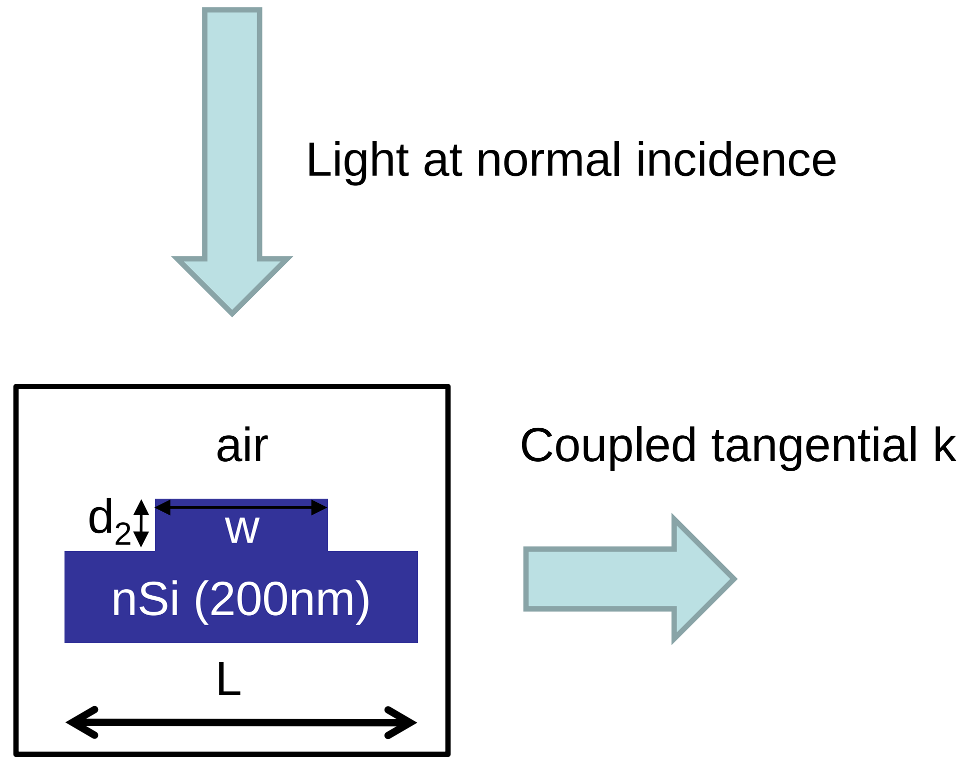
Light trapping: Bloch modes



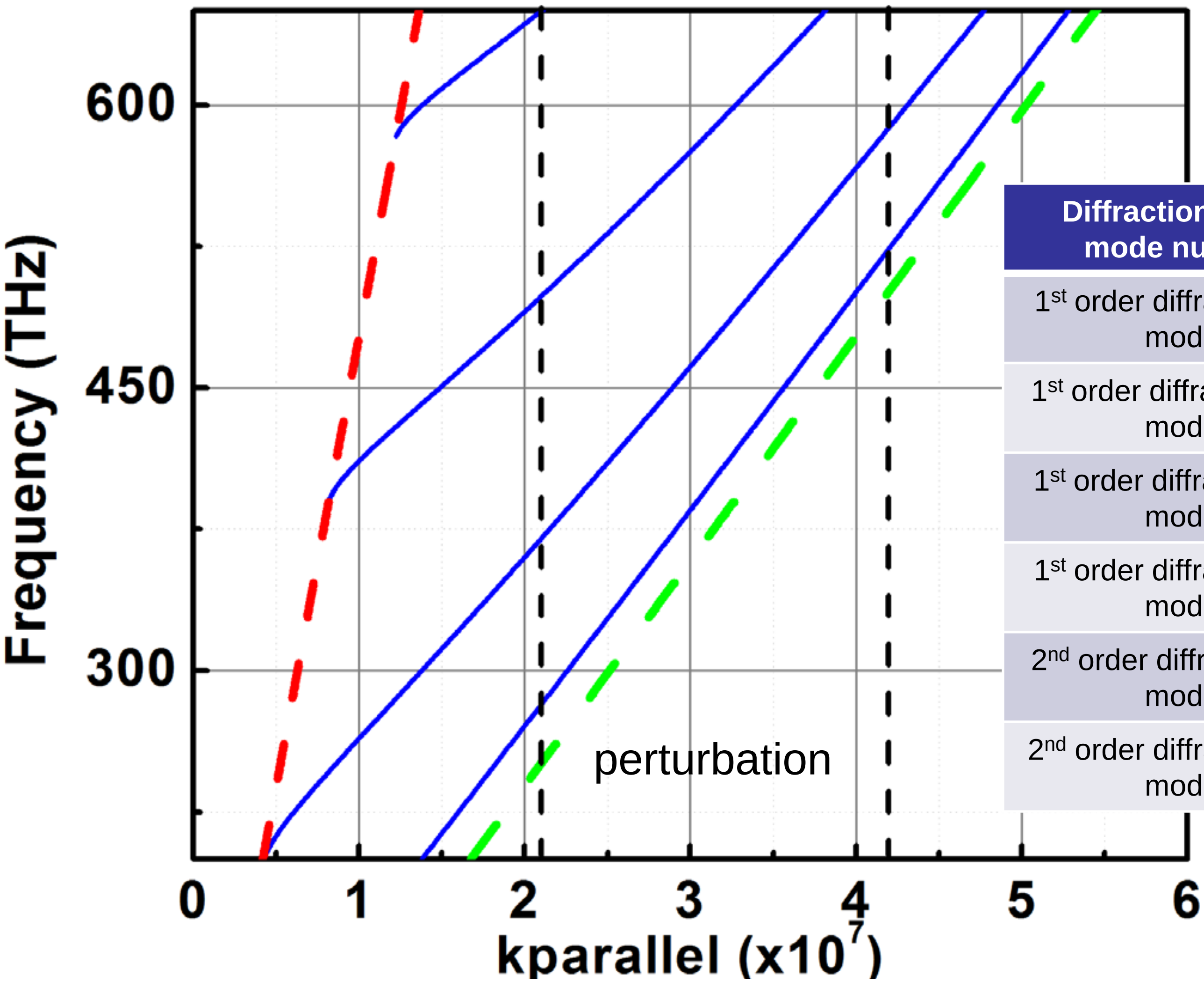
Light trapping: Diffraction aided Waveguiding

$$k_2 \sin\theta = k_1 \sin\varphi + \frac{2\pi m}{L}$$

Outgoing tangential | Incoming tangential | Phase term

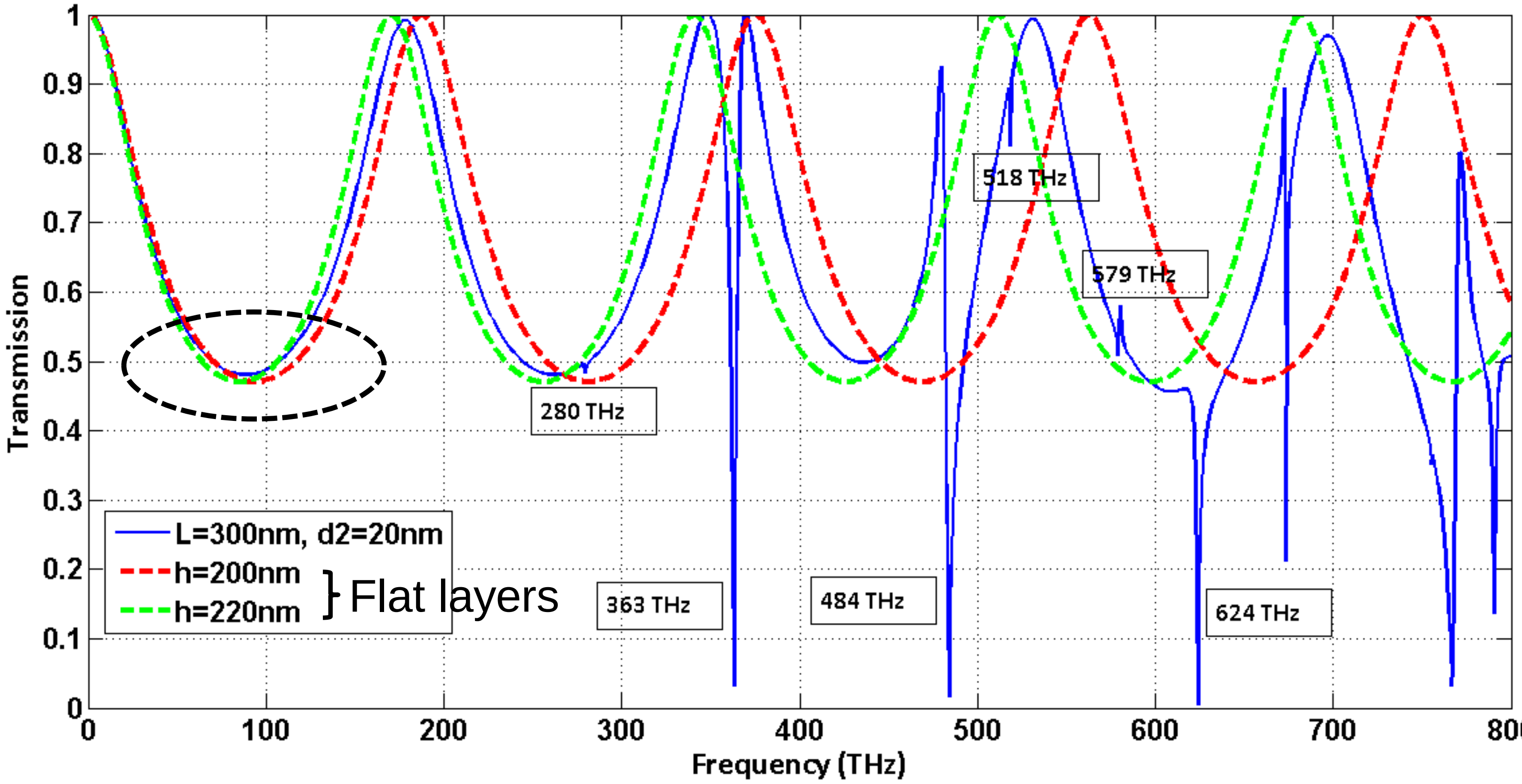


Light trapping: Diffraction aided Waveguiding

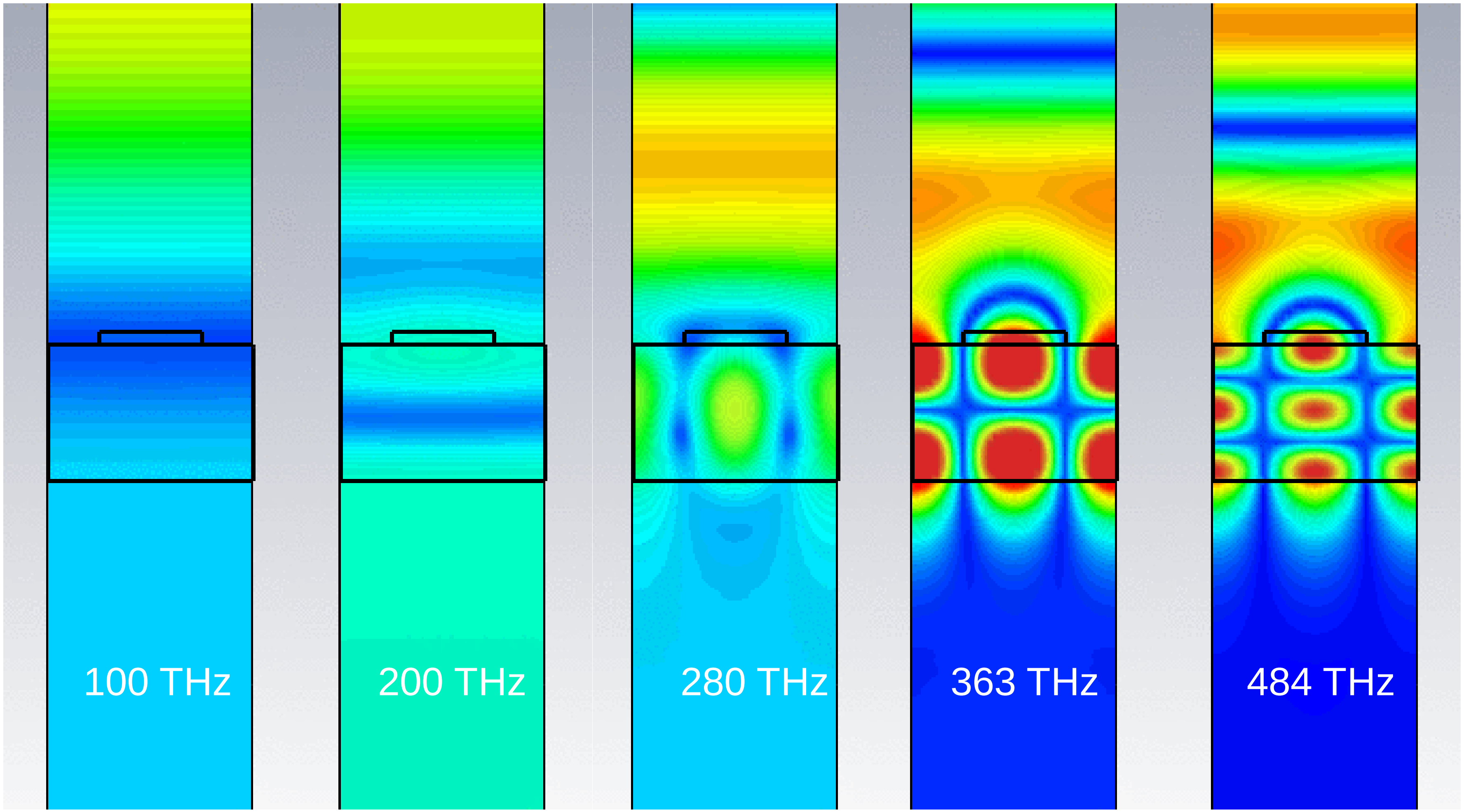


Diffraction order, mode number	Frequency (THz)
1st order diffraction, 1st mode	282
1st order diffraction, 2nd mode	369
1st order diffraction, 3rd mode	496
1st order diffraction, 4th mode	647
2nd order diffraction, 1st mode	524
2nd order diffraction, 2nd mode	587

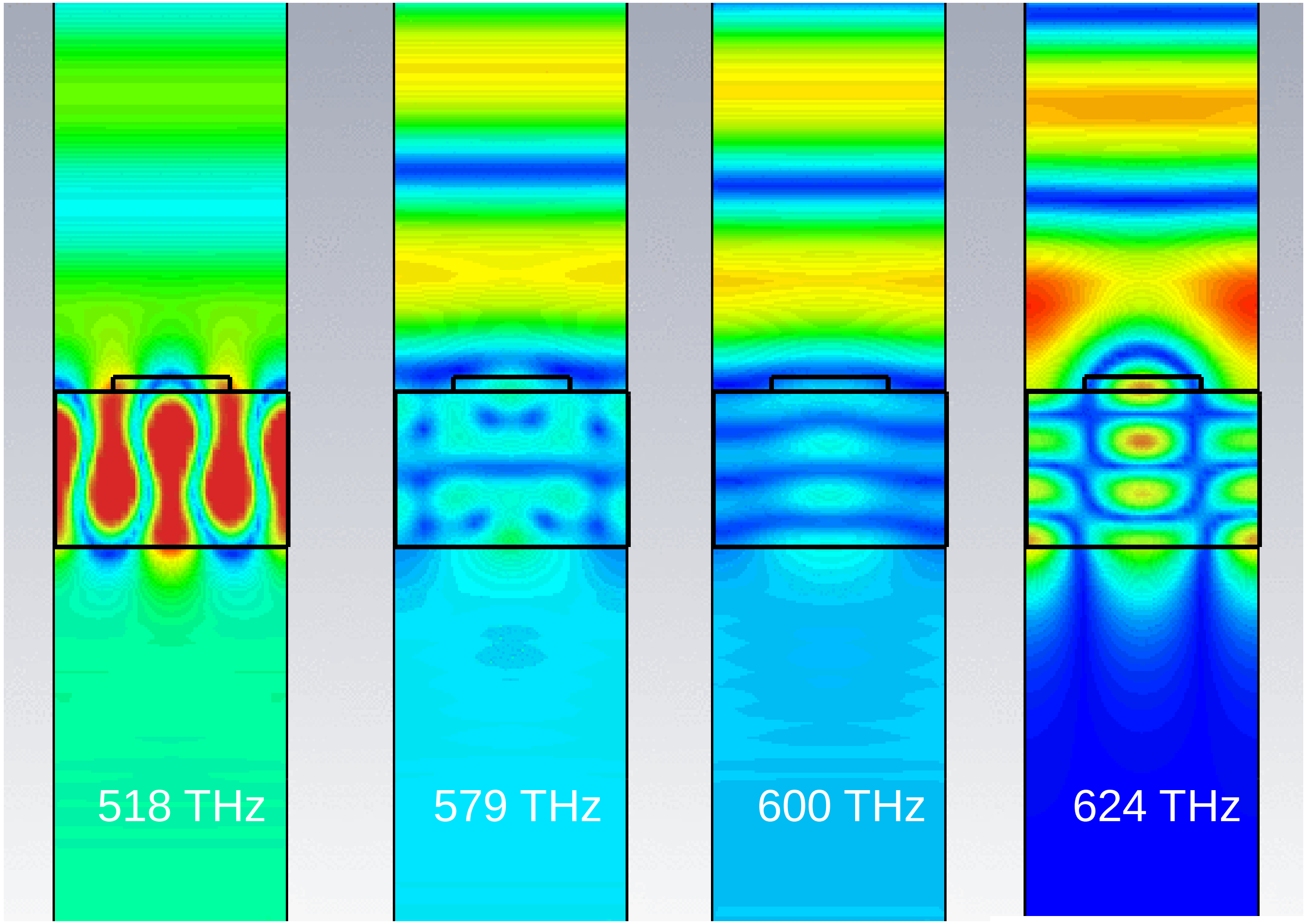
Light trapping: Diffraction aided Waveguiding



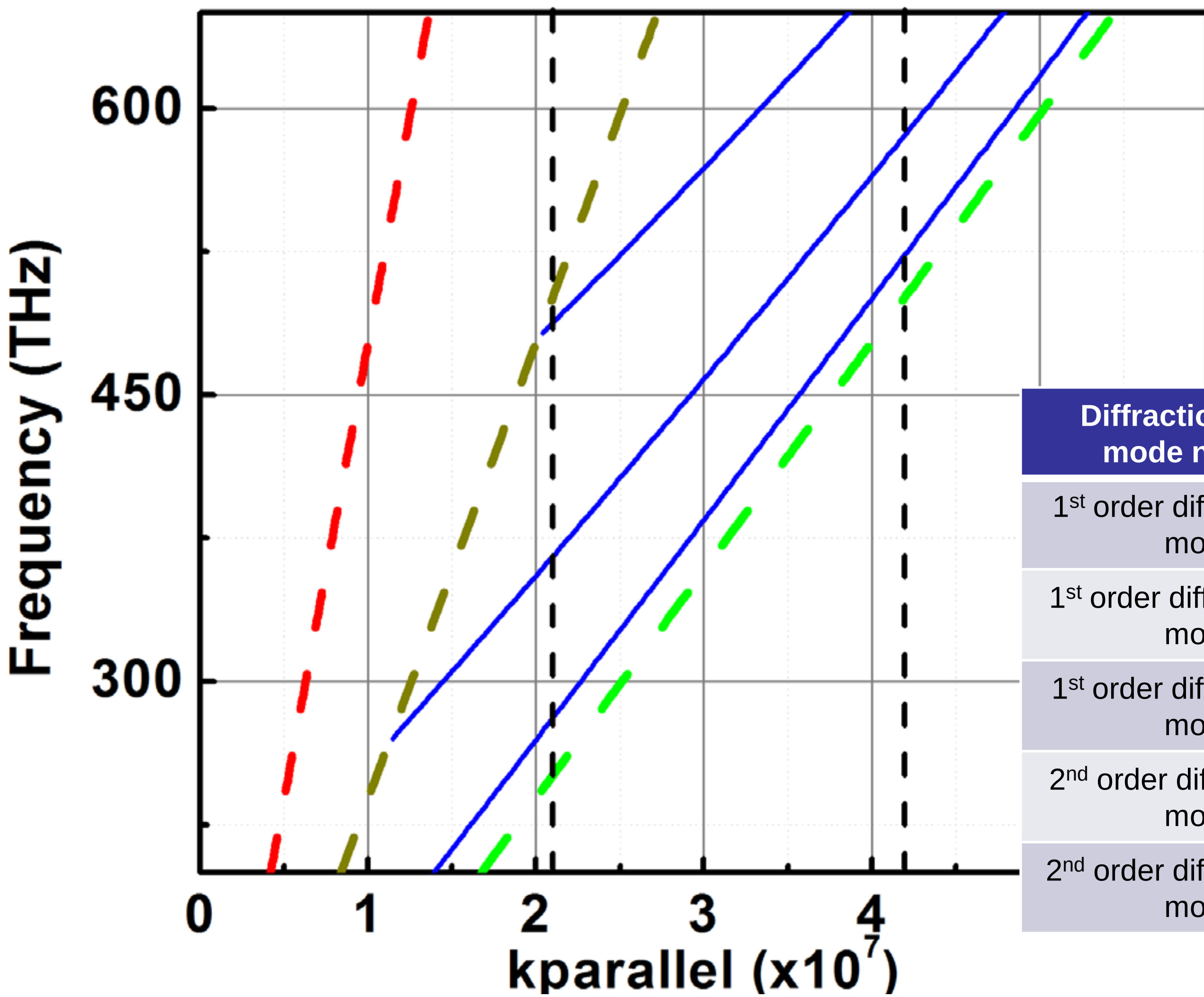
Light trapping: Diffraction aided Waveguiding

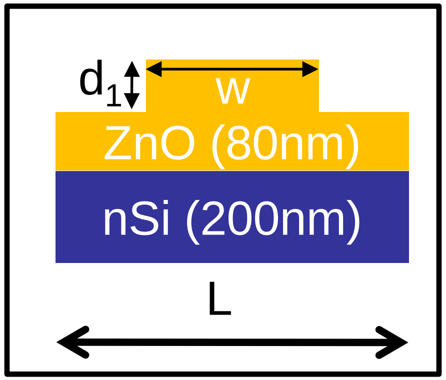


Light trapping: Diffraction aided Waveguiding



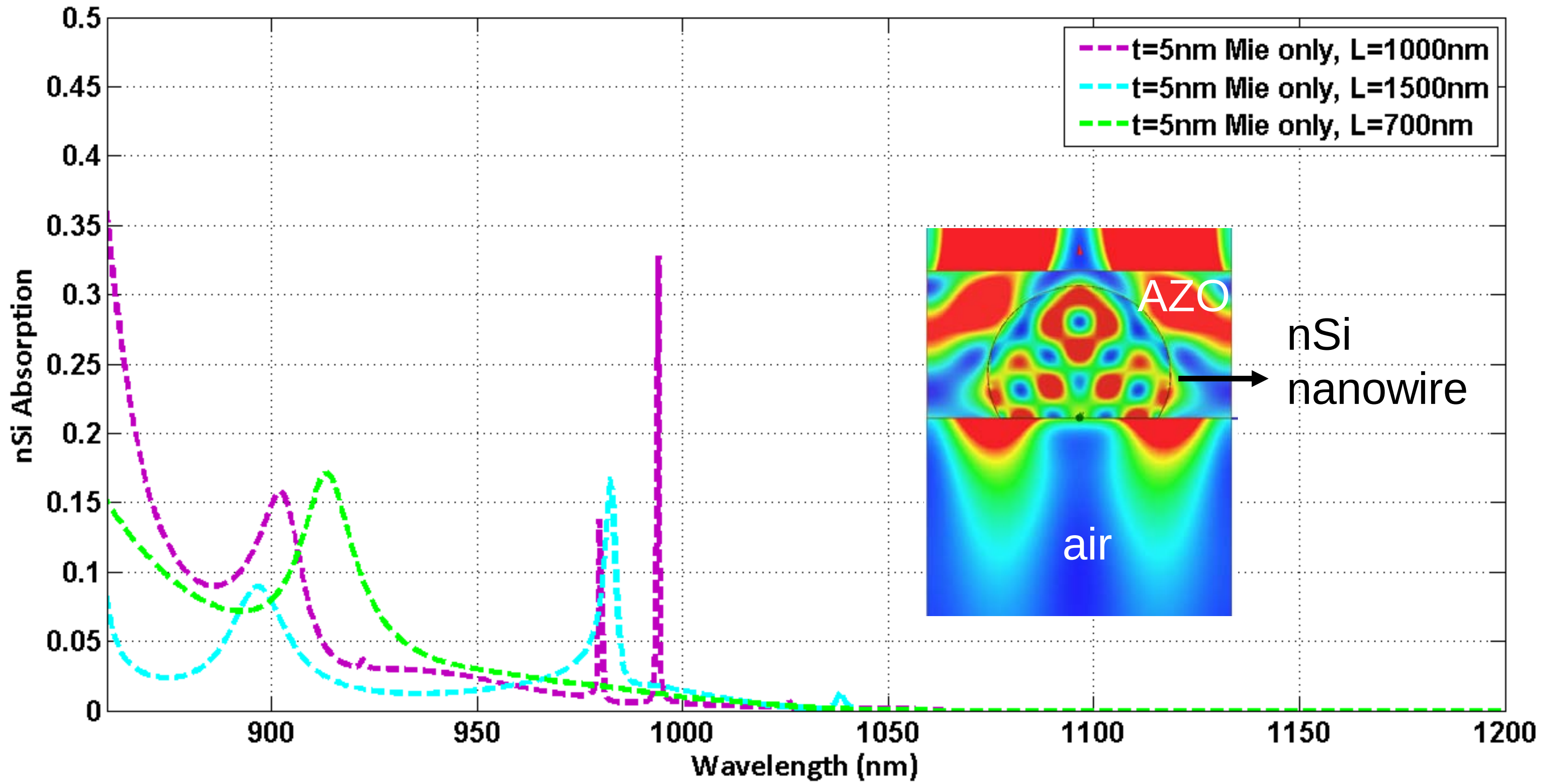
Light trapping: Diffraction aided Waveguiding



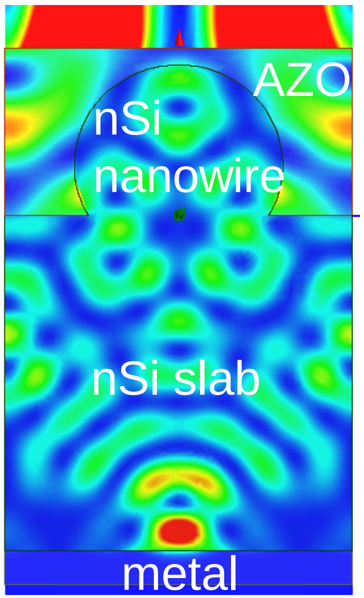


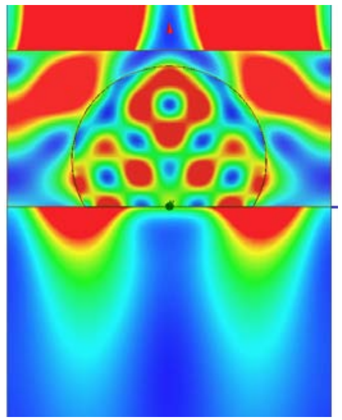
Diffraction order, mode number	Frequency (THz)
1st order diffraction, 1st mode	279
1st order diffraction, 2nd mode	363
1st order diffraction, 3rd mode	485
2nd order diffraction, 1st mode	524
2nd order diffraction, 2nd mode	585

Light trapping: Mie resonances

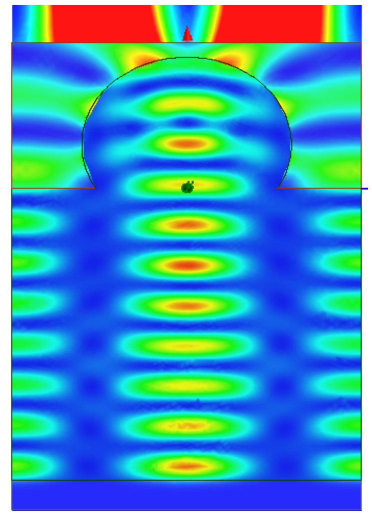


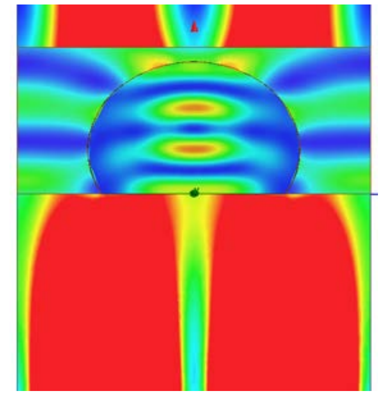
Light trapping: Mie resonances





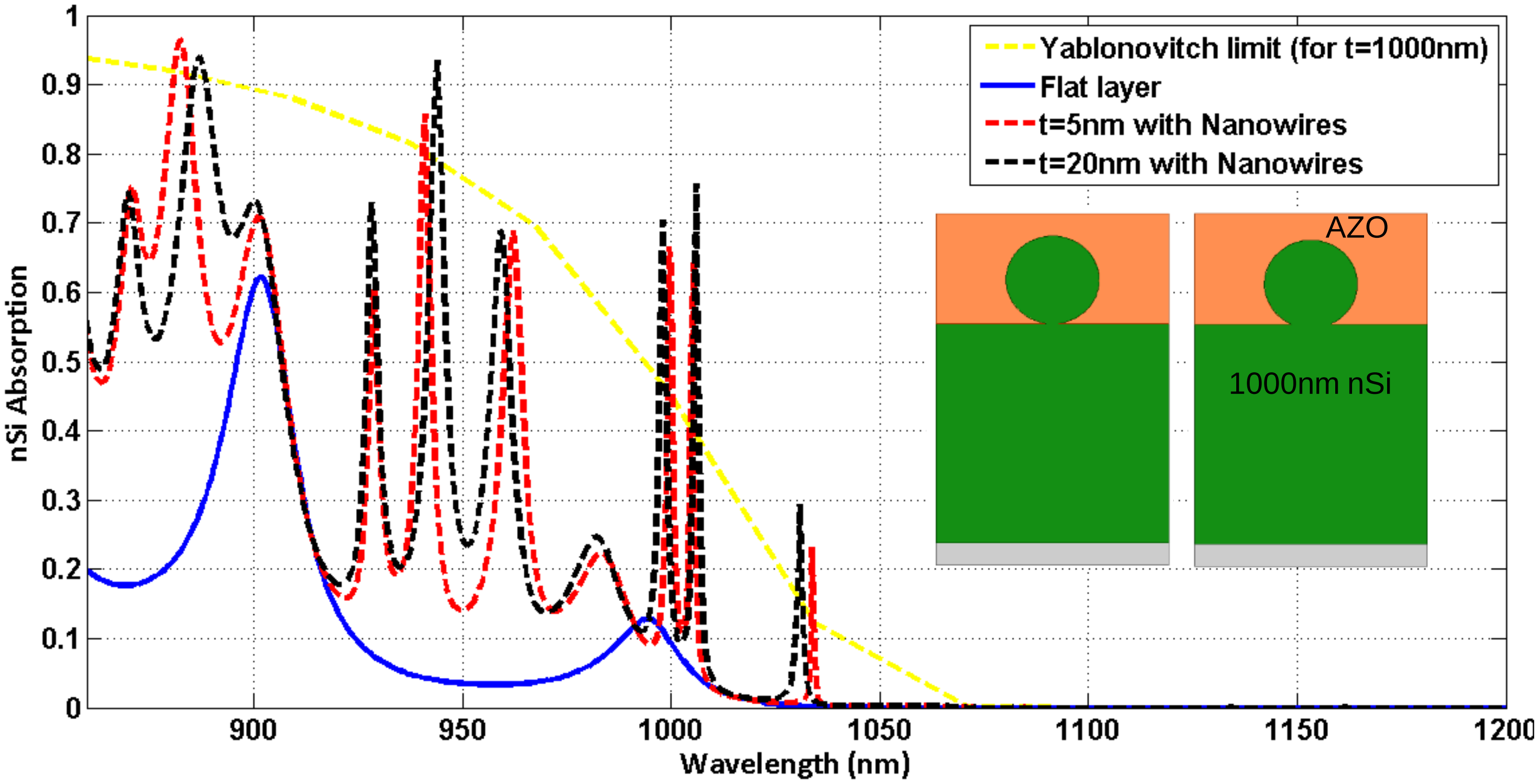
Without slab



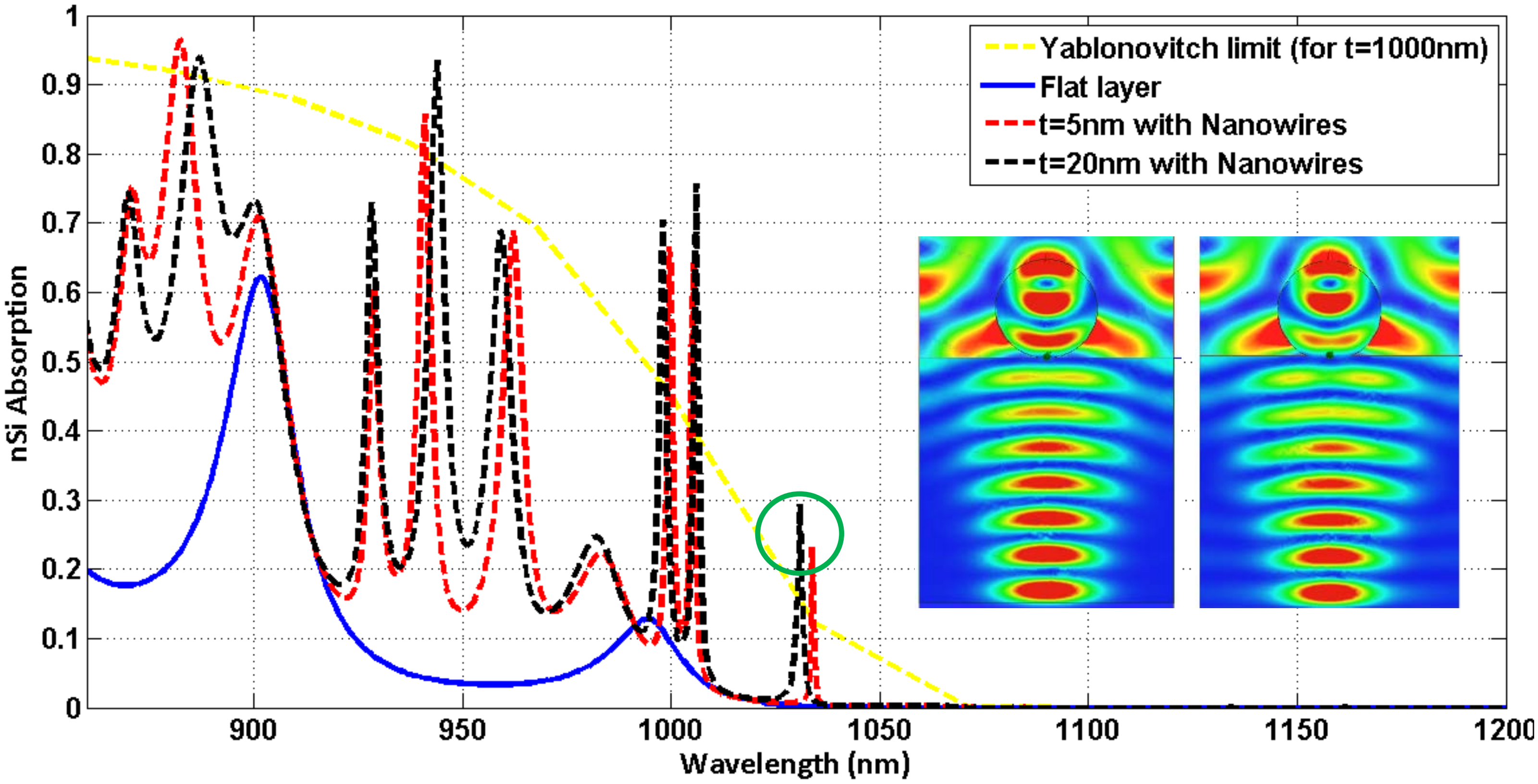


Without slab

Light trapping: Hybridization

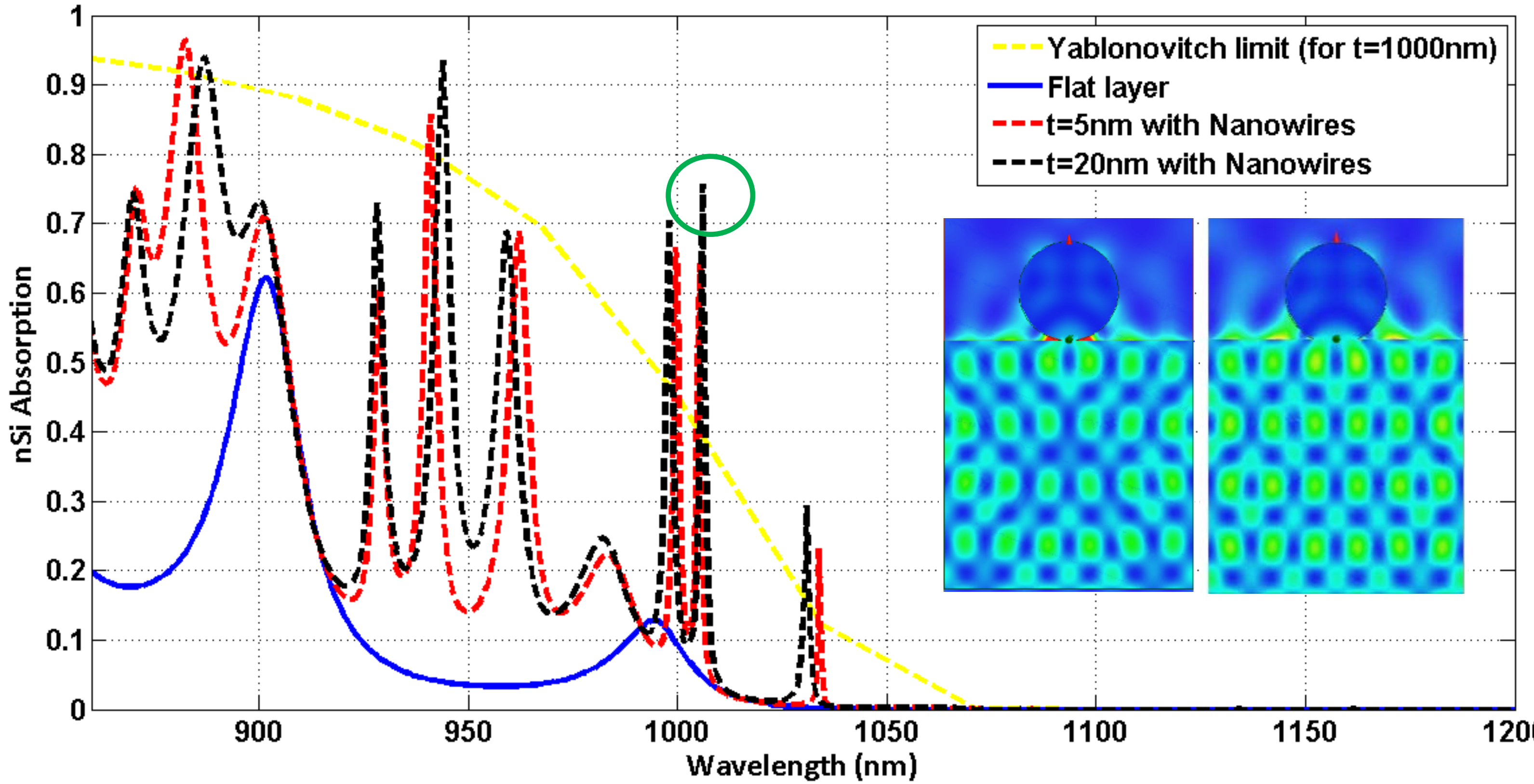


Light trapping: Hybridization



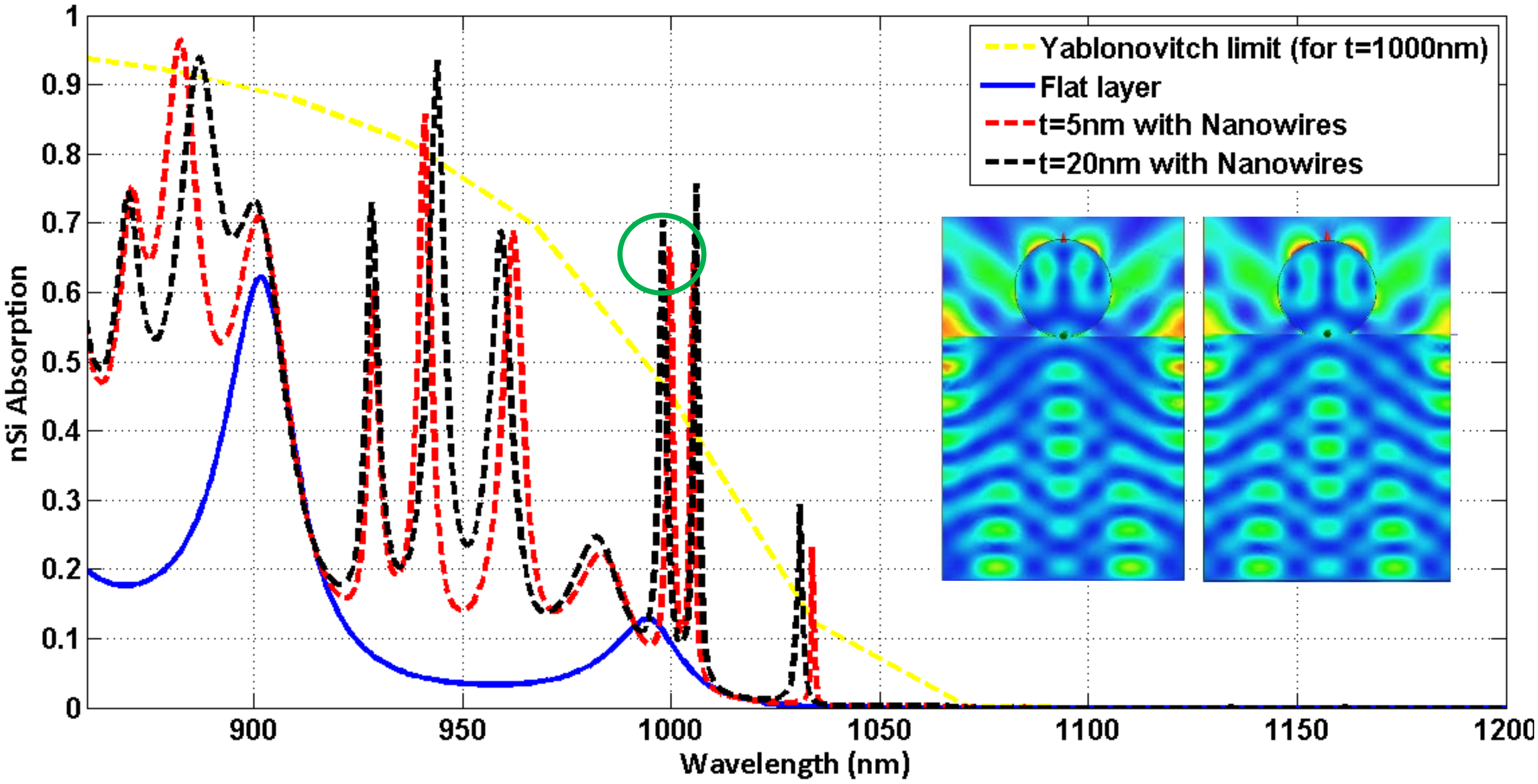
Mie/Bloch wave Hybridization

Light trapping: Hybridization



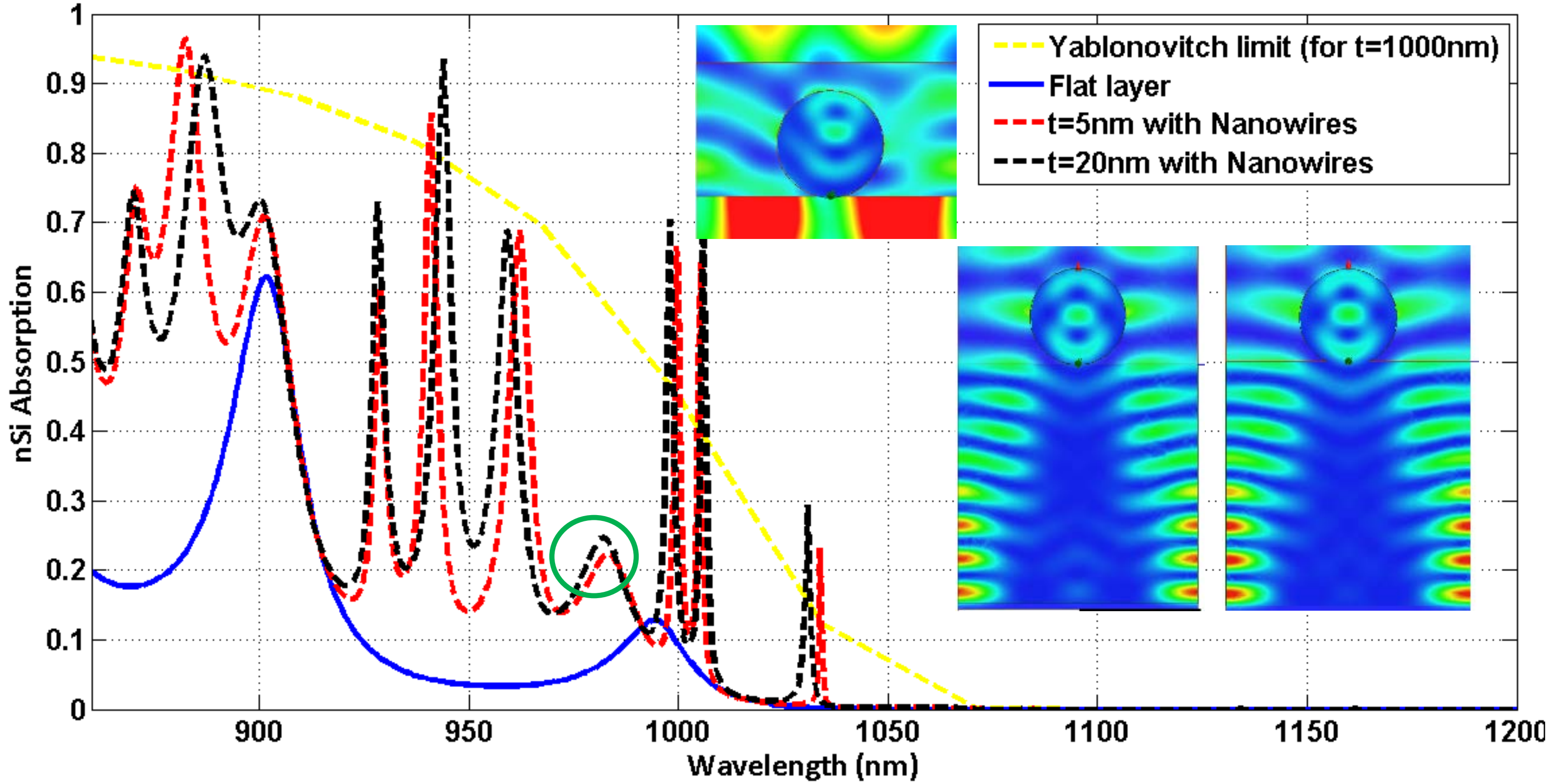
Waveguiding

Light trapping: Hybridization



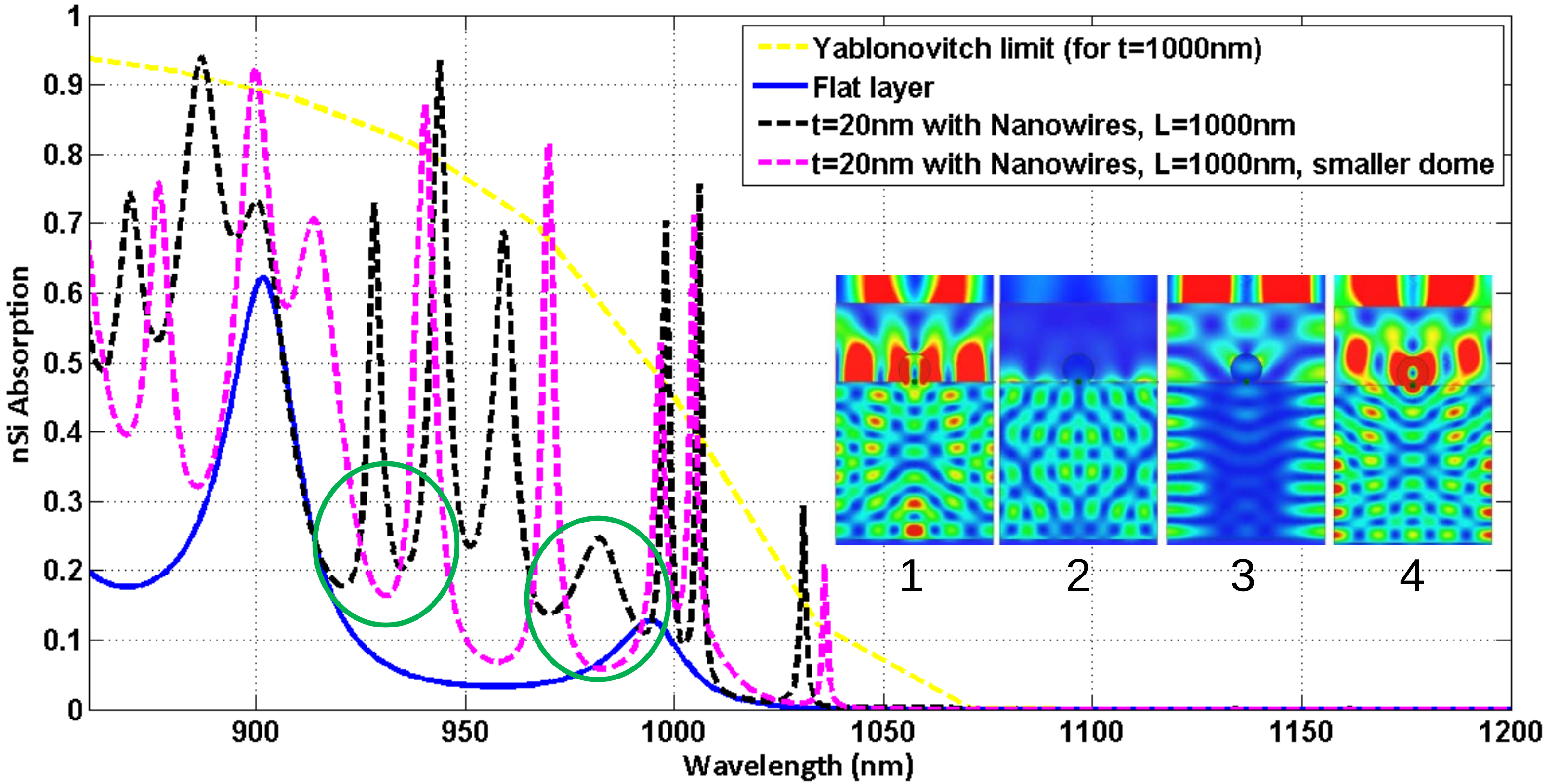
Mie/Bloch wave Hybridization

Light trapping: Hybridization



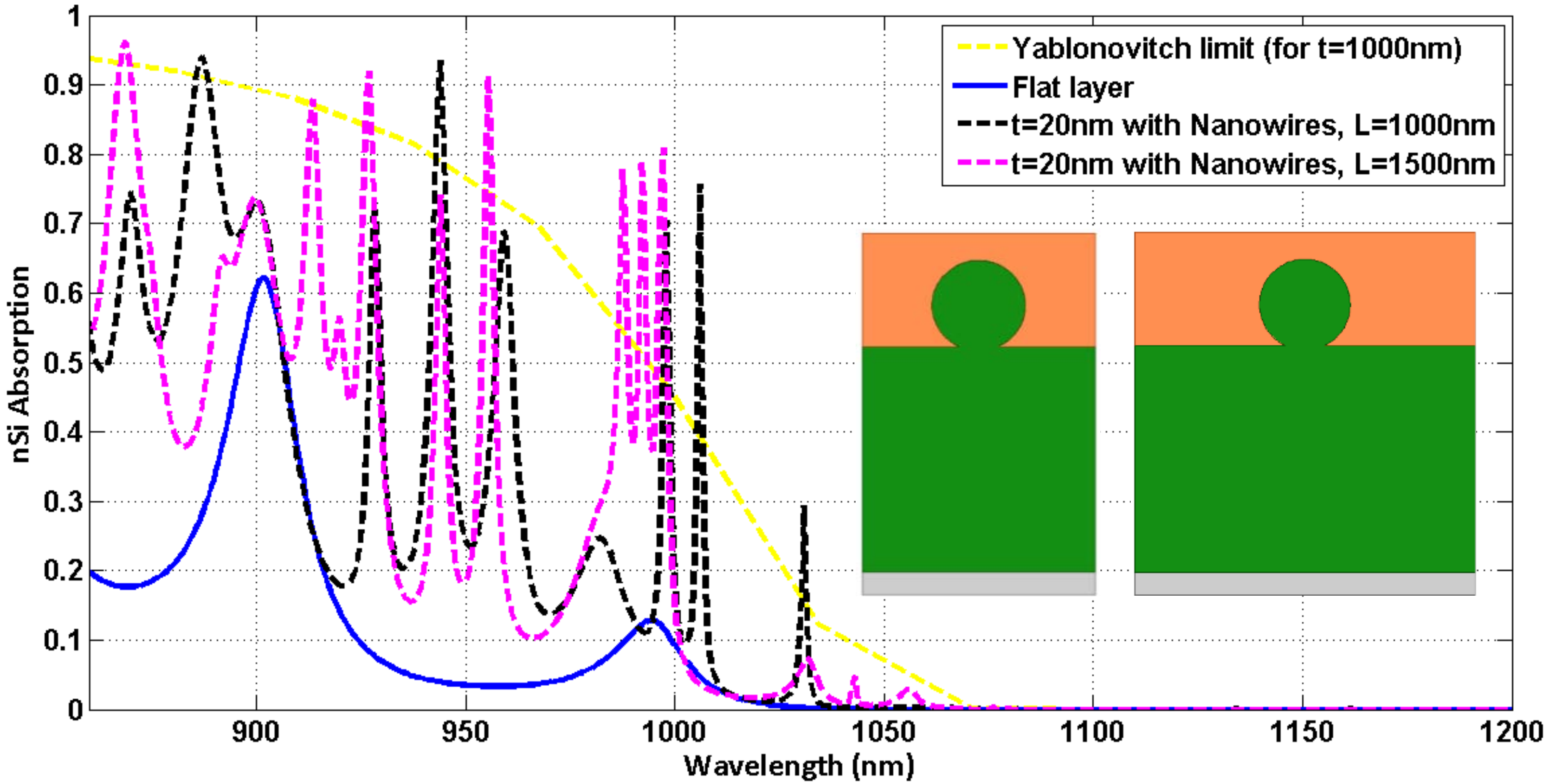
Mie Hybridization

Light trapping: Hybridization



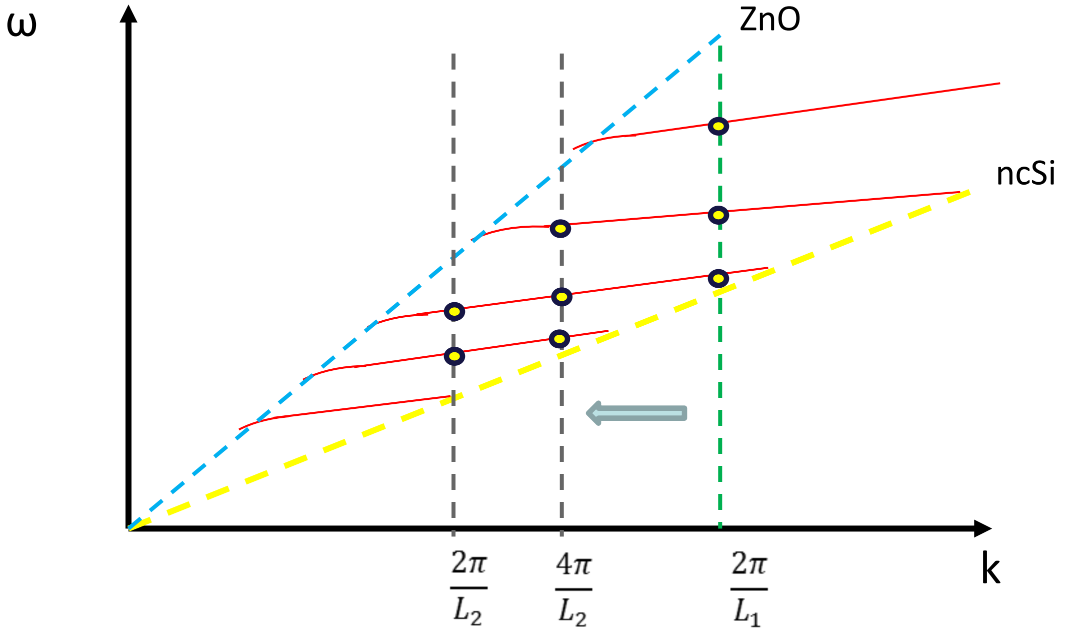
Smaller nanowire/dome

Light trapping: Hybridization



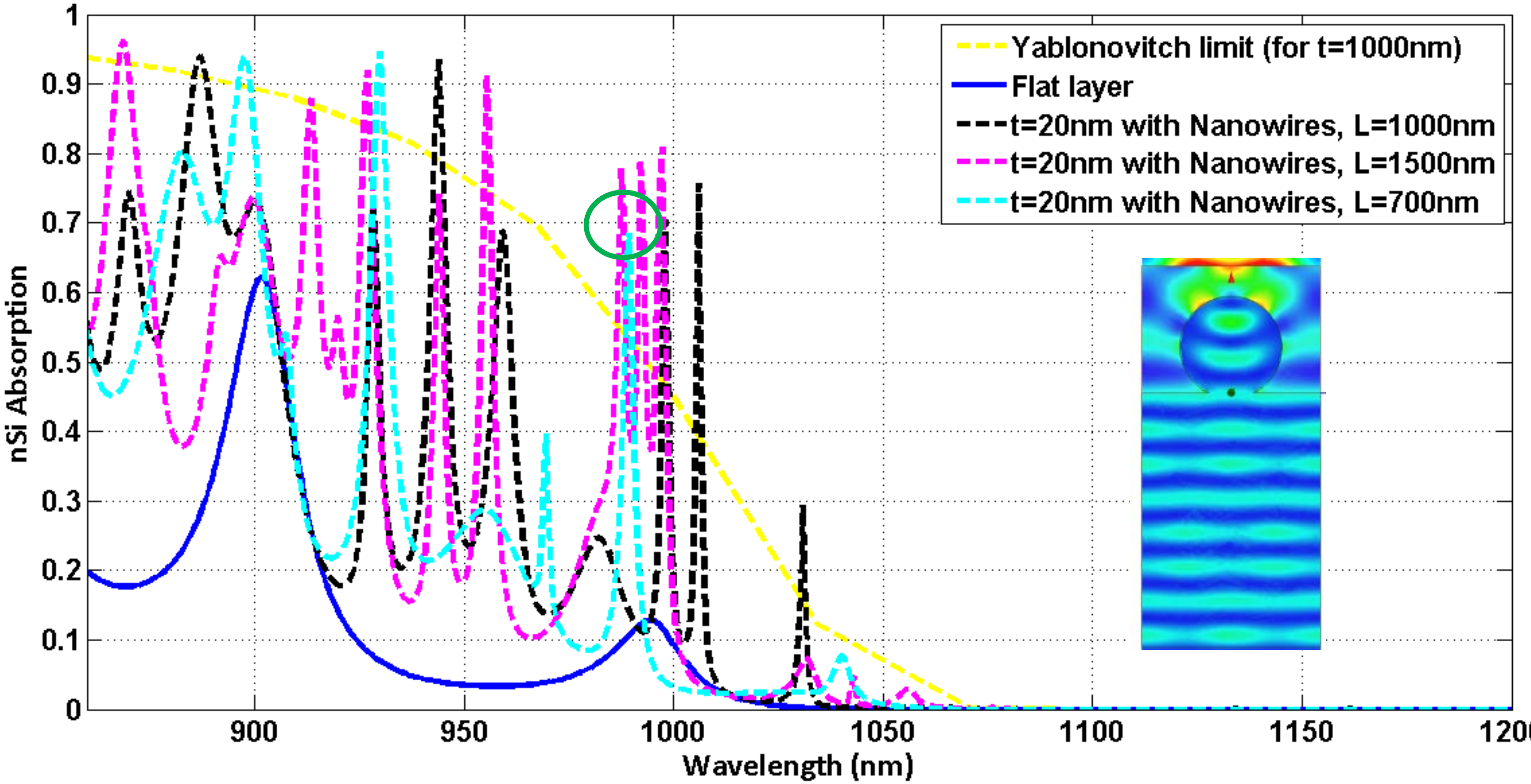
Longer L

Light trapping: Hybridization



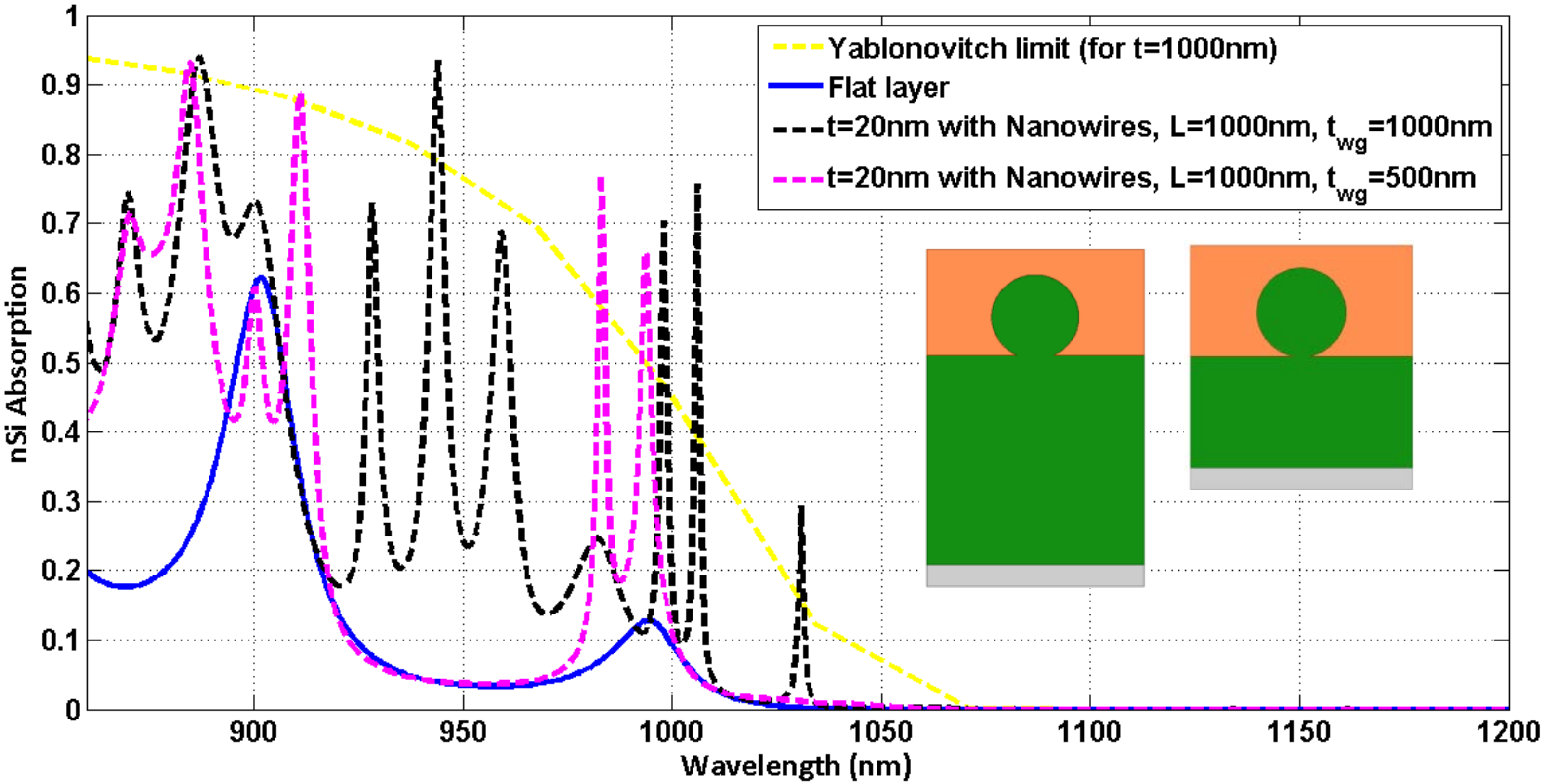
The effect of L spacing

Light trapping: Hybridization



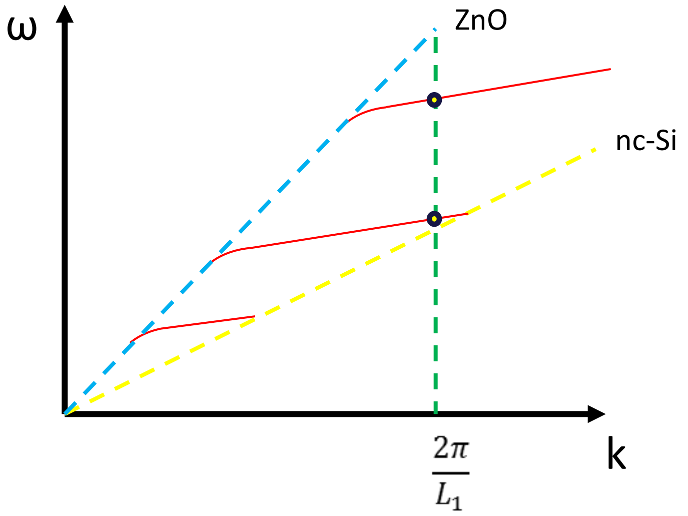
Shorter L

Light trapping: Hybridization



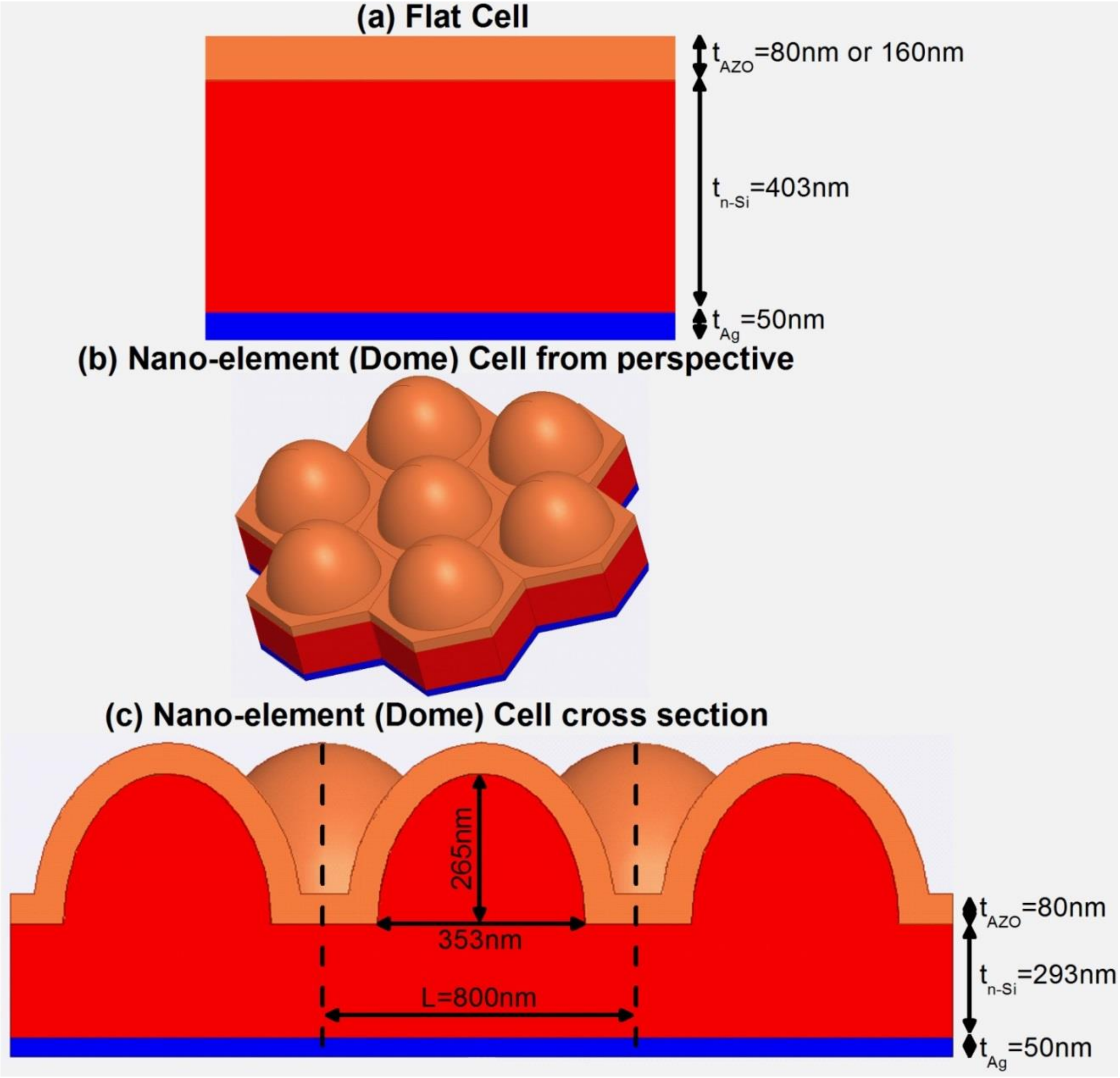
Waveguide thickness

Light trapping: Hybridization

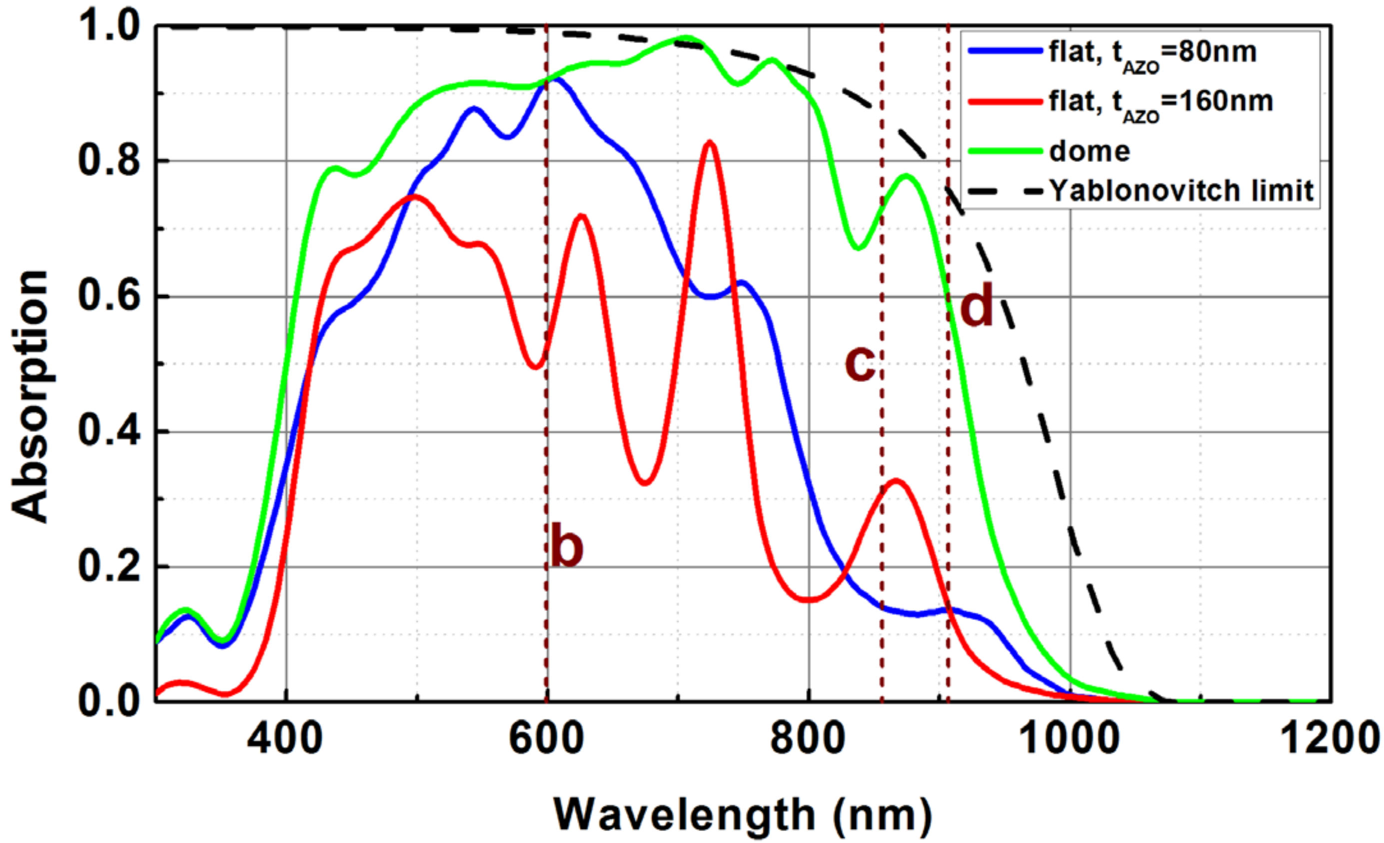


The effect of waveguide thickness

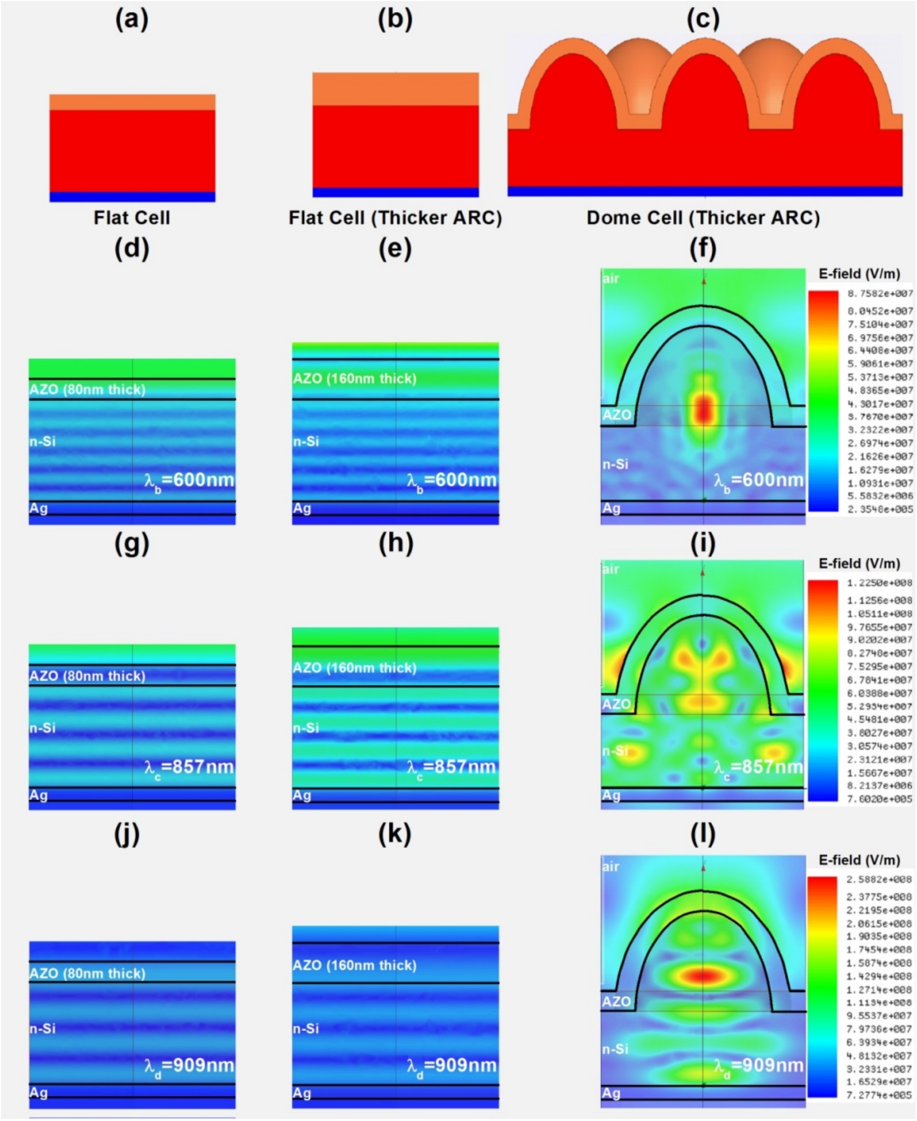
Light trapping: Hybridization



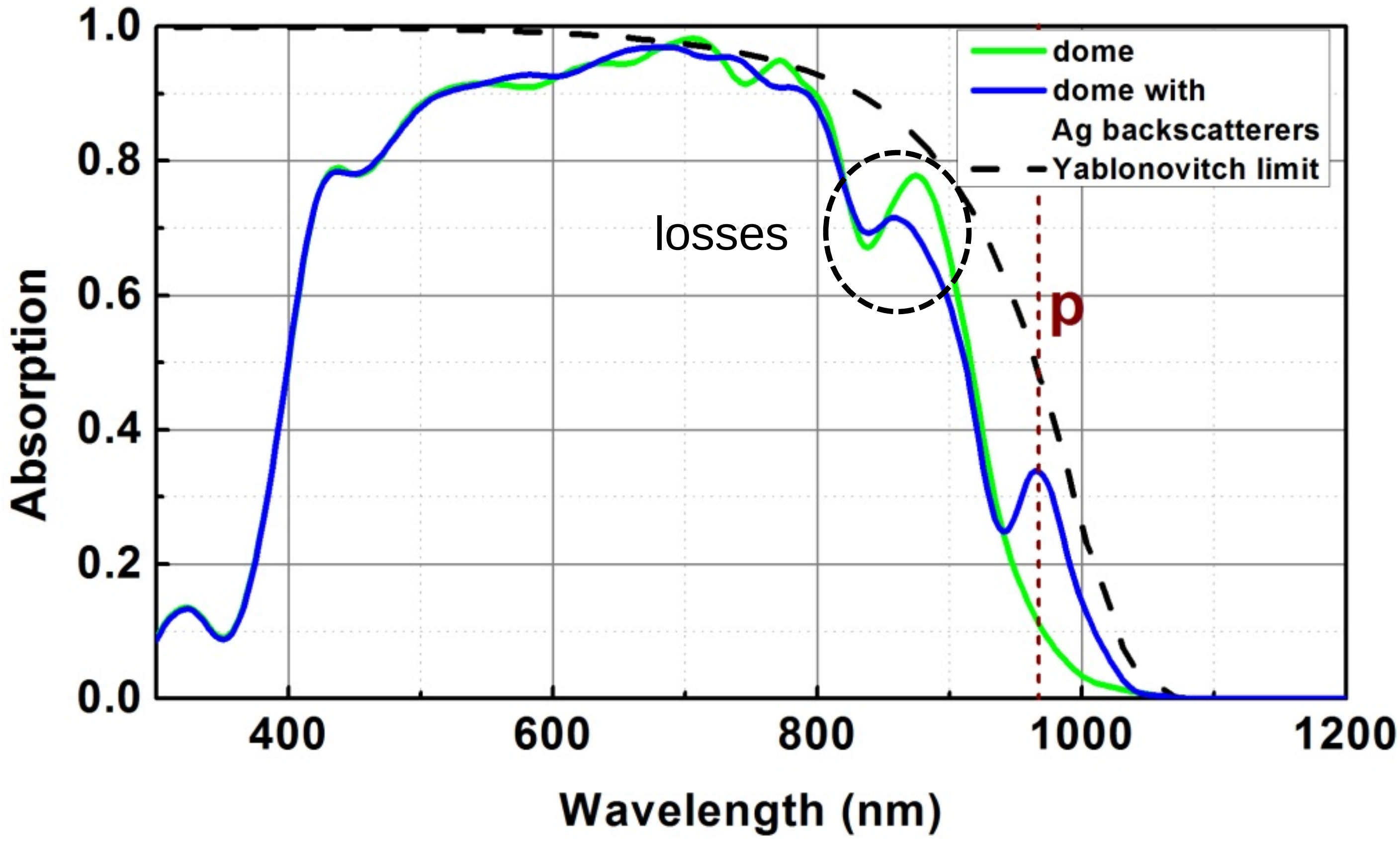
Light trapping: Hybridization



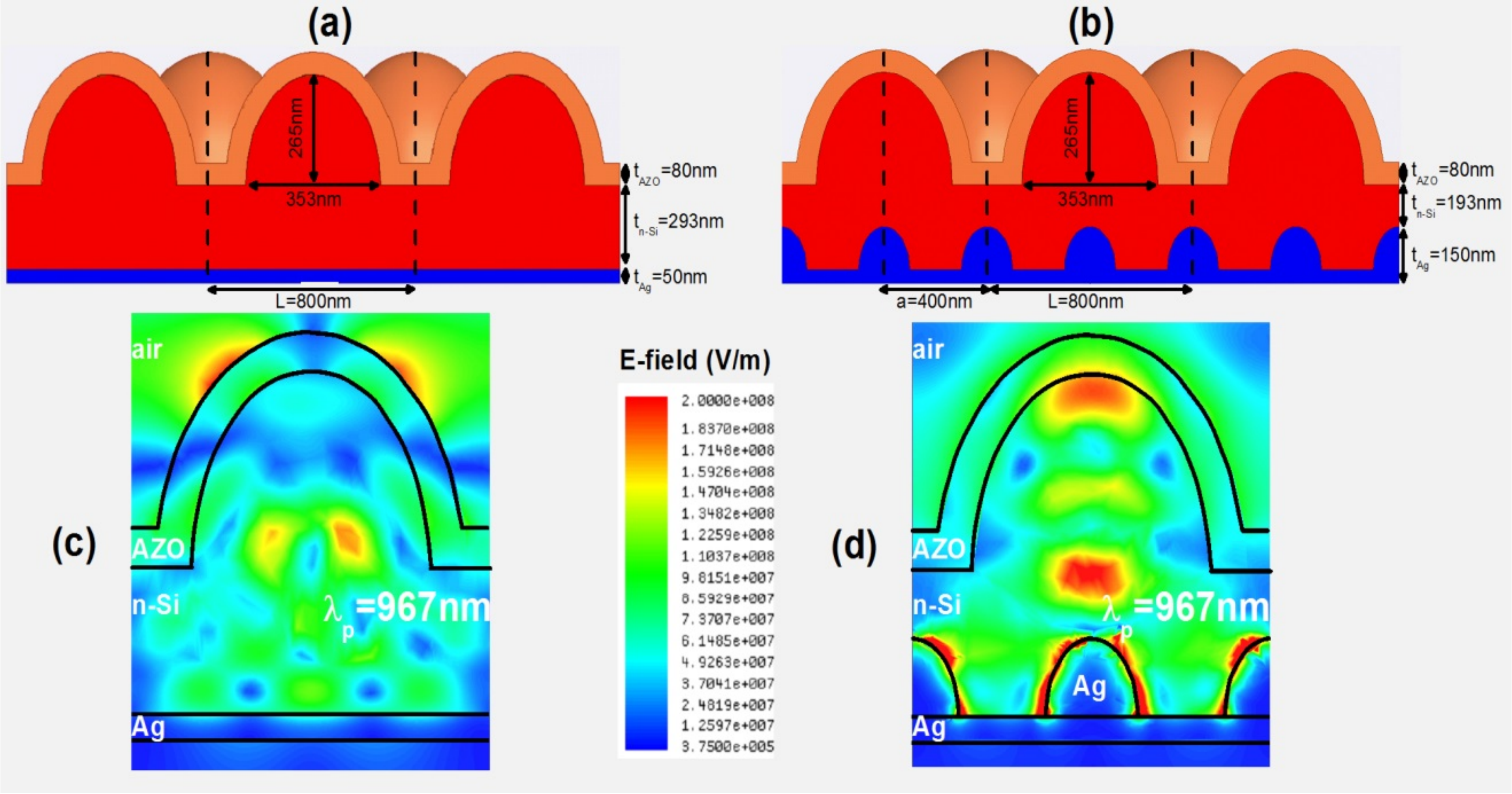
Light trapping: Hybridization



Light trapping: Plasmonics



Light trapping: Plasmonics



Examples: Mie Resonances

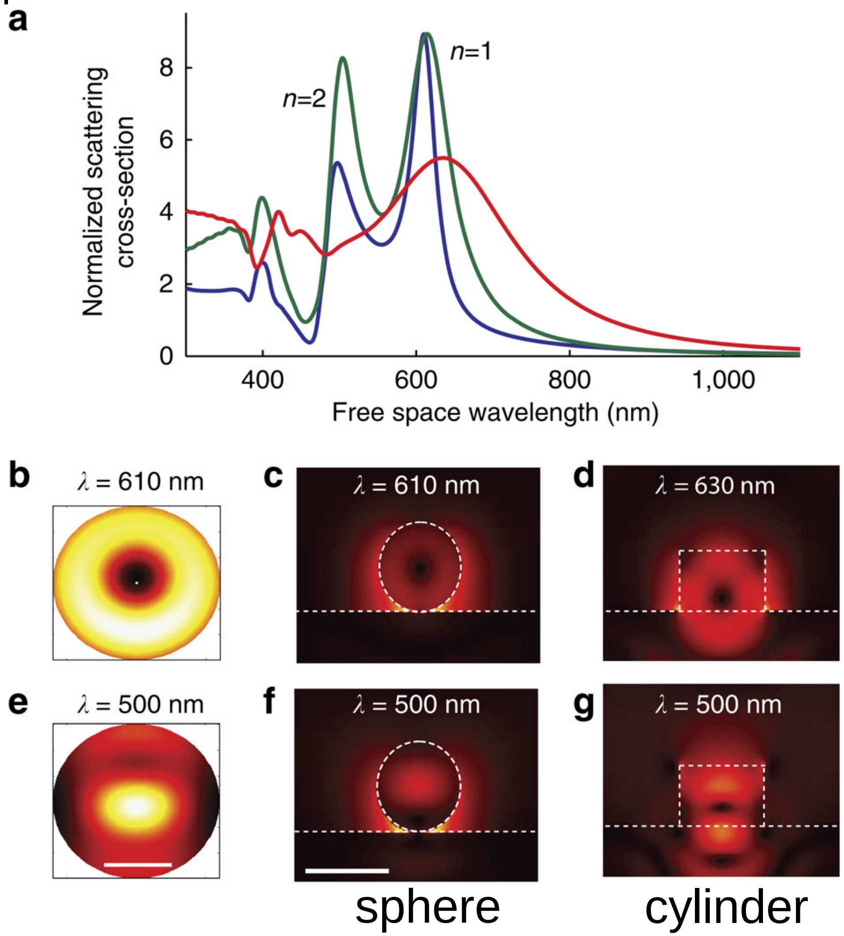
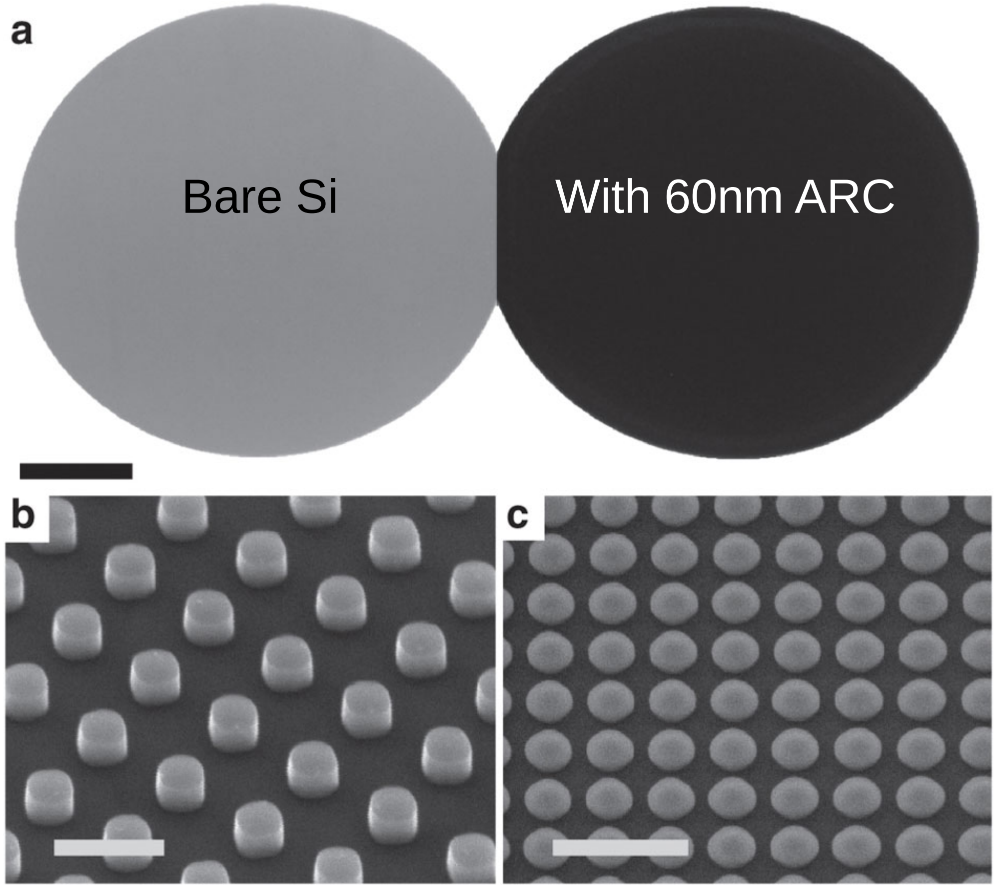


Fig. 2

Introduction of a leaky channel into the substrate

Fig. 2: “Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators” P. Spinelli, M. A. Verschuuren, A. Polman, Nature Comm. 3, 692 (2012).

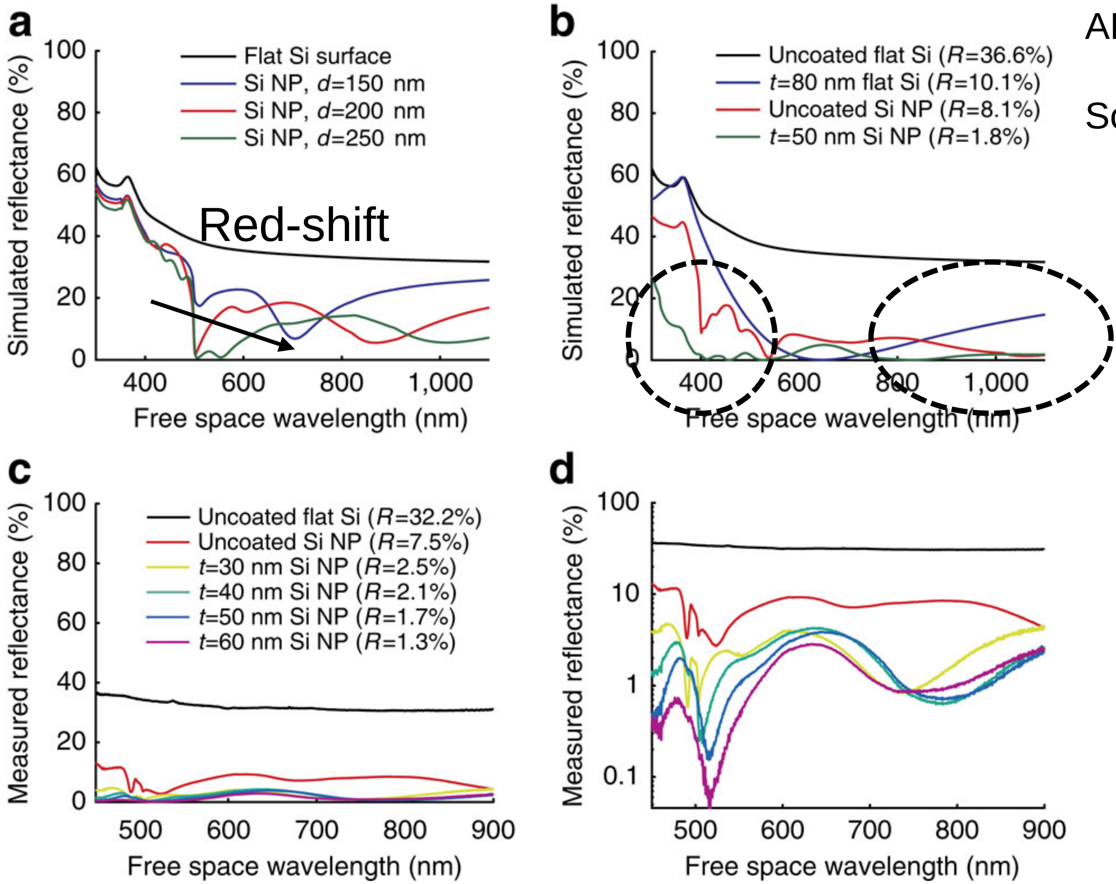
Examples: Mie Resonances



from 40º   Fig. 3

Fig. 3: “Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators” P. Spinelli, M. A. Verschuuren, A. Polman, Nature Comm. 3, 692 (2012).

Examples: Mie Resonances



ARC tuned for UV-blue

Scattering after 800nm

Fig. 4

Fig. 4: “Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators” P. Spinelli, M. A. Verschuuren, A. Polman, Nature Comm. 3, 692 (2012).

Examples: Hybridization

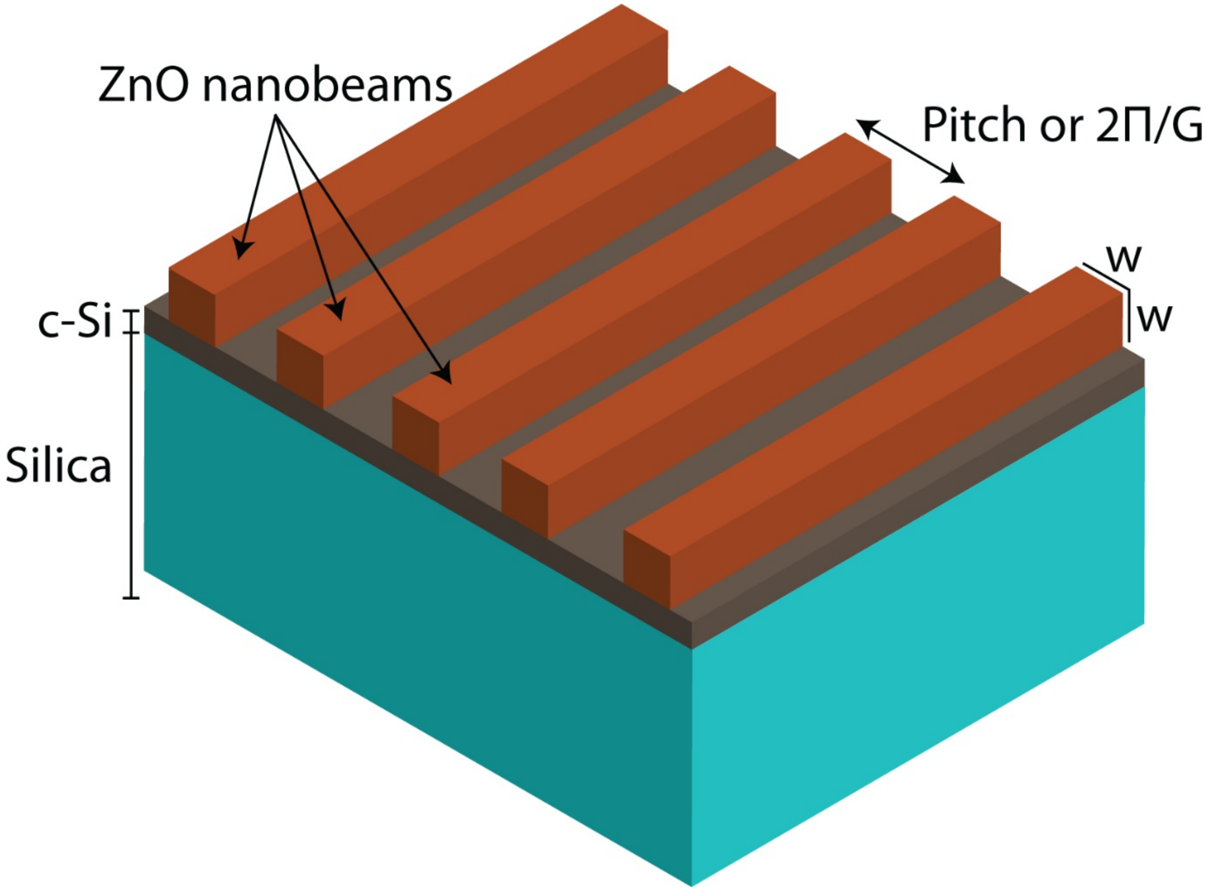


Fig. 5

Fig. 5: “Nanophotonics light trapping with patterned transparent conductive oxides” A. P. Vasudev, J. A. Schuller, M. L. Brongersma Optics Express 10, A385-A394 (2012).

Examples: Hybridization

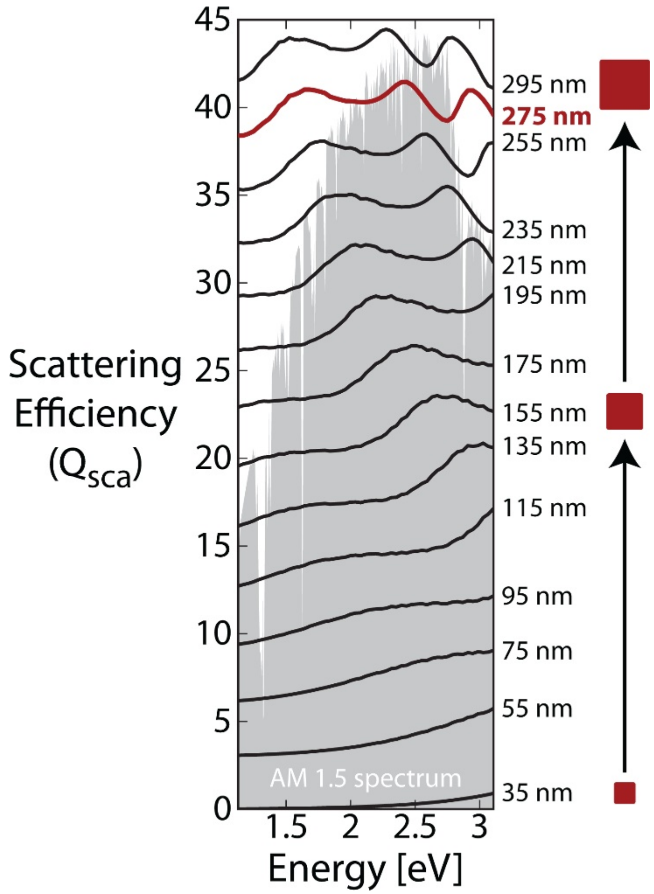


Fig. 6

Fig. 6: "Nanophotonics light trapping with patterned transparent conductive oxides" A. P. Vasudev, J. A. Schuller, M. L. Brongersma Optics Express 10, A385-A394 (2012).

Examples: Hybridization

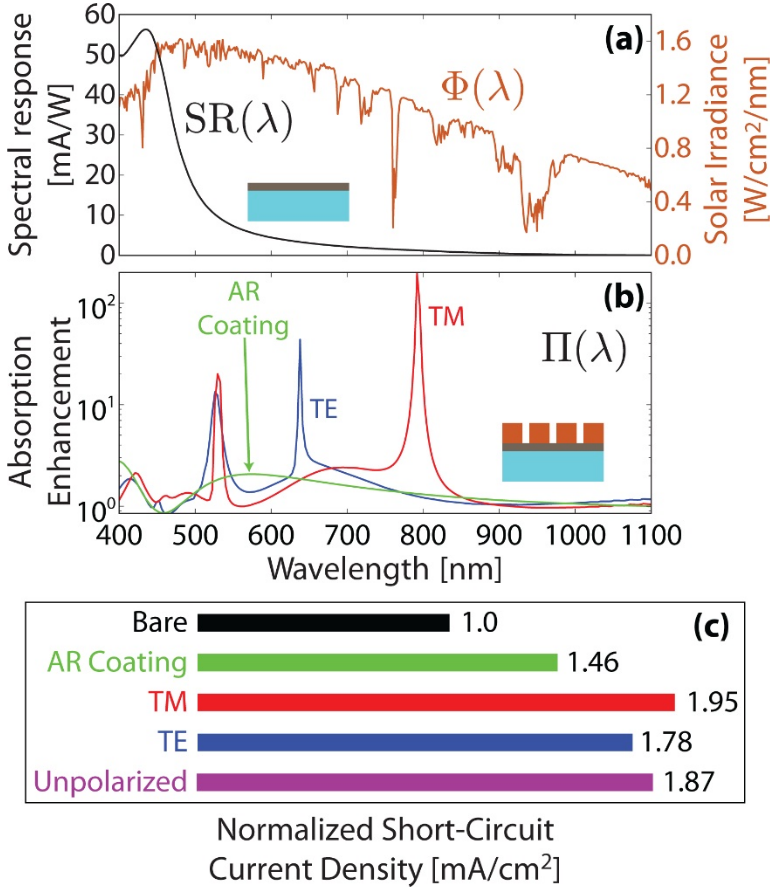


Fig. 7

Fig. 7: “Nanophotonics light trapping with patterned transparent conductive oxides” A. P. Vasudev, J. A. Schuller, M. L. Brongersma Optics Express 10, A385-A394 (2012).

Examples: Hybridization

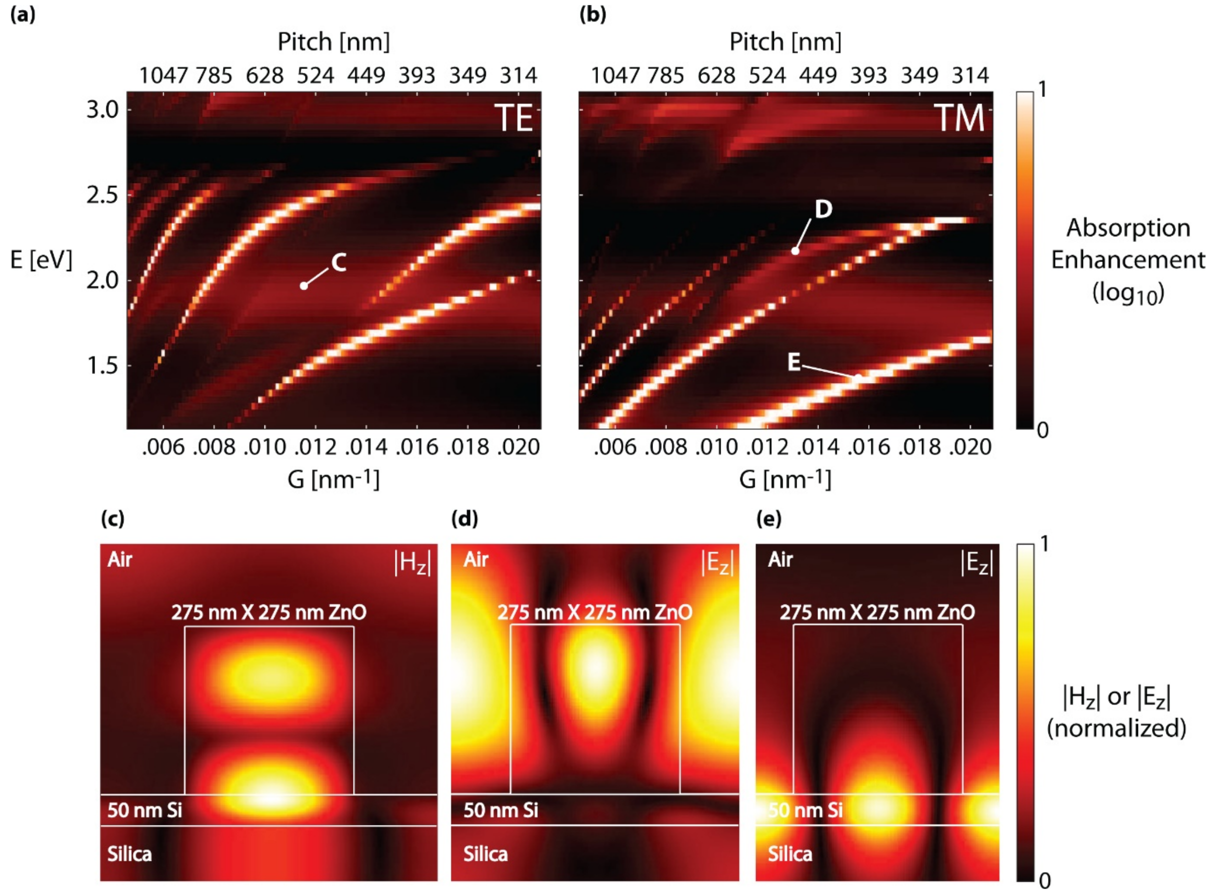


Fig. 8

Fig. 8: “Nanophotonics light trapping with patterned transparent conductive oxides” A. P. Vasudev, J. A. Schuller, M. L. Brongersma Optics Express 10, A385-A394 (2012).

Examples: Plasmonics

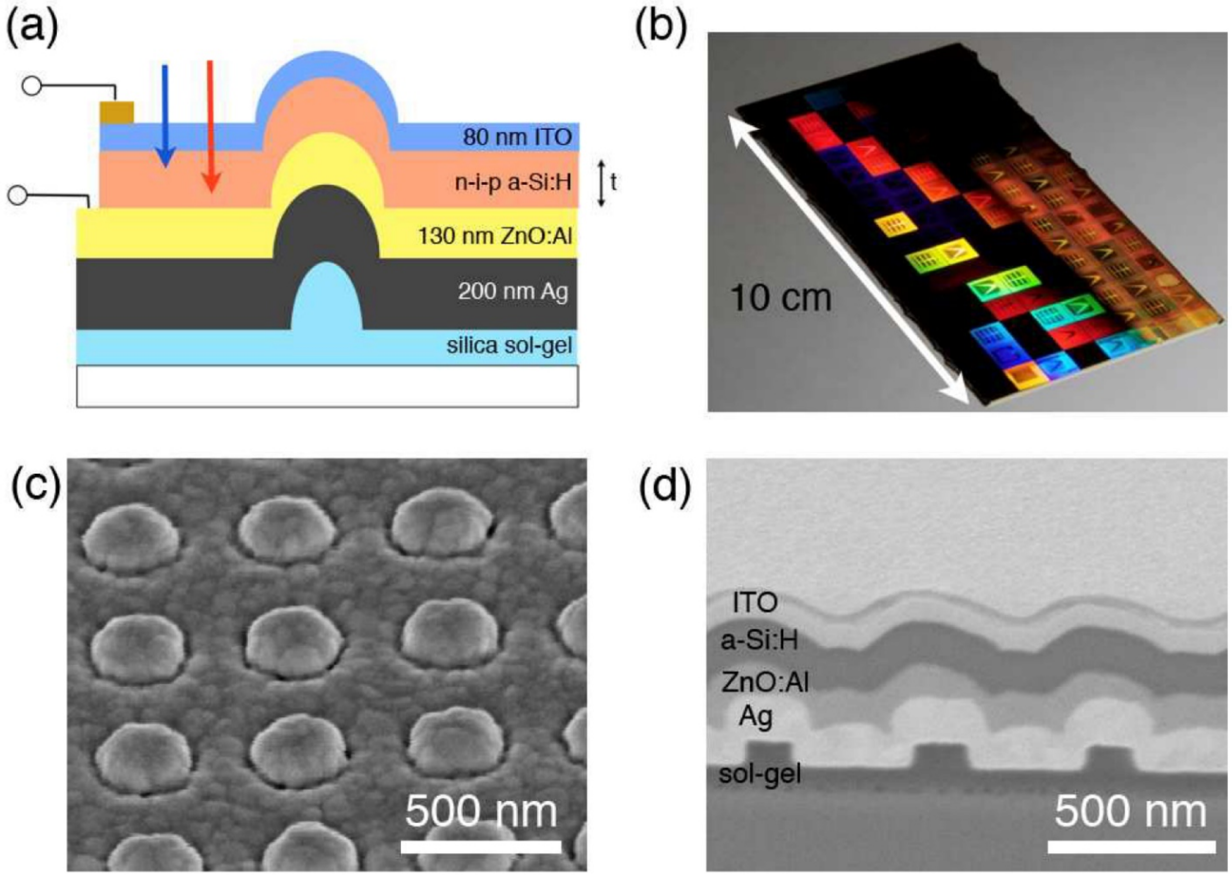


Fig. 9

Fig. 9: “Light trapping in ultrathin plasmonic solar cells” V. E. Ferry, M. A. Verschuuren, H. B. T. Li, E. Verhagen, R. J. Walters, R. E. I. Schropp, H. A. Atwater, A. Polman Optics Express 18, A237-A245 (2010).

Examples: Plasmonics

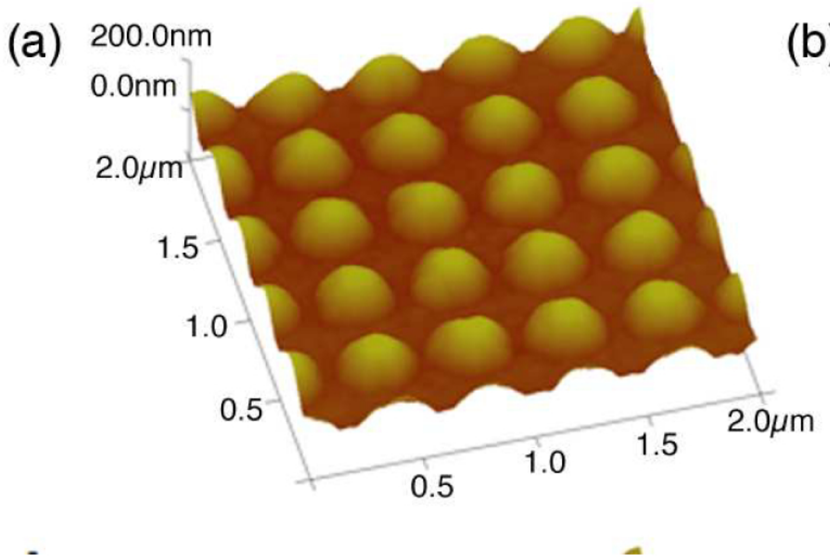


Fig. 10

Fig. 10: “Light trapping in ultrathin plasmonic solar cells” V. E. Ferry, M. A. Verschuuren, H. B. T. Li, E. Verhagen, R. J. Walters, R. E. I. Schropp, H. A. Atwater, A. Polman Optics Express 18, A237-A245 (2010).

Examples: Plasmonics

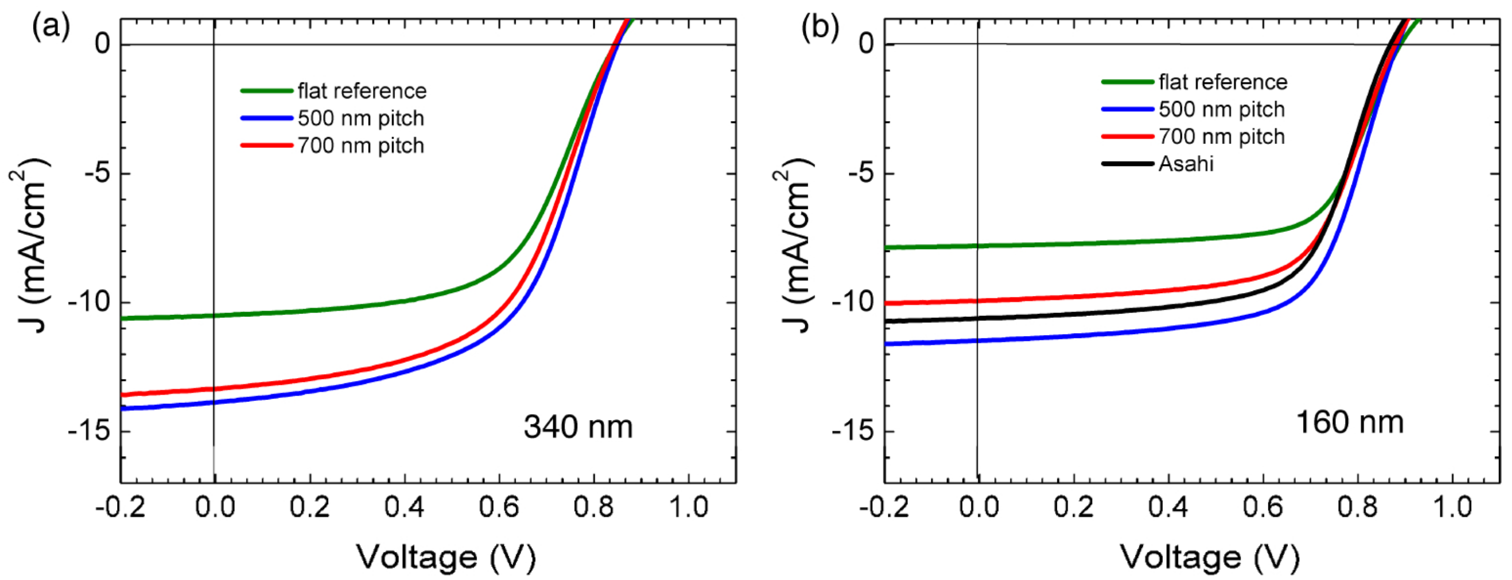
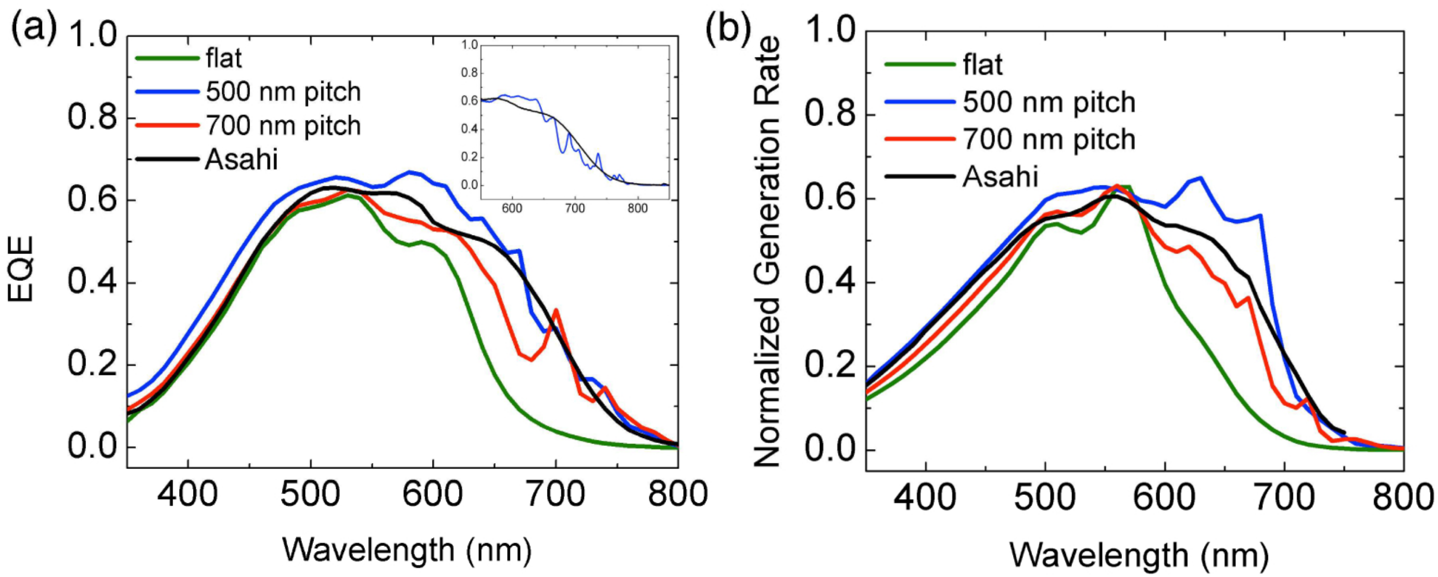


Fig. 10

Fig. 10: “Light trapping in ultrathin plasmonic solar cells” V. E. Ferry, M. A. Verschuuren, H. B. T. Li, E. Verhagen, R. J. Walters, R. E. I. Schropp, H. A. Atwater, A. Polman Optics Express 18, A237-A245 (2010).

Examples: Plasmonics



simulation

measurement

Fig. 11

Fig. 11: "Light trapping in ultrathin plasmonic solar cells" V. E. Ferry, M. A. Verschuuren, H. B. T. Li, E. Verhagen, R. J. Walters, R. E. I. Schropp, H. A. Atwater, A. Polman Optics Express 18, A237-A245 (2010).

Examples: Plasmonics

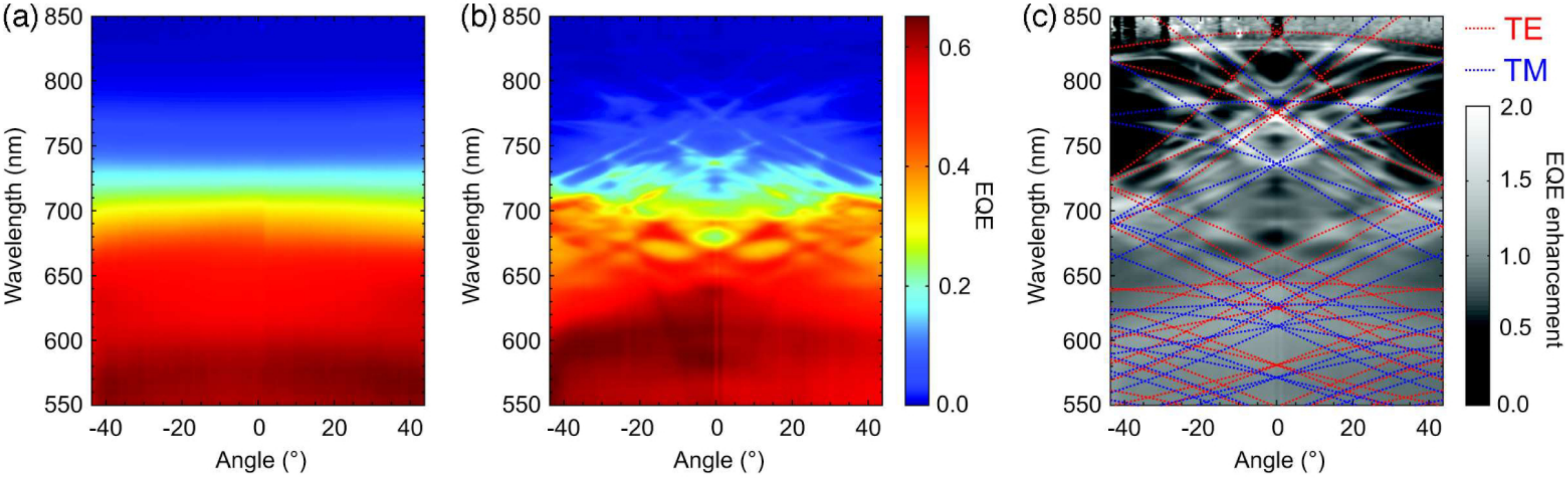


Fig. 12

Fig. 12: "Light trapping in ultrathin plasmonic solar cells" V. E. Ferry, M. A. Verschuuren, H. B. T. Li, E. Verhagen, R. J. Walters, R. E. I. Schropp, H. A. Atwater, A. Polman Optics Express 18, A237-A245 (2010).

Examples: Waveguiding

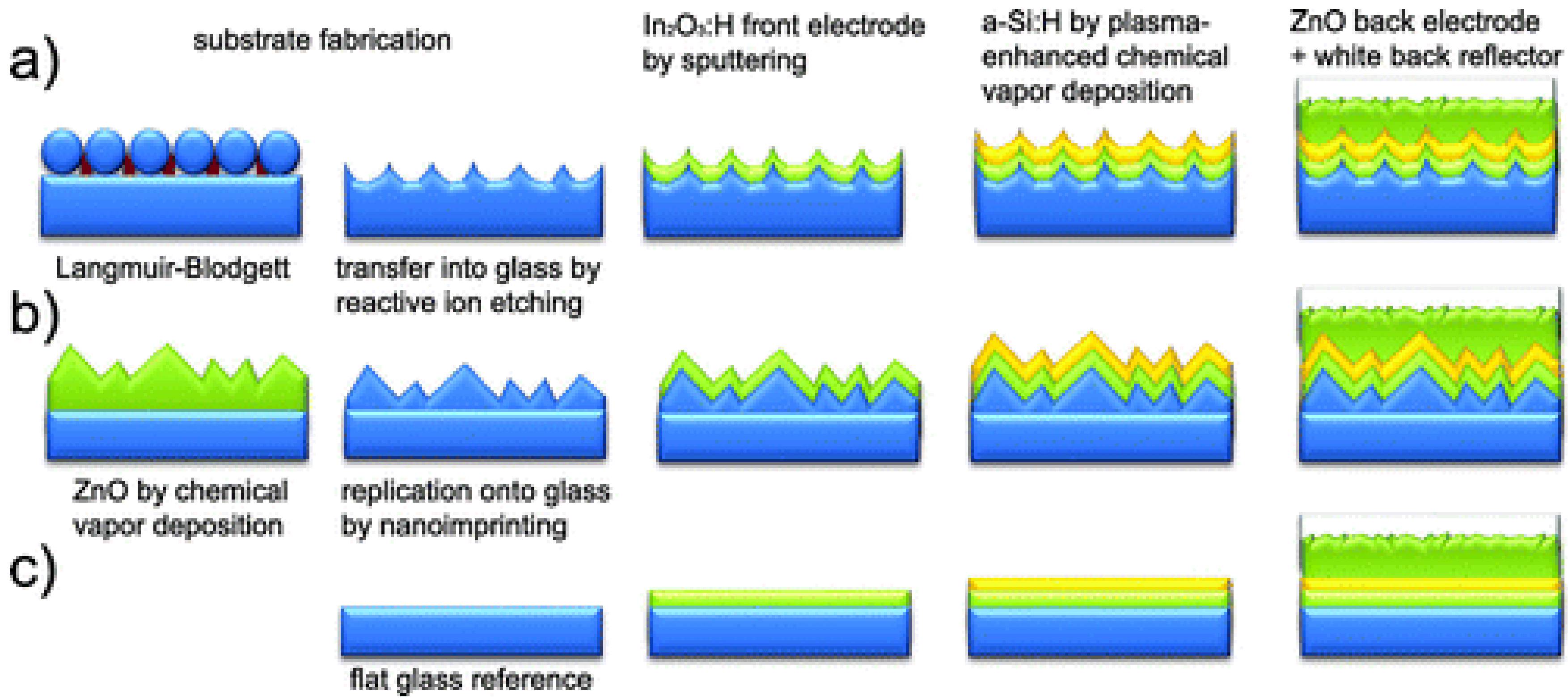


Fig. 13

Fig. 13: “Light Trapping in Solar Cells: Can Periodic Beat Random?” C. Battaglia, C.-M. Hsu, K. Soderstrom, J. Escarre, F.-J. Haug, M. Charriere, M. Boccard, M. Despeisse, D. T. L. Alexander, M. Cantoni, Y. Cui, C. Ballif ACS Nano 6, 2790-2797, 2012.

Examples: Waveguiding

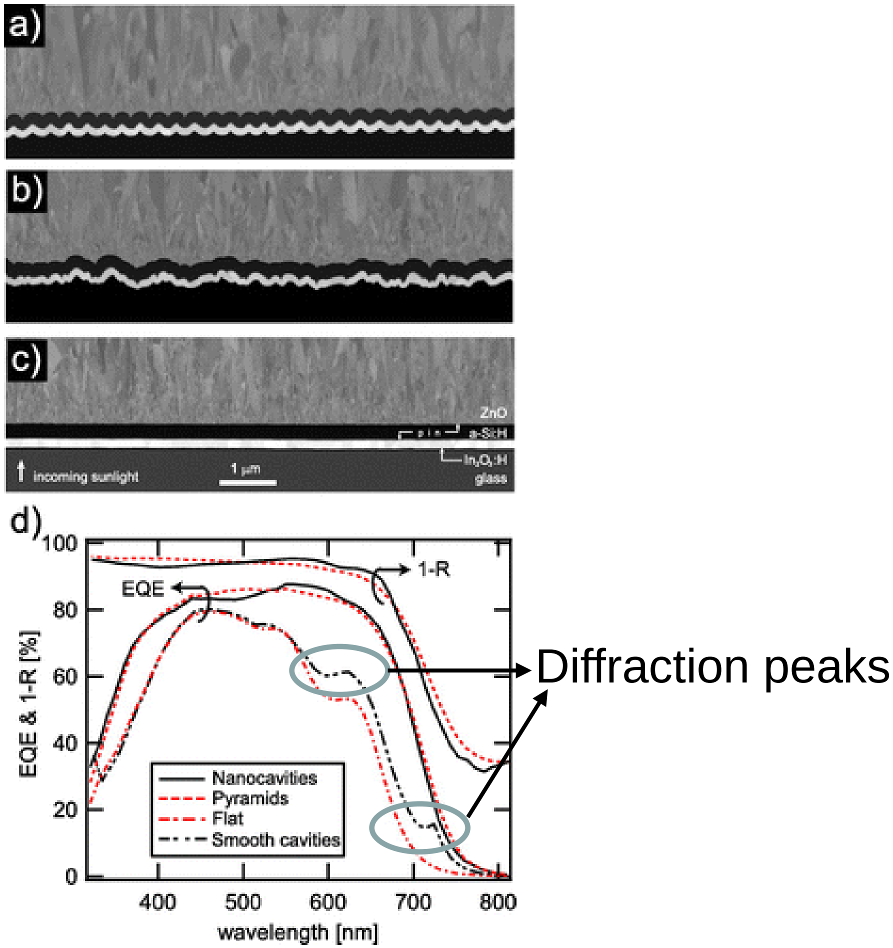
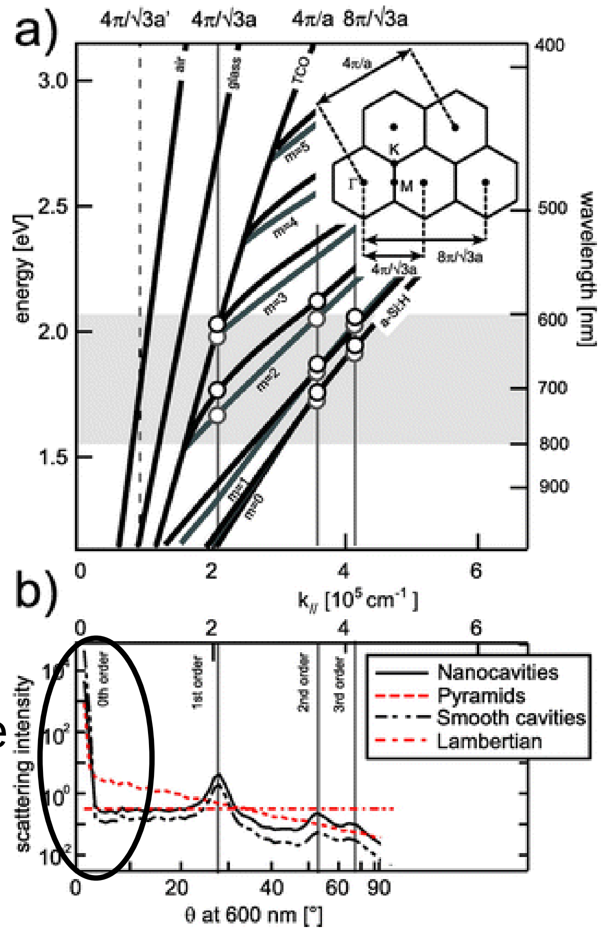


Fig. 14

Fig. 14: "Light Trapping in Solar Cells: Can Periodic Beat Random?" C. Battaglia, C.-M. Hsu, K. Soderstrom, J. Escarre, F.-J. Haug, M. Charriere, M. Boccard, M. Despeisse, D. T. L. Alexander, M. Cantoni, Y. Cui, C. Ballif ACS Nano 6, 2790-2797, 2012.

Examples: Waveguiding



Most of the power is here

Fig. 15

Fig. 15: "Light Trapping in Solar Cells: Can Periodic Beat Random?" C. Battaglia, C.-M. Hsu, K. Soderstrom, J. Escarre, F.-J. Haug, M. Charriere, M. Boccard, M. Despeisse, D. T. L. Alexander, M. Cantoni, Y. Cui, C. Ballif ACS Nano 6, 2790-2797, 2012.

Examples: Waveguiding

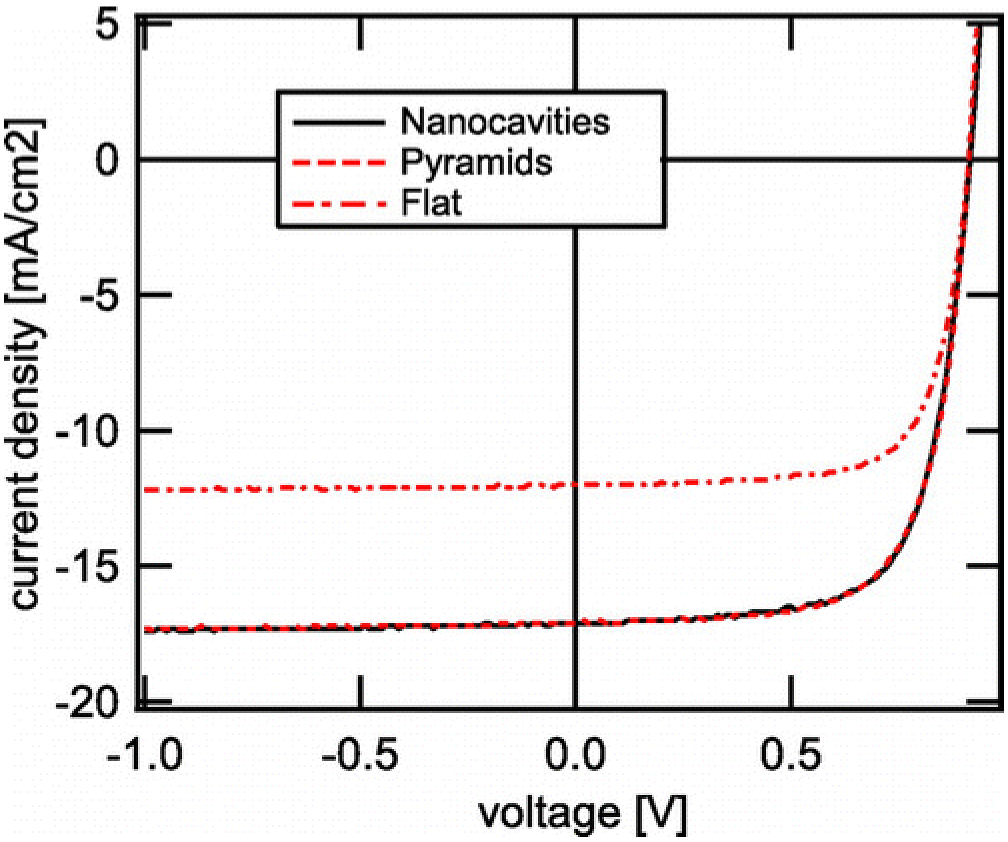


Fig. 16

Fig. 16: "Light Trapping in Solar Cells: Can Periodic Beat Random?" C. Battaglia, C.-M. Hsu, K. Soderstrom, J. Escarre, F.-J. Haug, M. Charriere, M. Boccard, M. Despeisse, D. T. L. Alexander, M. Cantoni, Y. Cui, C. Ballif ACS Nano 6, 2790-2797, 2012.

Examples: Photonic Crystals

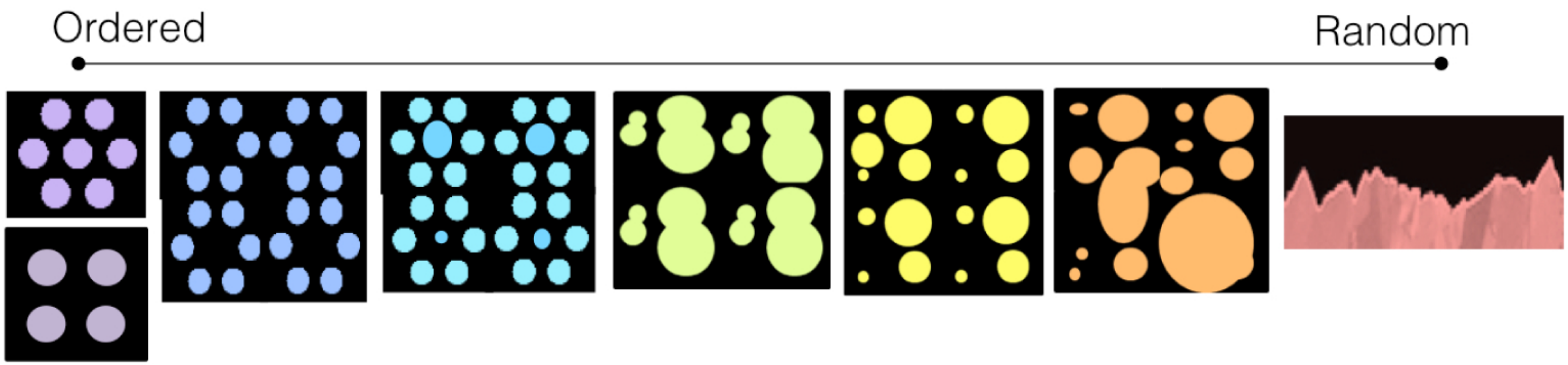


Fig. 17

Fig. 17: “Light Trapping in ultrathin silicon photonic crystal superlattices with randomly-textured dielectric incouplers” D. M. Callahan, K. A. W. Horowitz, H. A. Atwater Optics Express 21, 30315-30326 (2013).

Examples: Photonic Crystals

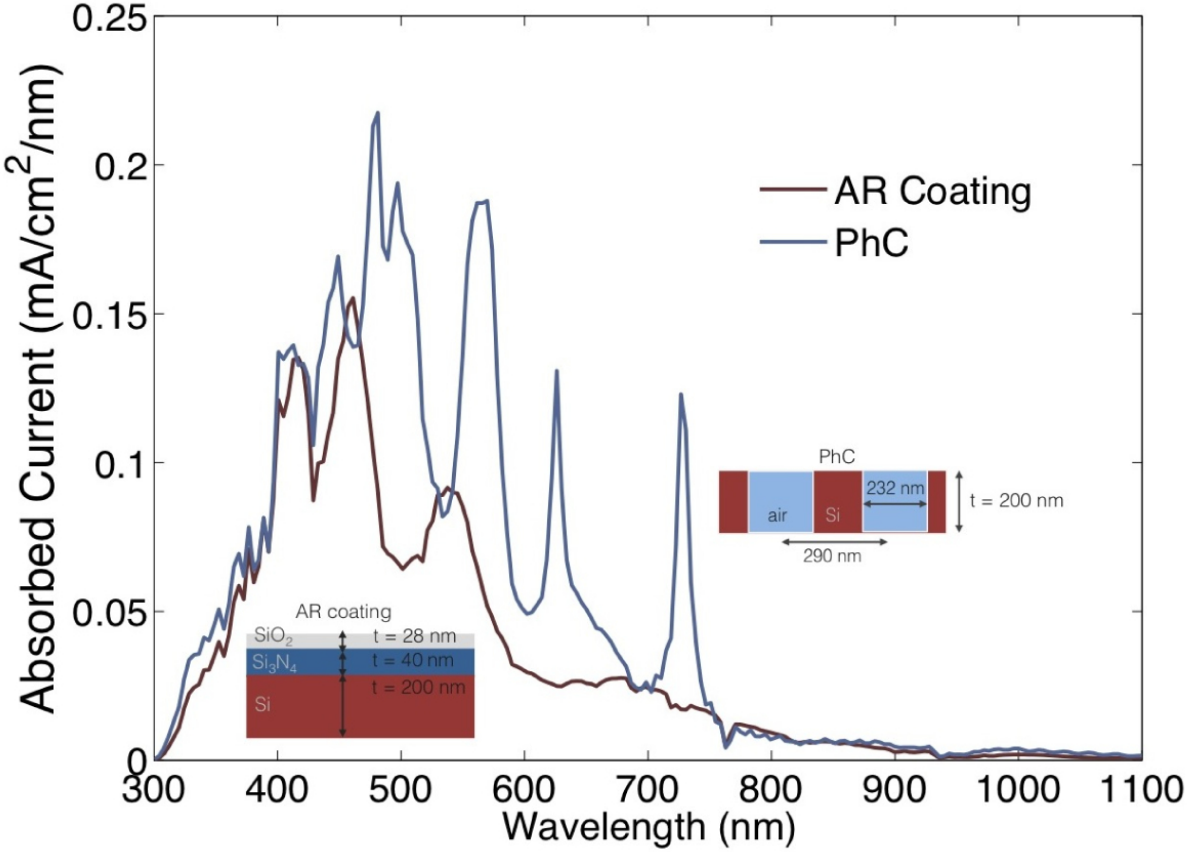


Fig. 18

Fig. 18: “Light Trapping in ultrathin silicon photonic crystal superlattices with randomly-textured dielectric incouplers” D. M. Callahan, K. A. W. Horowitz, H. A. Atwater Optics Express 21, 30315-30326 (2013).

Examples: Photonic Crystals

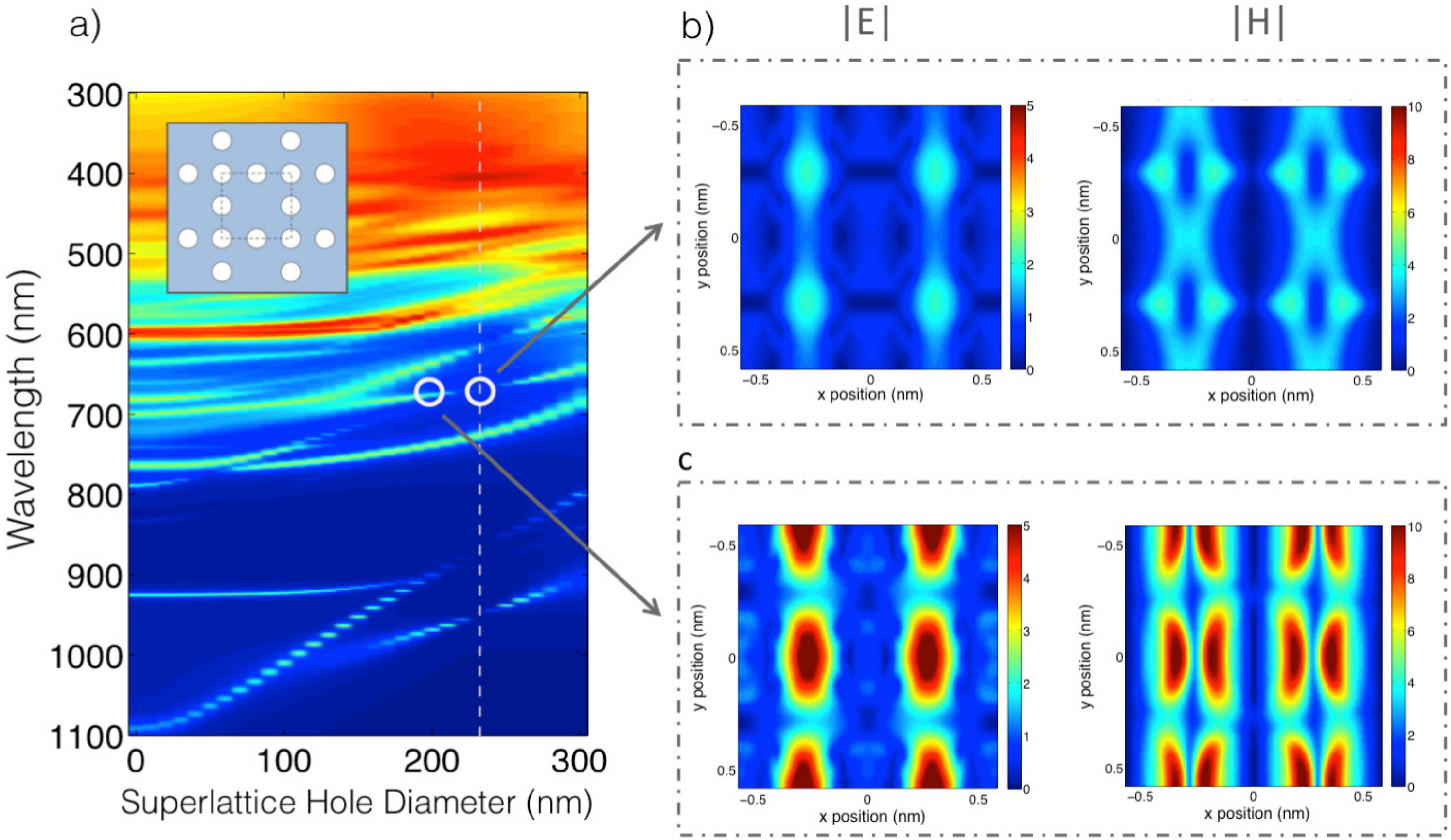


Fig. 19

Fig. 19: "Light Trapping in ultrathin silicon photonic crystal superlattices with randomly-textured dielectric incouplers" D. M. Callahan, K. A. W. Horowitz, H. A. Atwater Optics Express 21, 30315-30326 (2013).

Examples: Photonic Crystals

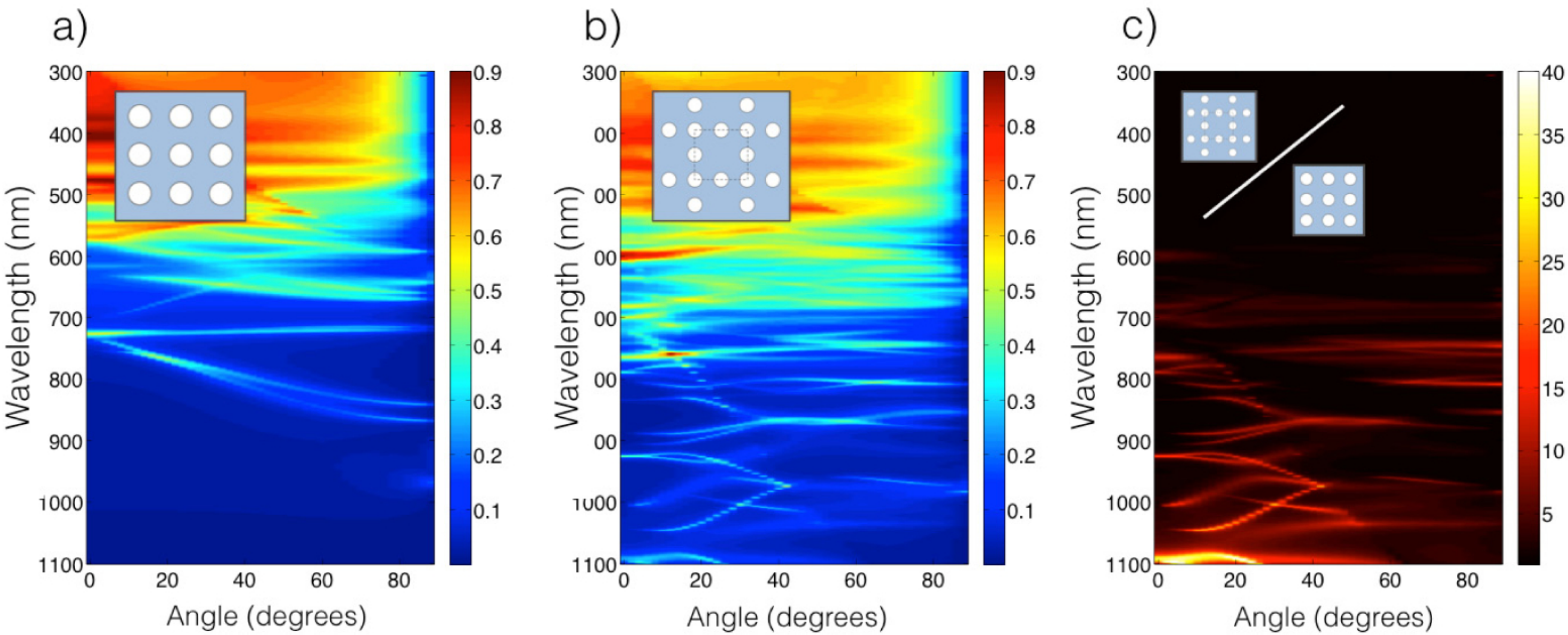


Fig. 20

Fig. 20: “Light Trapping in ultrathin silicon photonic crystal superlattices with randomly-textured dielectric incouplers” D. M. Callahan, K. A. W. Horowitz, H. A. Atwater Optics Express 21, 30315-30326 (2013).

Examples: Photonic Crystals

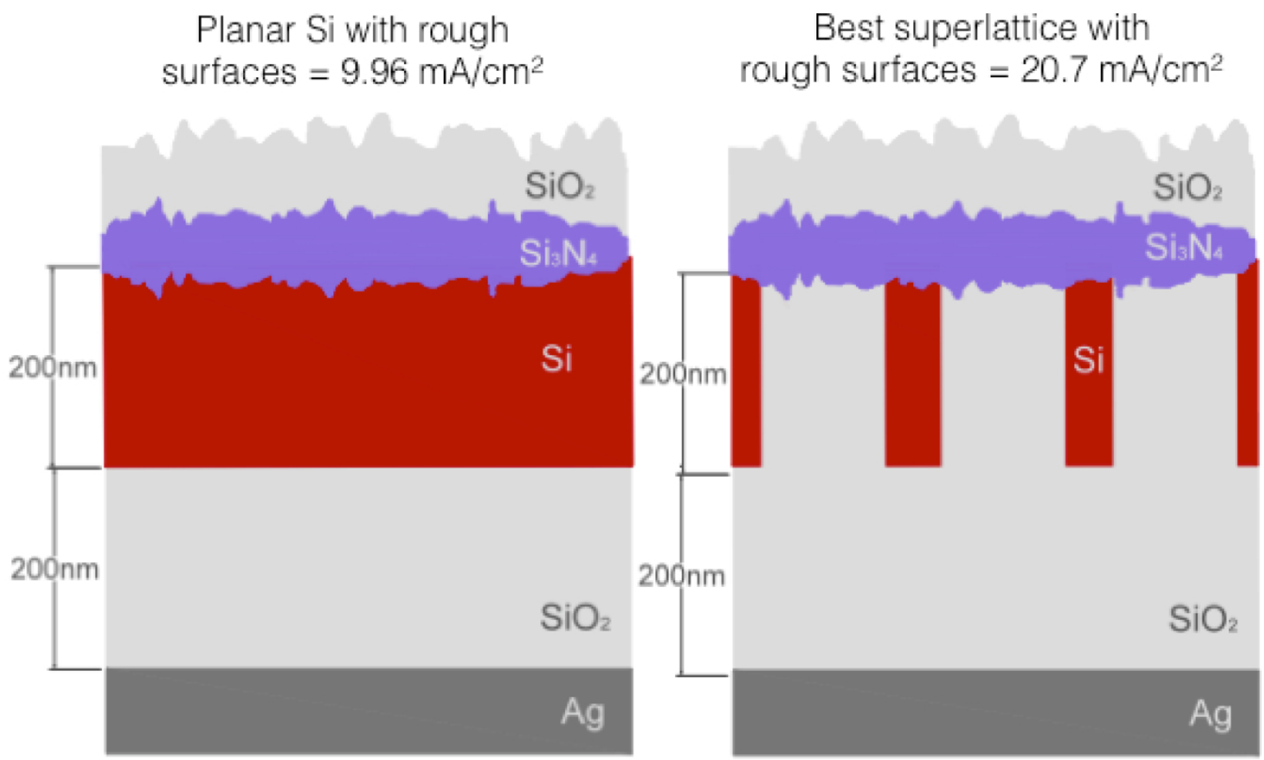


Fig. 21

Fig. 21: "Light Trapping in ultrathin silicon photonic crystal superlattices with randomly-textured dielectric incouplers" D. M. Callahan, K. A. W. Horowitz, H. A. Atwater Optics Express 21, 30315-30326 (2013).

Examples: Photonic Crystals

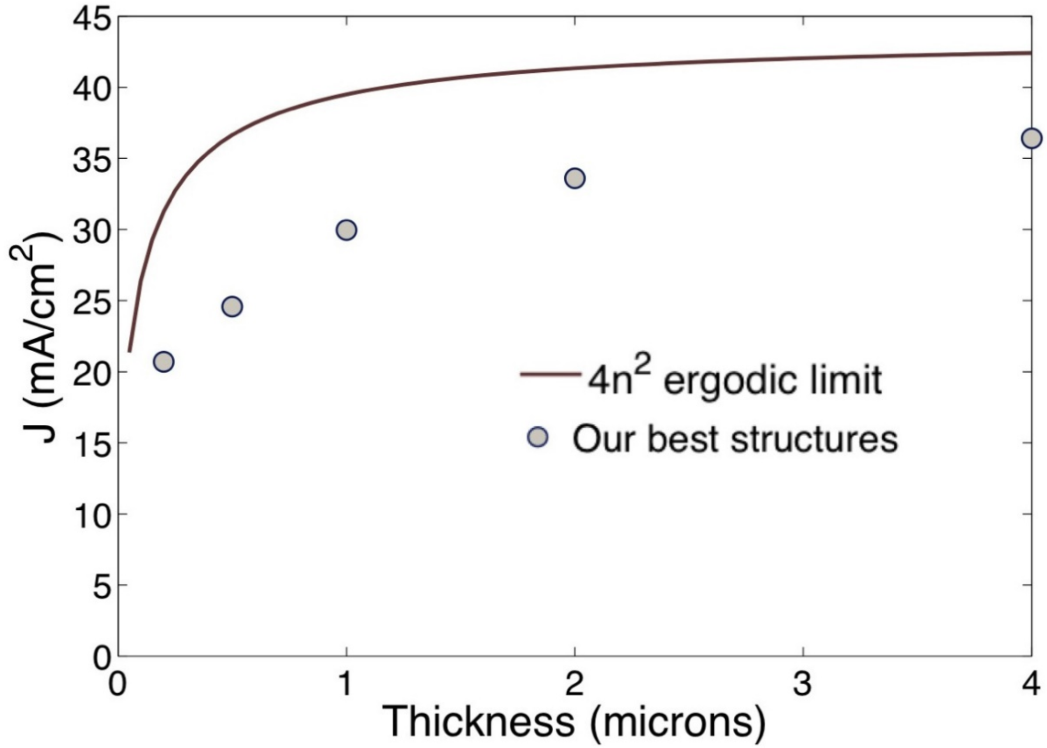


Fig. 22

Fig. 22: “Light Trapping in ultrathin silicon photonic crystal superlattices with randomly-textured dielectric incouplers” D. M. Callahan, K. A. W. Horowitz, H. A. Atwater Optics Express 21, 30315-30326 (2013).