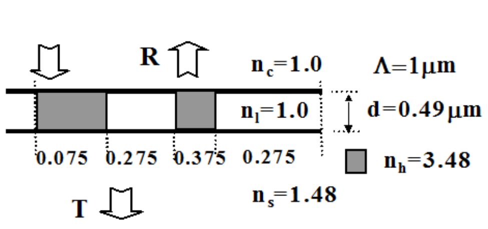
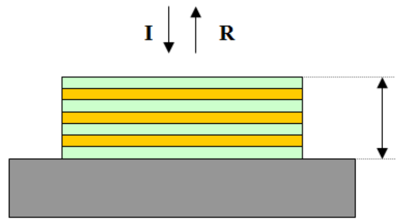
Guided-mode resonance (GMR) effect for filtering devices in LCD display panels

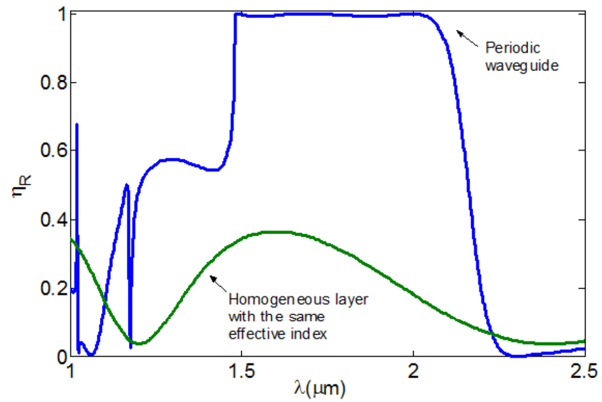
송 석 호, 한양대학교 물리학과, http://optics.anyang.ac.kr/~shsong

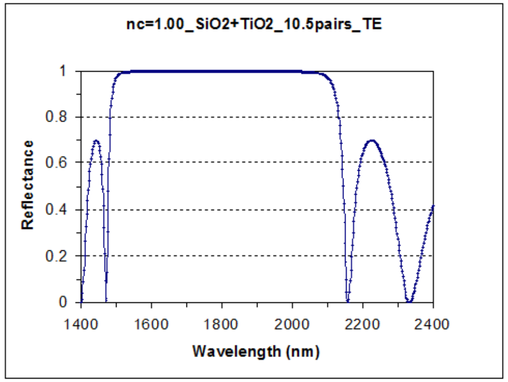


Single-layer SOI resonance device



21-layer SiO_2/TiO_2 Bragg stack





Key notes

1. What is the GMR effect of waveguide gratings?
2. What is the photonic band structure (or, dispersion relation)?
3. What can we play with GMR filters for display?
4. What is the practical difficulties to be solved in GMR applications?

GMR color filter

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 18, NO. 20, OCTOBER 15, 2006

Fabrication of Transmission Color Filters Using Silicon Subwavelength Gratings on Quartz Substrates

Yoshiaki Kanamori, Masaya Shimono, and Kazuhiro Hane Department of Nanomechanics, Tohoku University

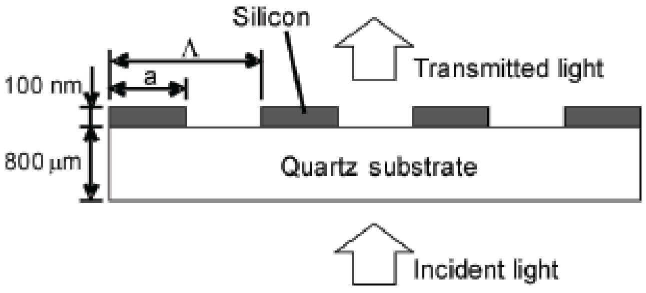


Fig. 1. Schematic of the fabricated color filter design. The grating period and width are defined as Λ and a, respectively.

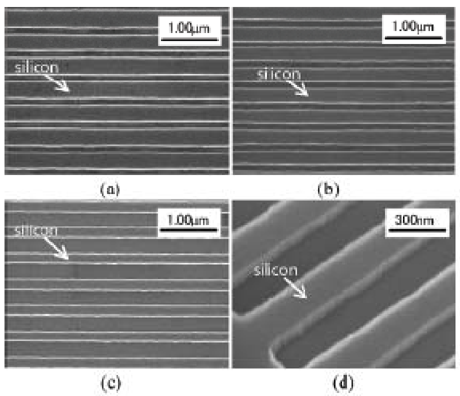


Fig. 2. SEM photographs of the fabricated gratings for (a) red (Λ = 400 nm, a = 279 nm), (b) green (Λ = 350 nm, a = 231 nm), and (c) blue (Λ = 440 nm, a = 177 nm) filters. (d) Oblique view of the fabricated grating for the blue filter at the edge.

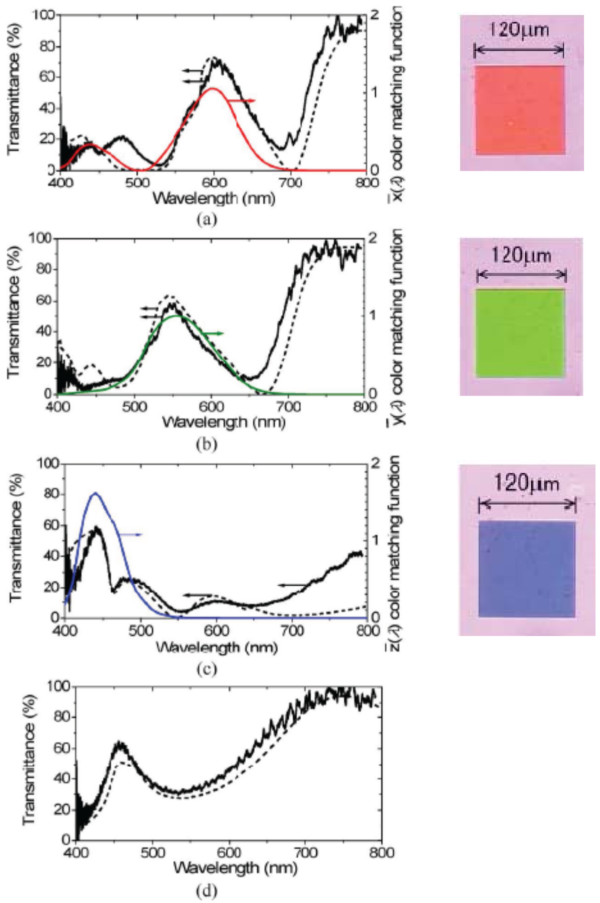


Fig. 4. Transmittances measured as a function of incident light wavelength for (a) red, (b) green, and (c) blue filters. (d) Transmittance of the bare SOQ substrate as a function of incident light wavelength. (Color version available online at http://ieeexplore.ieee.org.)

GMR color filter

《연구논문》 Hankook Kwanghak Hoeji, Volume 19, Number 1, February 2008

광파장 이하의 주기를 갖는 다결정 실리콘 격자 기반의 컬러필터

윤여택 · 이홍식 · 이상신[†]

광운대학교 전자공학과

㊝ 139-701 서울특별시 노원구 월계동 447-1

김상훈 · 박주도 · 이기동

엘지전자기술원 소자재료연구소

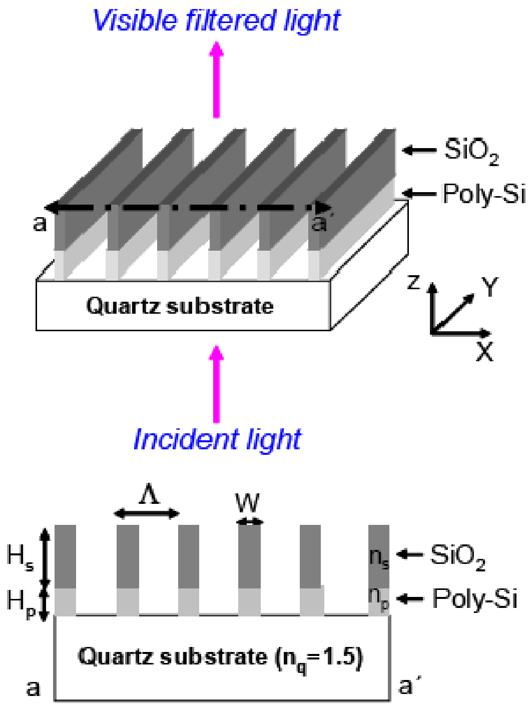
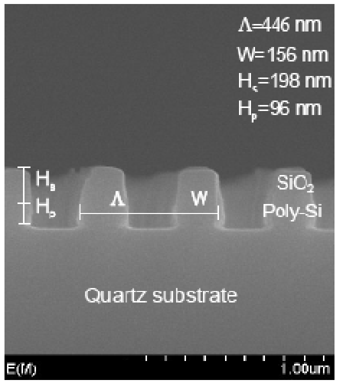
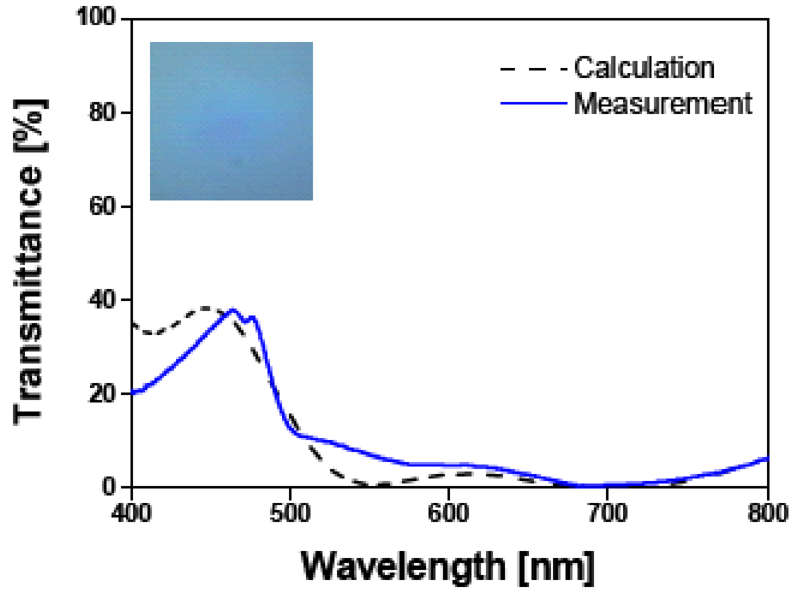


그림 1. 제안된 다결정 실리콘 컬러필터 구조.





GMR color filter

APPLIED PHYSICS LETTERS **94**, 213104 (2009)

High angular tolerant color filter using subwavelength grating

Byoung-Ho Cheong,[1] O. N. Prudnikov,[1] Eunhyoung Cho,[2] Hae-Sung Kim,[2] Jaeho Yu,[1] Young-Sang Cho,[1] Hwan-Young Choi,[1,a)] and Sung Tae Shin[1]
[1]*LCD R & D Center, Samsung Electronics Co., Nongseo-dong, Yongin-si, Gyeonggi-do 446-711,*

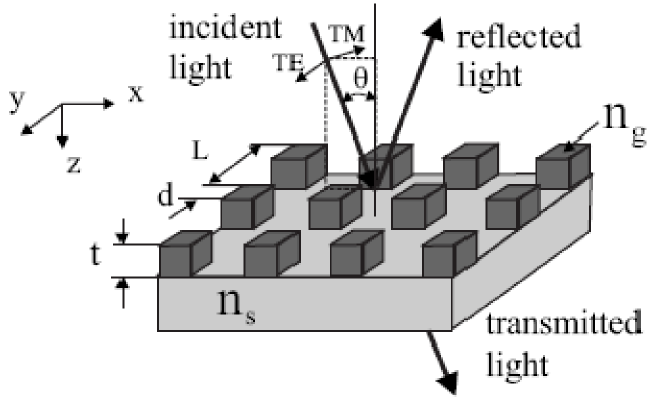


FIG. 1. Schematic geometry of subwavelength 2D grating structure.

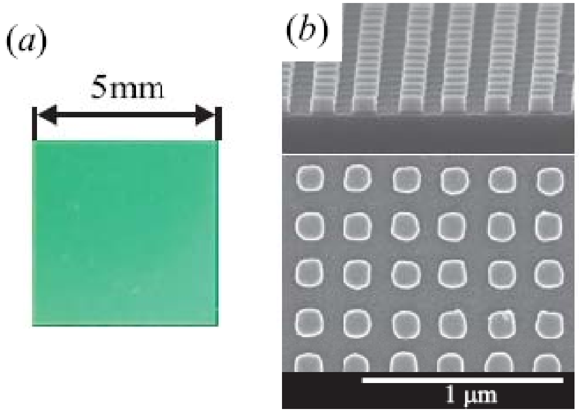


FIG. 4. (Color) (a) Photographic color image and (b) scanning electron microscope image of fabricated subwavelength grating slab.

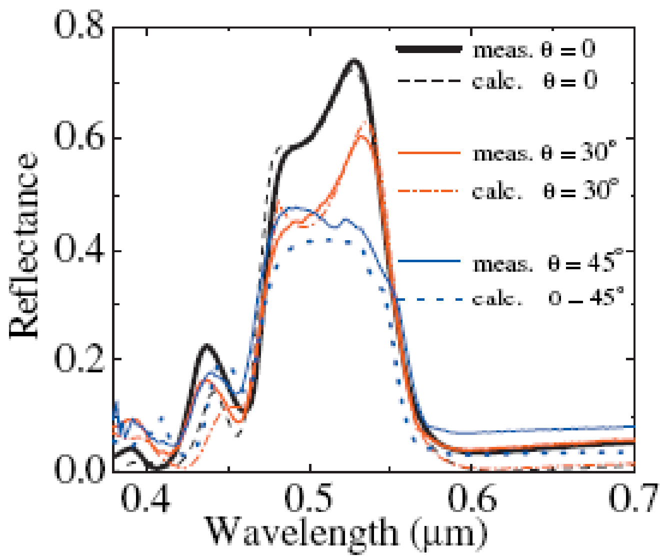


FIG. 5. (Color) Comparisons of measured and calculated reflectance curves with respect to different incident angles θ (unpolarized light).

GMR polarizer

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 20, NO. 22, NOVEMBER 15, 2008

Silicon-Layer Guided-Mode Resonance Polarizer With 40-nm Bandwidth

K. J. Lee, R. LaComb, B. Britton, M. Shokooh-Saremi, H. Silva, E. Donkor, Y. Ding, and R. Magnusson

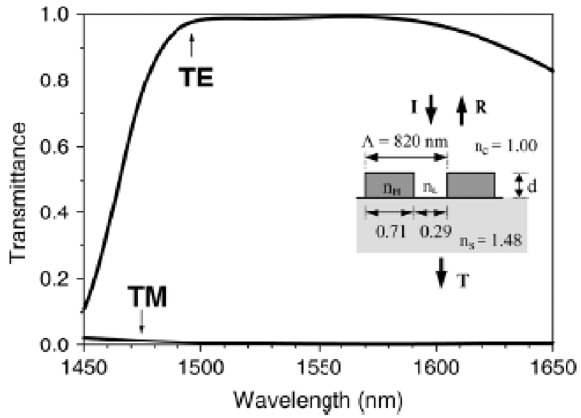


Fig. 2. Calculated spectral response of the designed GMR polarizer for TM- and TE-polarizations. The parameters are as follows: Thickness $d = 500$ nm; refractive indices $n_H = 3.48$, $n_L = 1.00$, $n_c = 1.00$, $n_s = 1.48$; grating period $\Lambda = 820$ nm; filling factor $f = 0.71$; incident angle $\theta_{in} = 0^\circ$ (normal incidence).

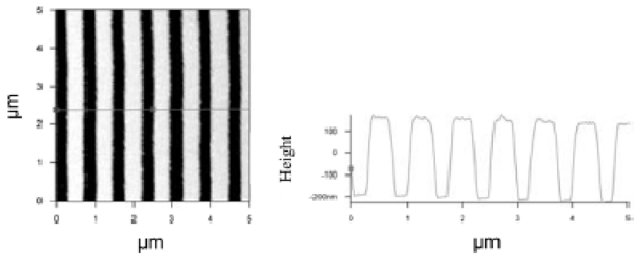


Fig. 4. AFM image of the polarizer and its profile quantifying the etch depth as 355 nm.

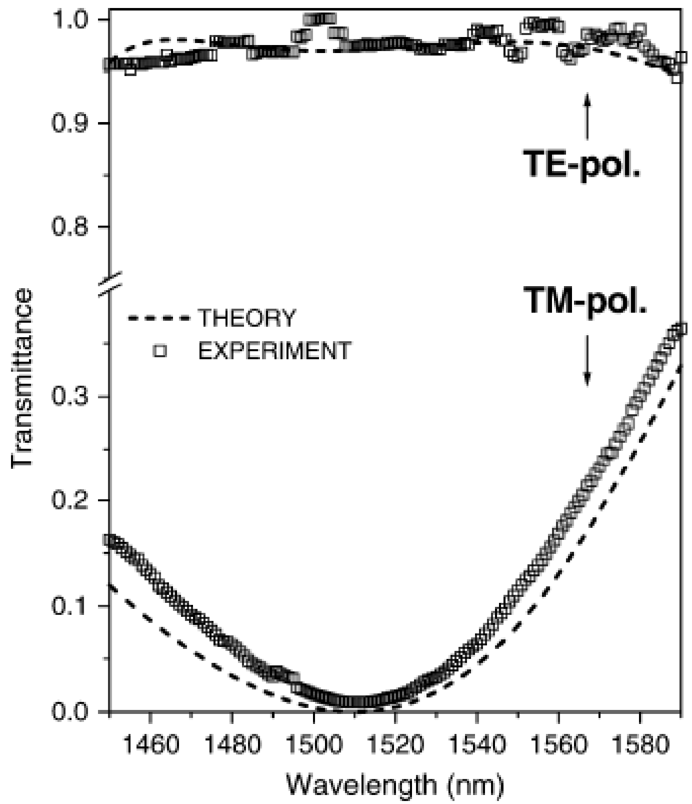
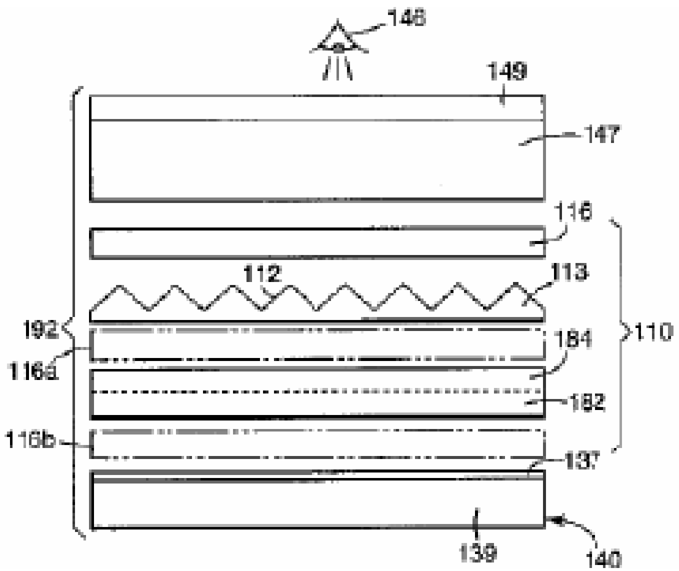


Fig. 5. Theoretical (dashed line) and experimental (hollow dot) spectral response of the fabricated GMR device for both TE- and TM-polarized incident waves. The experimental data is corrected for a ~4% reflection at the backside of the substrate. Note that the vertical axis is divided.

GMR polarizer

Reflective polarizer display, US 5828488 (1995.03.10), 3M (St. Paul, MN)



DBEF와 편광필름의 투과도(532nm) (투과단위 :uW)

Input	5mW							
	DBEF(l)+532nm(l)		DBEF(–)+532nm(l)		DBEF(–)+532nm(–)		DBEF(l)+532nm(–)	
각도	투과	투과효율	투과	투과효율	투과	투과효율	투과	투과효율
0	4230	0,846	40	0,008	4420	0,884	130	0,026
5	4230	0,846	39	0,0078	4420	0,884	17	0,0034
10	4190	0.838	620	0.124	4350	0.87	13	0.0026
15	4190	0,838	47	0,0094	4420	0,884	425	0,085
20	4220	0,844	47	0,0094	4440	0,888	4,3	0,00086
25	4150	0,83	33	0,0066	4500	0,9	25	0,005
30	4090	0,818	27	0,0054	4400	0,88	46	0,0092
35	4030	0.806	95	0.019	4200	0.84	9.5	0.0019
40	3950	0.79	44	0.0038	4600	0.92	11.7	0.00234
45	3810	0,762	2,3	0,00046	4340	0,868	48	0,0096
50	3630	0,726	18	0,0036	4350	0,87	80	0,016
55	3400	0,68	26	0,0052	4300	0,86	27	0,0054
60	3140	0.628	9	0.0018	4550	0.91	60	0.012
65	2760	0.552	9	0.0018	4350	0.87	14	0.0028
70	2320	0,464	3,2	0,00064	2800	0,56	9,6	0,00192
75	1860	0,372	7	0,0014	2700	0,54	52	0,0104
80	1130	0,226	40	0,008	2100	0,42	29	0,0058
85	5050	1,01						

	편광필름(l)+532nm(l)		편광필름(–)+532nm(l)		편광필름(–)+532nm(–)		편광필름(l)+532nm(–)	
각도	투과	투과효율	투과	투과효율	투과	투과효율	투과	투과효율
0	3650	0,73	3,03	0,000606	3590	0,718	3	0,0006
5	3540	0,708	3,31	0,000662	3600	0,72	2,84	0,000568
10	3520	0.704	3.31	0.000662	3640	0.728	2.84	0.000568
15	3620	0,724	3,34	0,000668	3690	0,738	2,78	0,000556
20	3700	0,74	3,32	0,000664	3720	0,744	2,77	0,000554
25	3600	0.72	3.46	0.000692	3750	0.75	2.83	0.000566
30	3710	0,742	3,4	0,00068	3770	0,754	2,81	0,000562
35	3580	0,716	3,49	0,000698	3810	0,762	2,8	0,00056
40	3460	0,692	3,47	0,000694	3850	0,77	2,9	0,00058
45	3200	0,64	3,48	0,000696	3890	0,778	2,93	0,000586
50	3210	0,642	3,58	0,000716	3930	0,786	2,96	0,000592
55	3010	0,602	3,57	0,000714	3960	0,792	3,06	0,000612
60	2660	0,532	3,63	0,000726	3950	0,79	3,17	0,000634
65	2370	0.474	3.59	0.000718	3860	0.772	3.33	0.000666
70	2020	0,404	3,54	0,000708	3690	0,738	3,35	0,00067
75	1660	0,332	3,32	0,000664	3340	0,668	3,35	0,00067
80	1140	0.228	2.92	0.000584	2640	0.528	3.12	0.000624
85	490	0,098	1,88	0,000376	1560	0,312	7,7	0,00154

GMR bandpass filter

Narrowing spectral width of green LED by GMR structure to expand color mixing field

S. H. Tu[1], Y. C. Lee[2], C. L. Hsu[1], W. P. Lin[1], M. L. Wu[1], T. S. Yang[1], J. Y. Chang[1]

1. Department of Optical and Photonics, National Central University, Jhongli, Taiwan 32001, ROC
2. Optical Science Center, National Central University, Jhongli, Taiwan, ROC

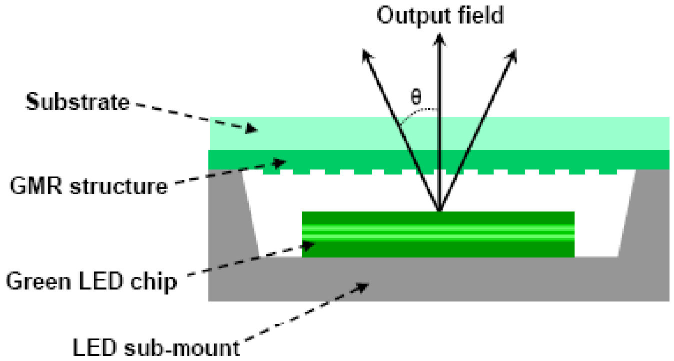
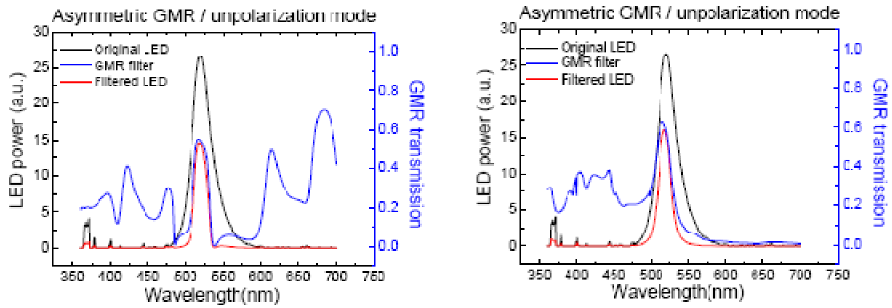
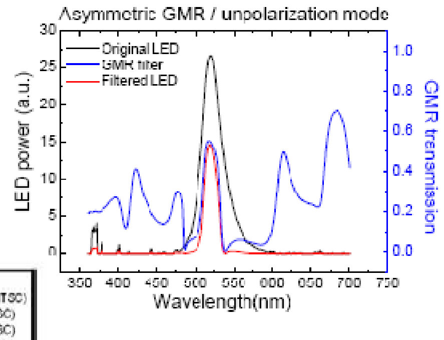


Fig. 2. Illustration of the structural arrangement for reducing the output spectral width of a green LED chip.





IR filters associate with an asymmetric grating structure and
d LED spectrum with a normally incident unpolarized plane
ding structure parameters of GMR filters are identical to the
ig. 5.

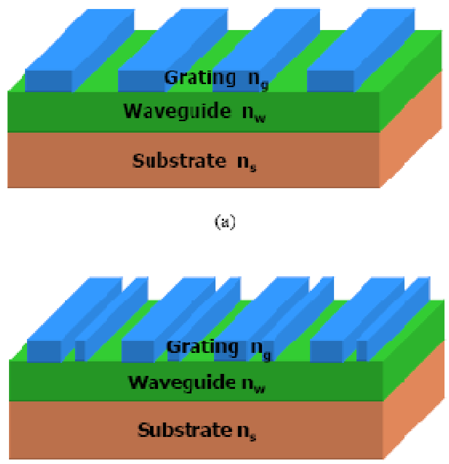
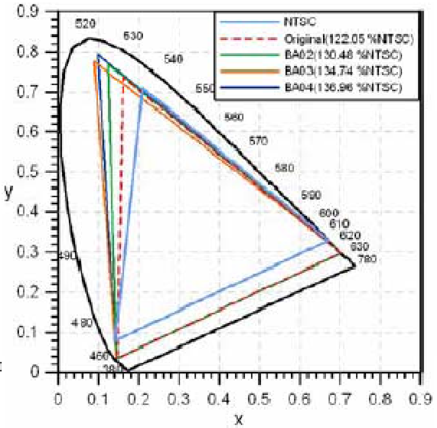
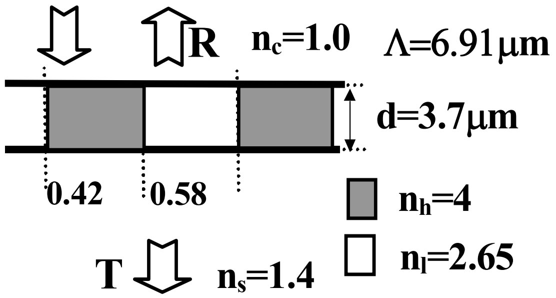


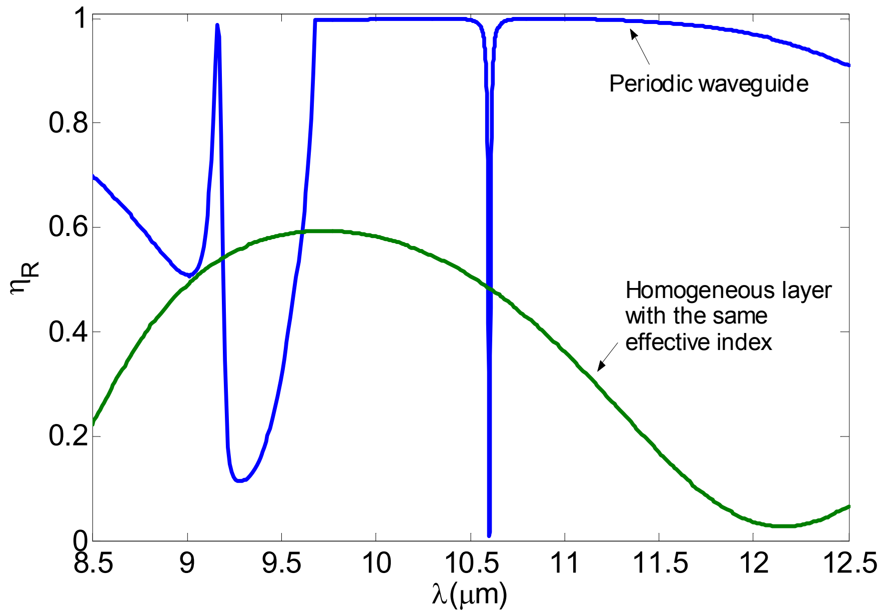
Fig. 1. Illustration of basic GMR filters associated with (a) symmetric ar asymmetric grating structures on a planar waveguide constructed transparent substrate.

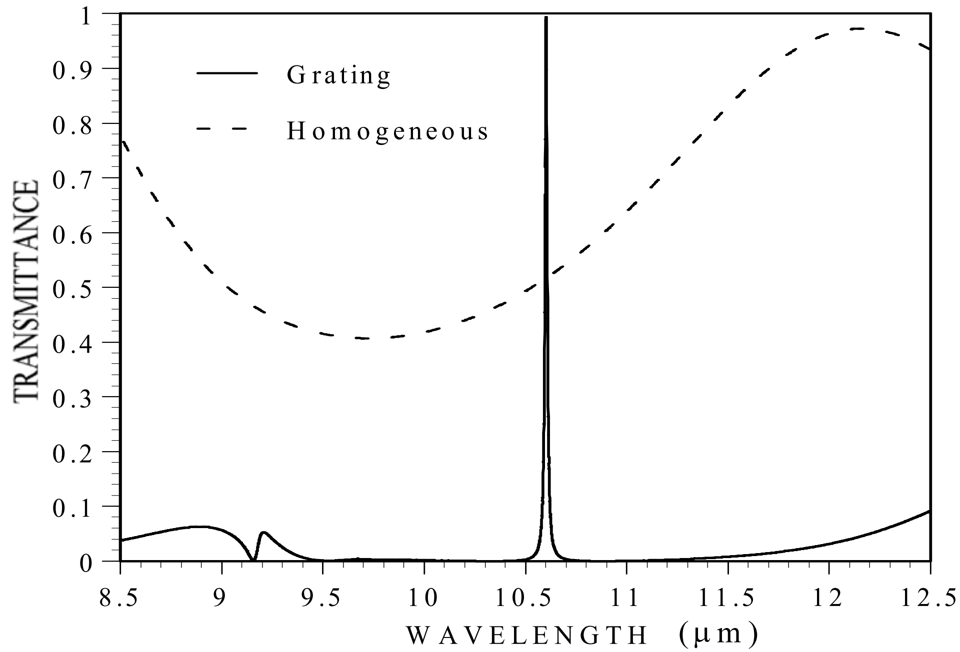


Narrow-line bandpass filters

R. Magnusson and S. S. Wang, Appl. Optics 34, 8106-8109 (1995).
S. Tibuleac and R. Magnusson, Opt. Lett. 26, 584-586 (2001).





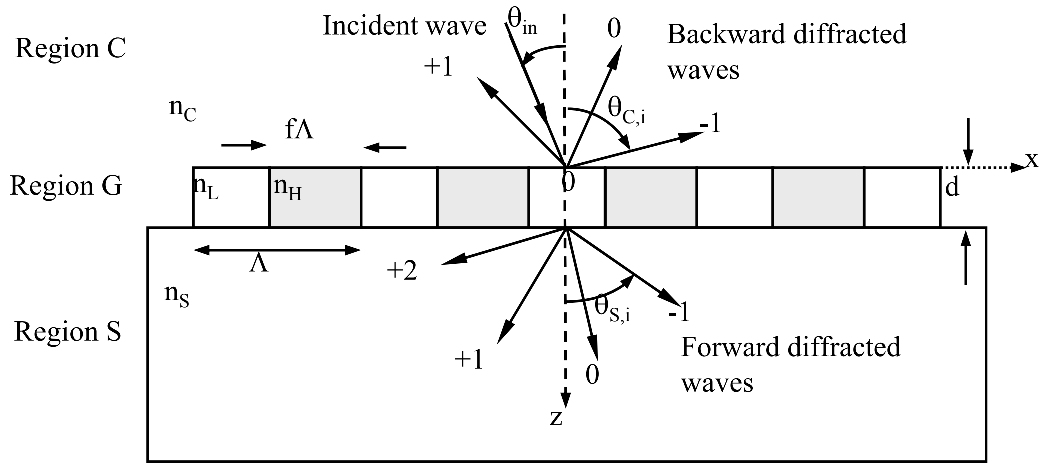


DIFFRACTIVE OPTICAL ELEMENTS (DOEs) ?

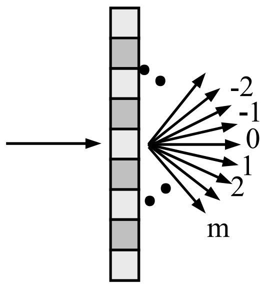
Transmission type

DOE/PhC : Fine spatial patterns arranged to control propagation of light

Grating Diffraction

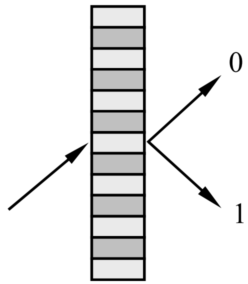


Operating Regimes



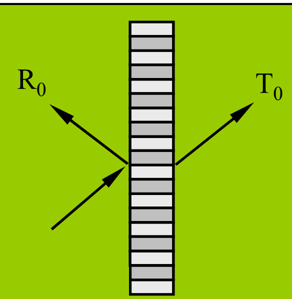
$$\Lambda(\sin\theta_{in} + \sin\theta_m) = m\lambda$$

Multiwave regime ($\Lambda >> \lambda$)



$$2\Lambda \sin\theta_{in} = \lambda$$

Two-wave regime ($\Lambda \sim \lambda$)



Zero-order regime ($\Lambda << \lambda$)

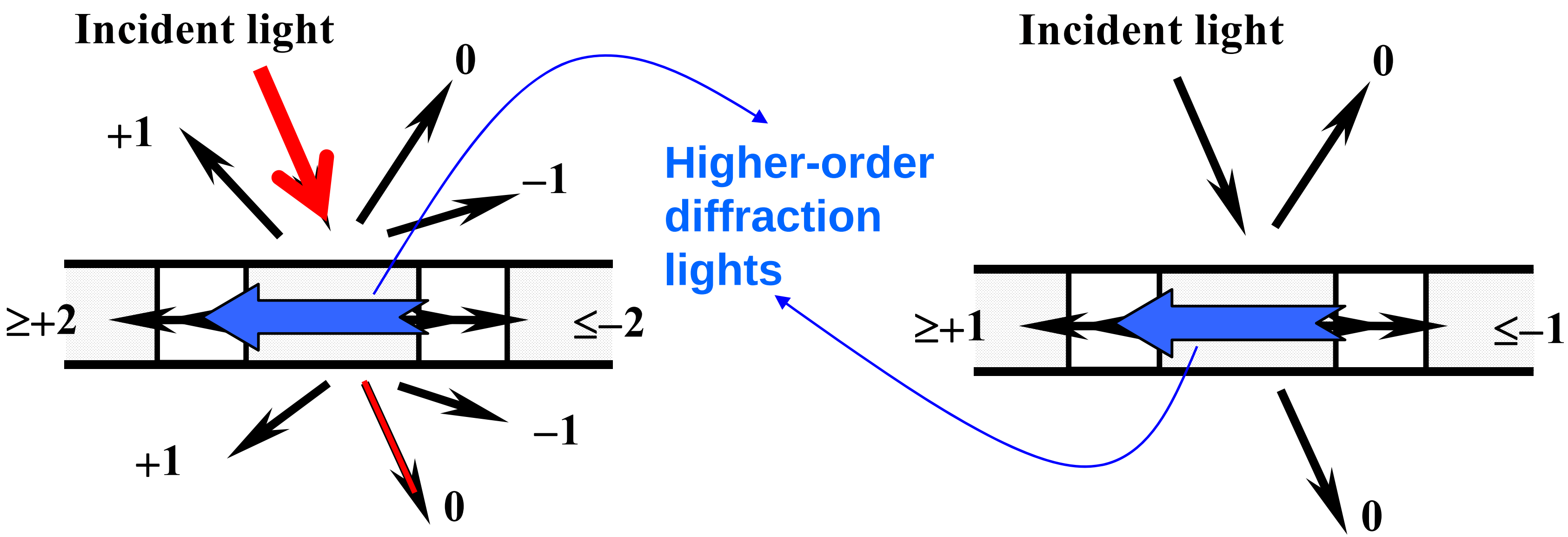
Basic resonance interactions

Excitation of a leaky guided mode

Consider simplest 1D WGG case for clarity

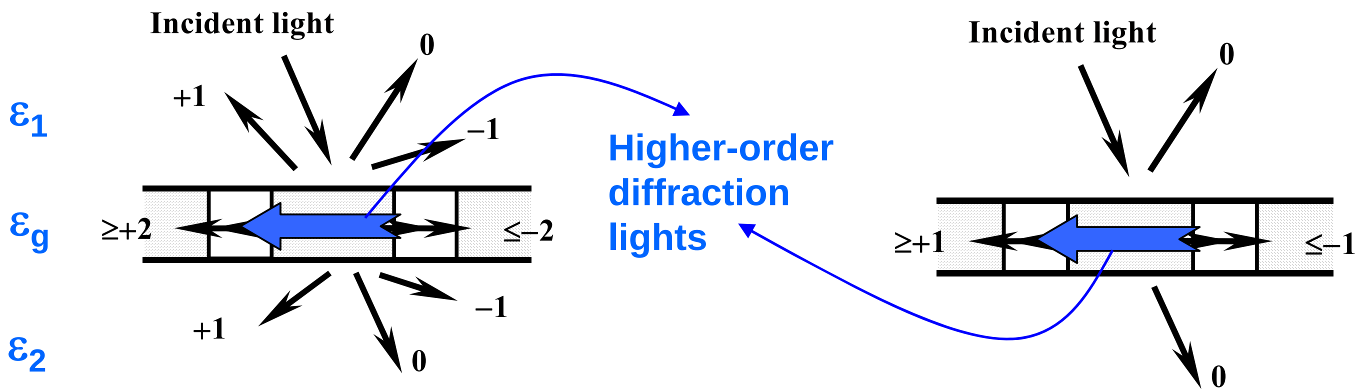
Higher-order diffraction regime

Zero-order diffraction regime



Diffraction order $\boxed{i = \cdots, -2, -1, 0, +1, +2, \cdots}$

Guided mode resonance (GMR)



If ε_g (average dielectric constant) > ε_1 , ε_2

the higher-order diffraction lights can be guided on a thin layer of grating.

➔ ***"Guided mode resonance (GMR)" of waveguide gratings***

Basic Concepts of GMR

Theory and applications of guided-mode resonance filters

S. S. Wang and R. Magnusson APPLIED OPTICS / Vol. 32, No. 14 / 10 May 1993, 2606

$$\epsilon_2(x) = \epsilon_g + \Delta\epsilon \cos Kx$$

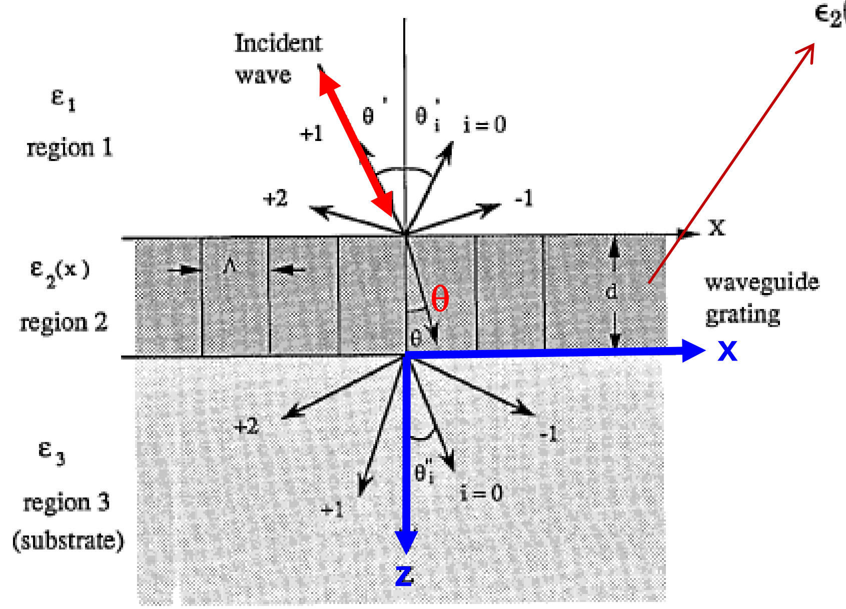


Fig. 1. Basic planar waveguide-grating model used. The angles θ_i' represent the angles of the wave vector of the ith backward-diffracted wave with respect to the z axis; θ_i'' are the corresponding angles for the forward-diffracted waves. The angle of incidence (θ') is arbitrary.

ε_g is the average relative permittivity,
$\Delta\varepsilon$ is the modulation amplitude,
$K = 2\pi/\Lambda$, where Λ is the grating period.

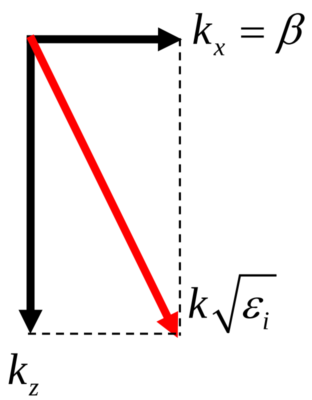
A guided wave can be excited
if the effective waveguide index of refraction, N,
is in the range

$$\boxed{\max\{\sqrt{\epsilon_1}, \sqrt{\epsilon_3}\} \leq |N| < \sqrt{\epsilon_g}}$$

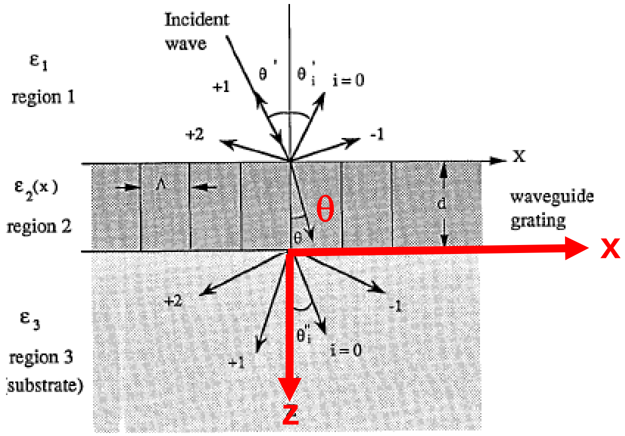
$$N \equiv \frac{\beta}{k} \qquad k = \frac{2\pi}{\lambda_0}$$

$$k_x \equiv \beta$$

$$k_z = \sqrt{k^2\varepsilon_g - k_x^2}$$



Propagation constant of waveguide grating



$$\epsilon_2(x) = \epsilon_g + \Delta\epsilon \cos Kx$$

Coupled-wave equations governing wave propagation in the waveguide grating can be expressed as

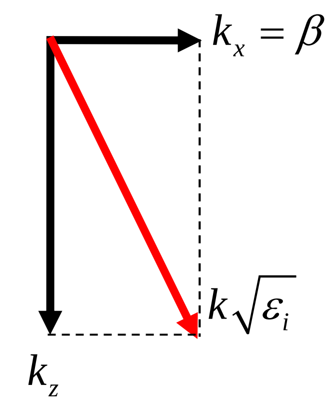
$$\frac{d^2\hat{S}_i(z)}{dz^2} + [k^2\epsilon_g - k_2(\sqrt{\epsilon_g}\sin\theta - i\lambda/\Lambda)^2\hat{S}_i(z) + \tfrac{1}{2}k^2\Delta\epsilon[\hat{S}_{i+1}(z) + \hat{S}_{i-1}(z)] = 0, \quad (1)$$

where $\hat{S}_i$ is the amplitude of the inhomogeneous plane wave of the ith space harmonic

As $\Delta\epsilon \to 0$, the wave equation associated with an unmodulated dielectric waveguide is given by

$$\frac{d^2E(z)}{dz^2} + (k^2\epsilon_g - \beta^2)E(z) = 0, \qquad (2)$$

$$\boxed{k_z = \sqrt{k^2\varepsilon_g - k_x^2} \quad (k_x = \beta)}$$

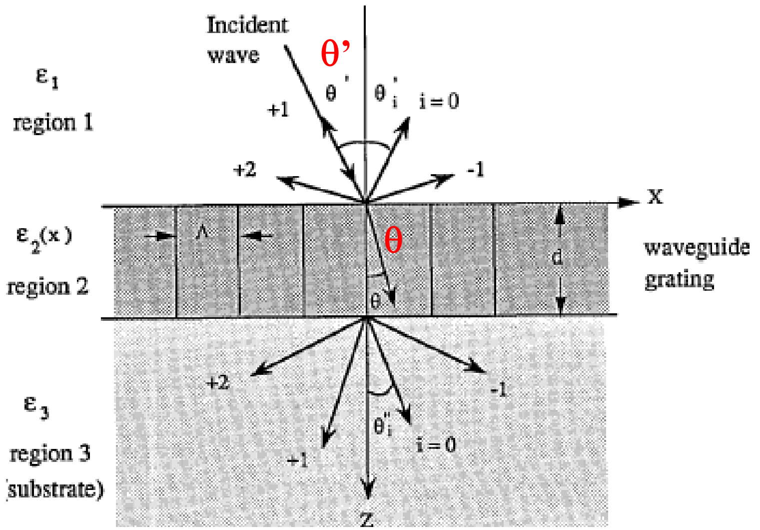


Letting $\Delta\epsilon \to 0$ in Eq. (1) and by direct comparison with Eq. (2),
we obtain the effective propagation constant of the waveguide grating:

$$\boxed{\beta \to \beta_i = k(\sqrt{\epsilon_g}\sin\theta - i\lambda/\Lambda)}$$

Propagation constant

Diffraction equation of waveguide grating



$$\max\{\sqrt{\epsilon_1}, \sqrt{\epsilon_3}\} \le |N| < \sqrt{\epsilon_g}$$

$$\beta \rightarrow \beta_i = k(\sqrt{\epsilon_g}\sin\theta - i\lambda/\Lambda)$$

where we use $\sqrt{\epsilon_1}\sin\theta' = \sqrt{\epsilon_g}\sin\theta$, with θ' being the external angle of incidence,

$$\boxed{\max\{\sqrt{\epsilon_1}, \sqrt{\epsilon_3}\} \le |\sqrt{\epsilon_1}\sin\theta' - i\lambda/\Lambda| < \sqrt{\epsilon_g}}$$

Diffraction equation

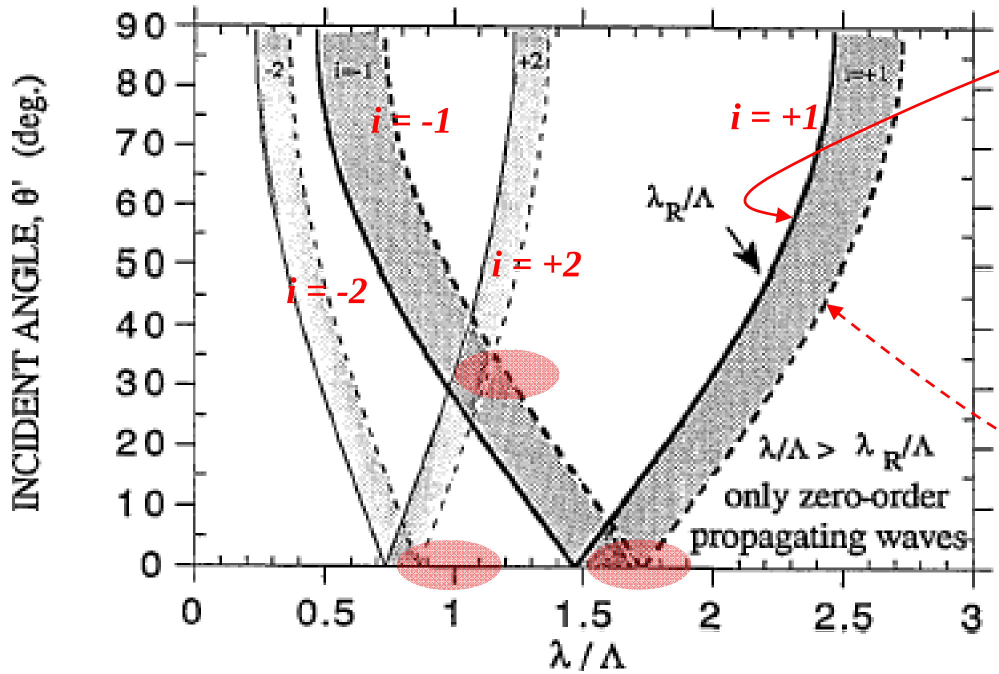


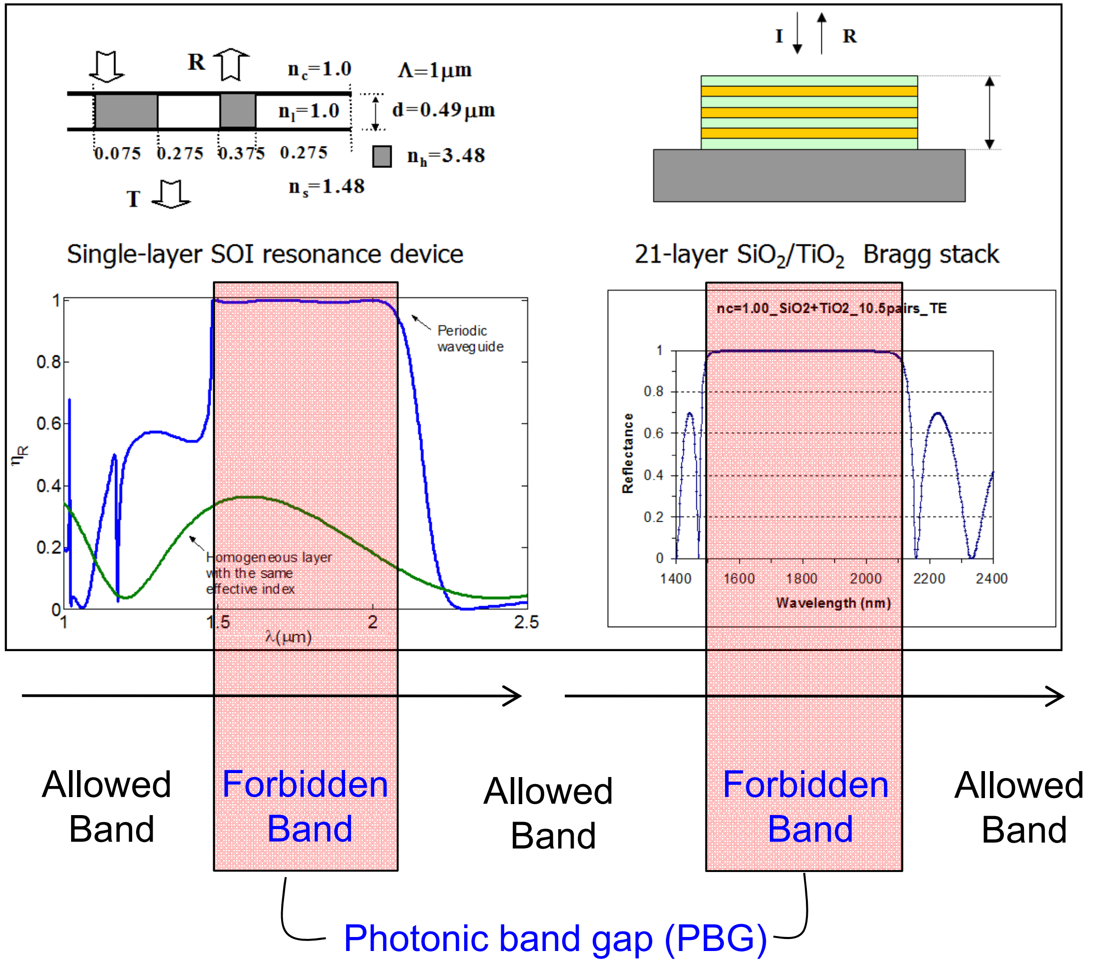
Fig. 3. Resonance regimes of waveguide gratings. The parameters are $\epsilon_1 = 1$, $\epsilon_g = 3$, and $\epsilon_3 = 2.161$.

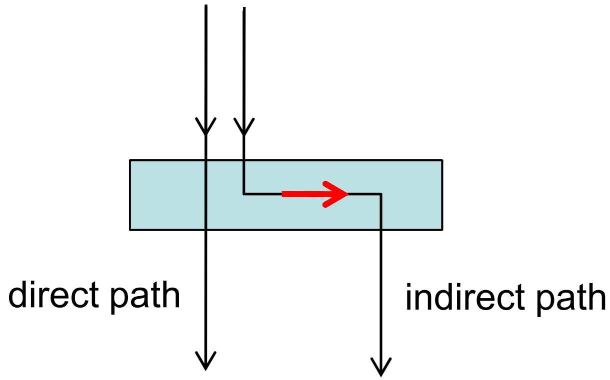
$$\max\left\{\sqrt{\varepsilon_1}, \sqrt{\varepsilon_3}\right\} = \left|\sqrt{\varepsilon_1}\sin\theta' - i\frac{\lambda}{\Lambda}\right|$$

$$\left|\sqrt{\varepsilon_1}\sin\theta' - i\frac{\lambda}{\Lambda}\right| < \sqrt{\varepsilon_g}$$

GMR filters

How to intuitively understand the GMR effect, for example, in mirrors?





Constructive/destructive Interference

Photon energy

Photonic band structure

No transmission of light within the bandgap due to destructive interference in transmitted light.

Photonic band structure is analogous to energy-band structure of electrons

Photons and Electrons

Nanophotonics, Paras N. Prasad, 2004, John Wiley & Sons, Inc., Hoboken, New Jersey., ISBN 0-471-64988-0

Both photons and electrons are elementary particles that simultaneously exhibit particle and wave-type behavior.

Photons and electrons may appear to be quite different as described by classical physics, which defines photons as electromagnetic waves transporting energy and electrons as the fundamental charged particle (lowest mass) of matter.

A quantum description, on the other hand, reveals that photons and electrons can be treated analogously and exhibit many similar characteristics.

Table 2.1. Similarities in Characteristics of Photons and Electrons

Photons	Electrons
Wavelength	
$\lambda = \frac{h}{p} = \frac{c}{\nu}$	$\lambda = \frac{h}{p} = \frac{h}{mv}$
Eigenvalue (Wave) Equation	
$\left\{\nabla \times \frac{1}{\varepsilon(r)} \nabla \times\right\} \mathbf{B}(r) = \left(\frac{\omega}{c}\right)^2 \mathbf{B}(r)$	$\hat{H}\psi(r) = -\frac{\hbar^2}{2m}(\nabla \cdot \nabla + V(r))\psi(r) = E\psi$
Free-Space Propagation	
Plane wave $\mathbf{E} = (\frac{1}{2})\mathbf{E}^\circ(e^{i\mathbf{k}\cdot\mathbf{r}-\omega t} + e^{-i\mathbf{k}\cdot\mathbf{r}+\omega t})$ $\mathbf{k}$ = wavevector, a real quantity	Plane wave: $\Psi = c(e^{i\mathbf{k}\cdot\mathbf{r}-\omega t} + e^{-i\mathbf{k}\cdot\mathbf{r}+\omega t})$ $\mathbf{k}$ = wavevector, a real quantity
Interaction Potential in a Medium	
Dielectric constant (refractive index)	Coulomb interactions
Propagation Through a Classically Forbidden Zone	
Photon tunneling (evanescent wave) with wavevector, **k**, imaginary and hence amplitude decaying exponentially in the forbidden zone	Electron-tunneling with the amplitude (probability) decaying exponentially in the forbidden zone
Localization	
Strong scattering derived from large variations in dielectric constant (e.g., in photonic crystals)	Strong scattering derived from a large variation in Coulomb interactions (e.g., in electronic semiconductor crystals)
Cooperative Effects	
Nonlinear optical interactions	Many-body correlation Superconducting Cooper pairs Biexciton formation

Consider free-space propagation of photons and electrons.

In a "free-space" propagation, there is no interaction potential or it is constant in space.
For photons, it simply implies that no spatial variation of refractive index *n* occurs.

The wavevector dependence of energy is different for photons (linear dependence) and electrons (quadratic dependence).

$$\omega = c|k| \qquad\qquad E = \frac{\hbar^2 k^2}{2m}$$

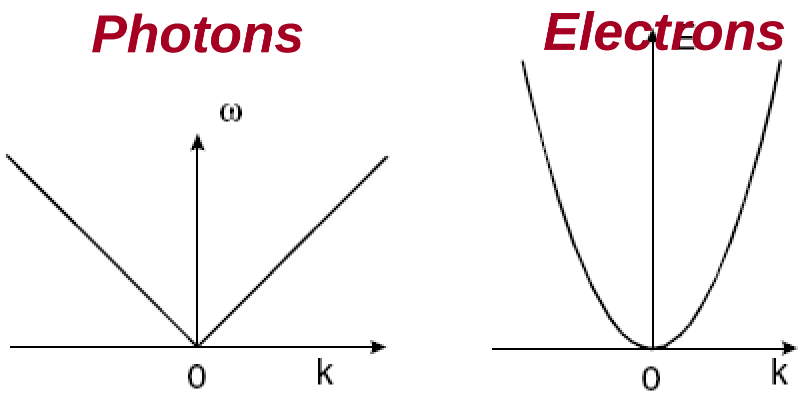
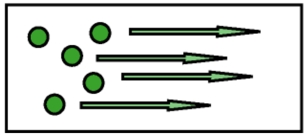


Figure 2.1. Dispersion relation showing the dependence of energy on the wavevector for a free-space propagation. (a) Dispersion for photons. (b) Dispersion for electrons.

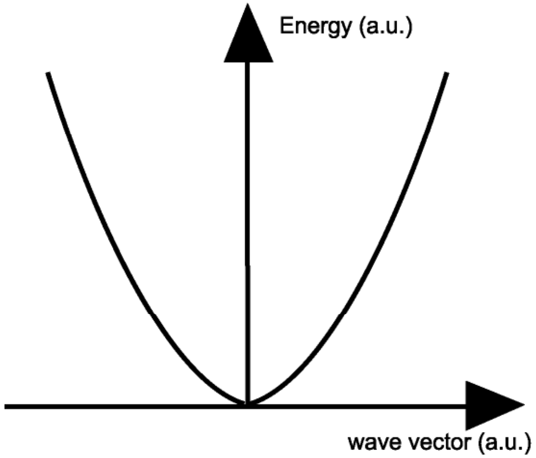
For free-space propagation, all values of frequency for photons and energy for electrons are permitted. This set of allowed continuous values of frequency (or energy) form together a band. The band structure refers to the characteristics of dependence of frequency ω (or energy) on wavevector k, called dispersion relation.

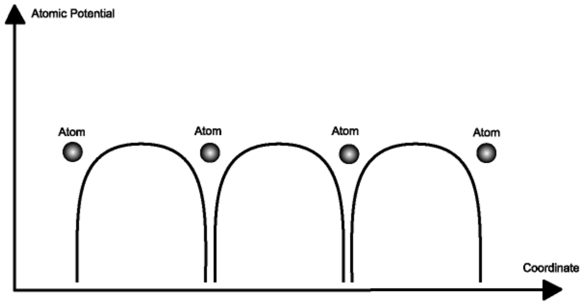
Energy band structure = Dispersion relation (ω-k relation)

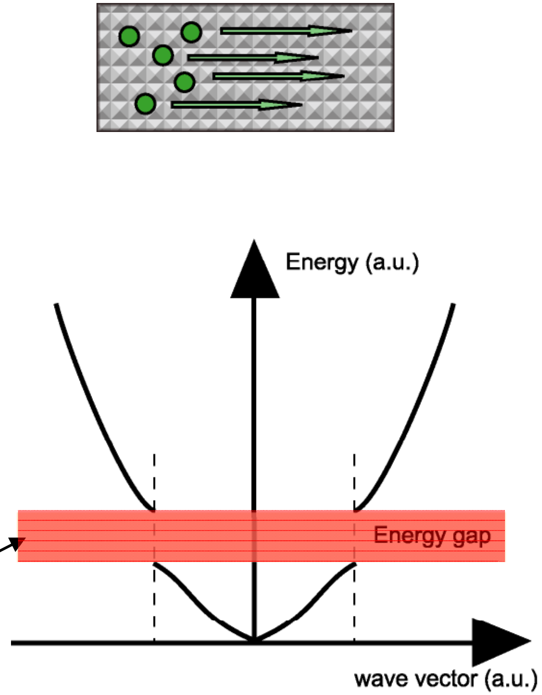
Photonic bandgap (PBG) is analogous to electron energy bandgap



$$E = \frac{\hbar^2}{2m} k^2$$



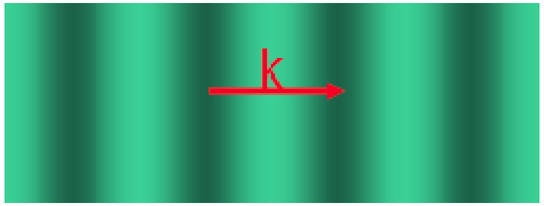




Gap in energy spectra of electrons arises in periodic structure

A simple example of the band-structure: vacuum (1d)

Vacuum: ε=1, μ=1, plane-wave solution to the Maxwell's equation:



$$\boxed{\mathbf{H}e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}}$$

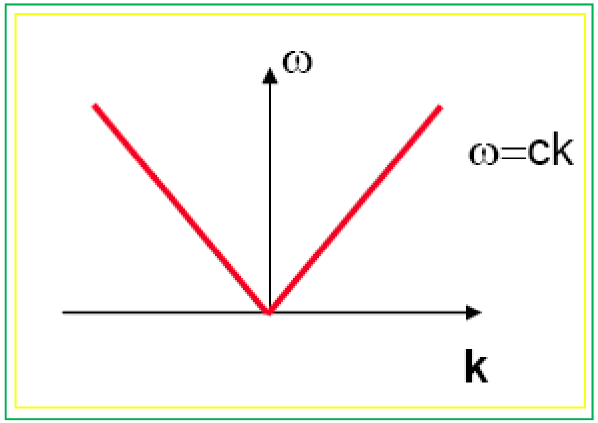
with a transversality constraints: $\mathbf{k} \bullet \mathbf{H} = 0$

A band structure, or dispersion relation defines the relation between the frequency ω, and the wavevector k.

$$\omega = c|\mathbf{k}|$$

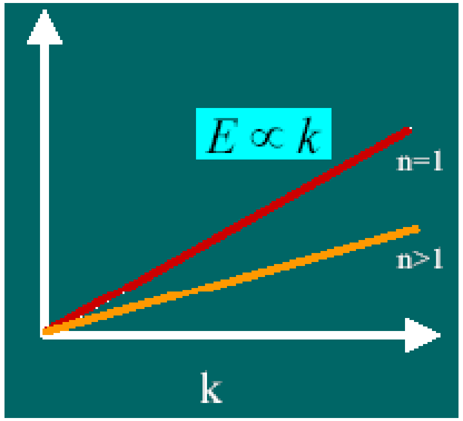
For a one-dimensional system, the band structure can be simply depicted as:

Dispersion curve (photonic band diagram)



PBG formation by periodic structures

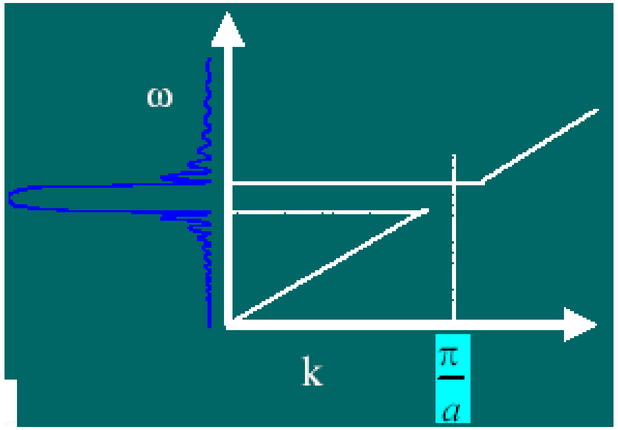
1. Dispersion curve for free space



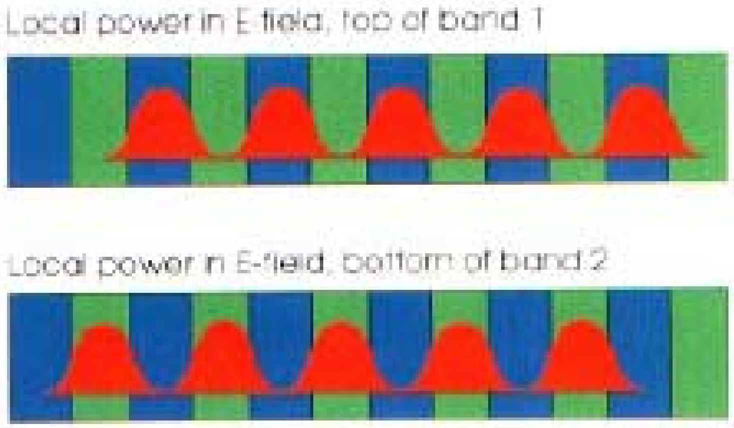
2. In a periodic system, when half the wavelength corresponds to the periodicity

$$\lambda/2 = a \quad k = \pi/a$$

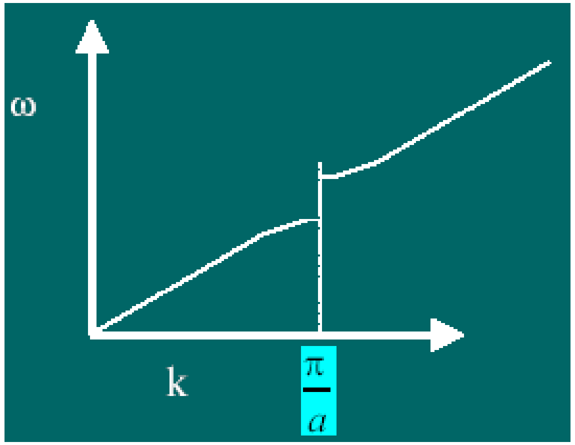
the Bragg effect prohibits photon propagation.



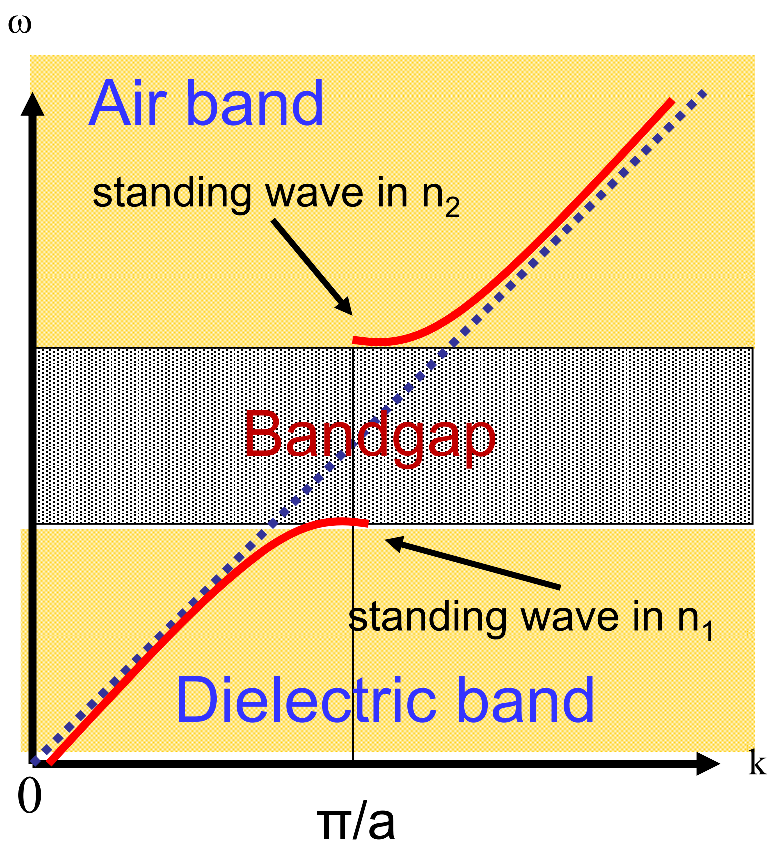
3. At the band edges, standing waves form, with the energy being either in the high or the low index regions

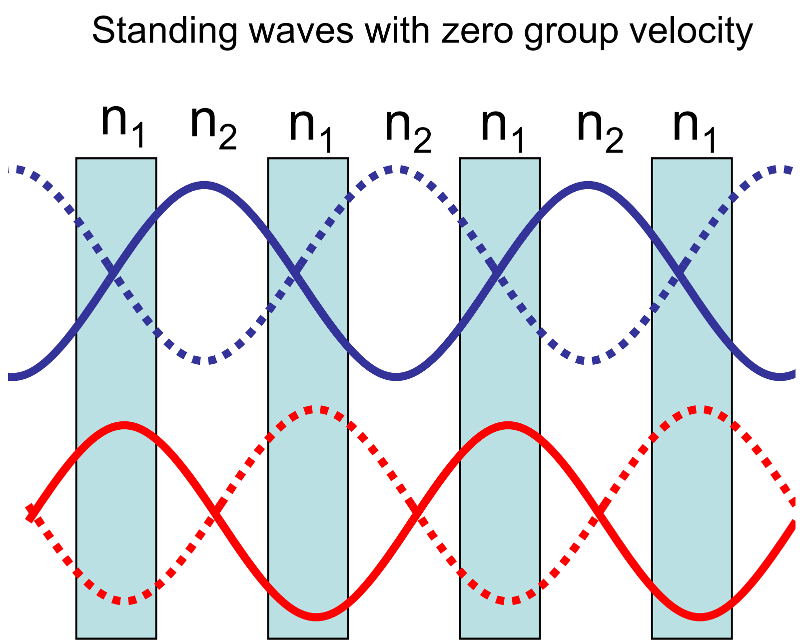


4. Standing waves transport no energy with zero group velocity



Standing waves at band edges

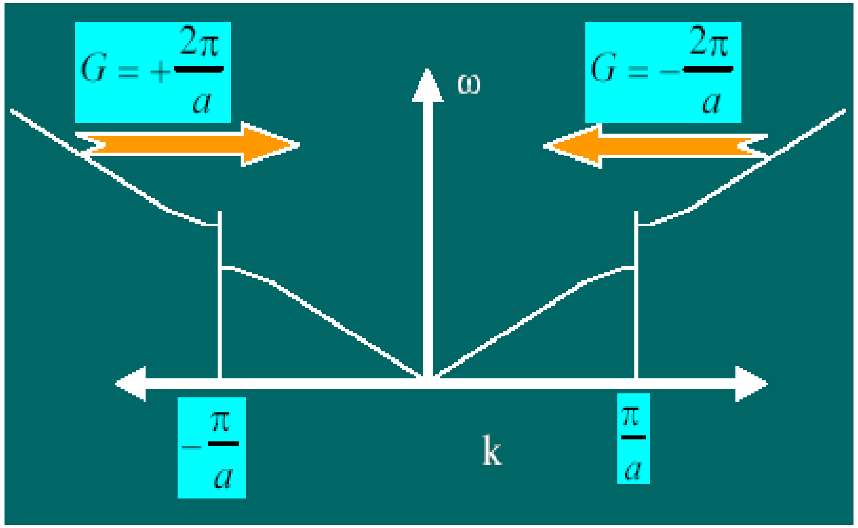


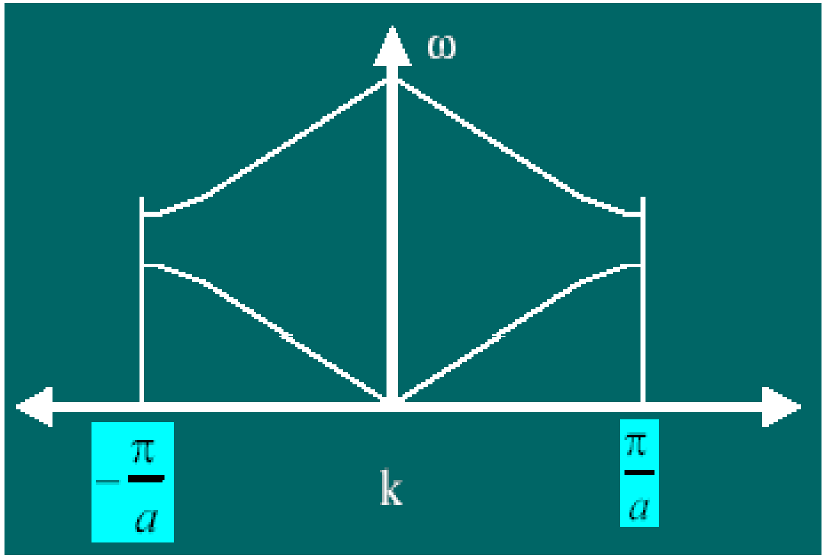


n_1: high index material
n_2: low index material

Reduced Brillouin zone

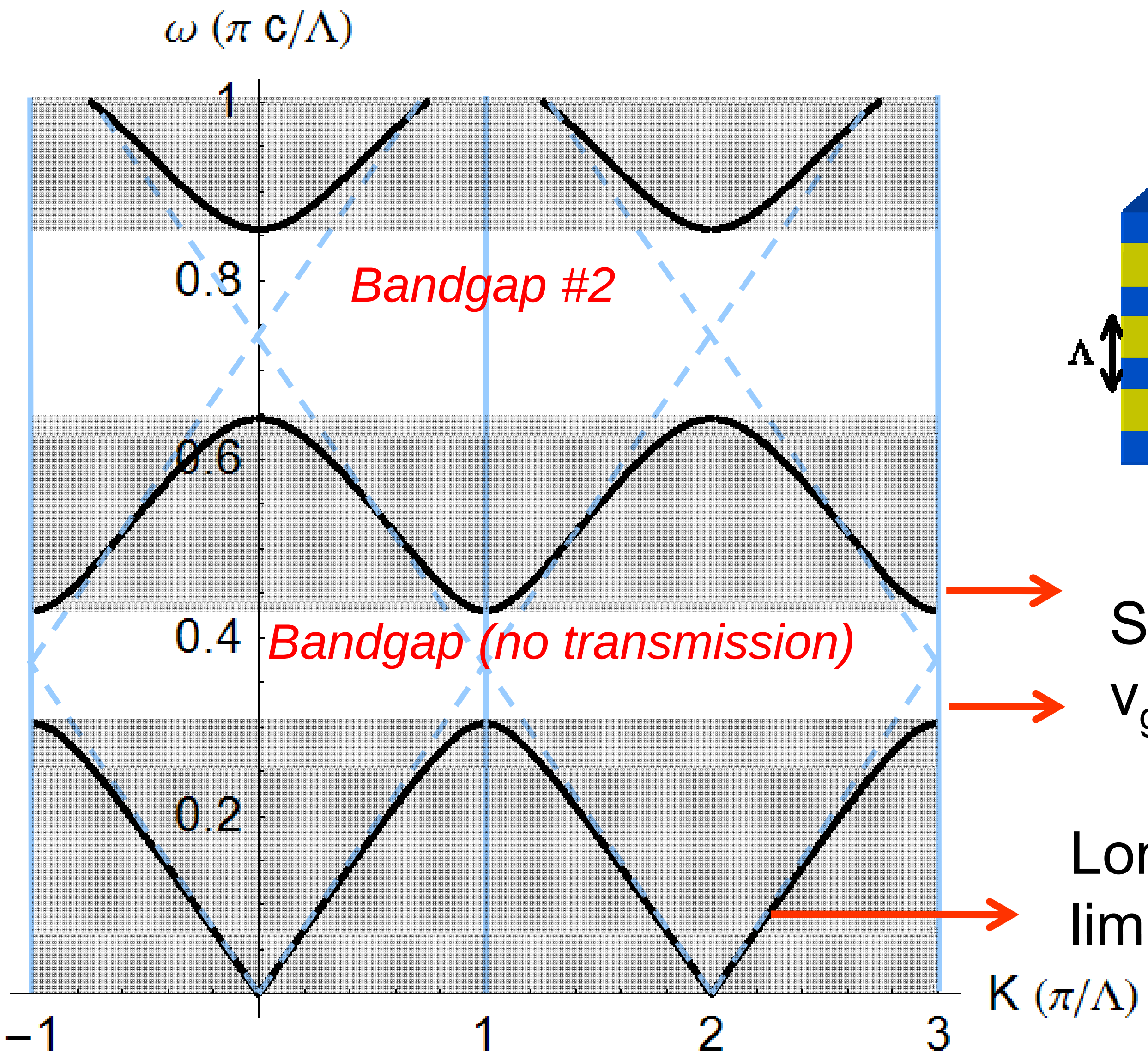
Plot the dispersion curves for both the positive and the negative sides, and then shift the curve segments with $|k|>\pi/a$ upward or downward one reciprocal lattice vectors.

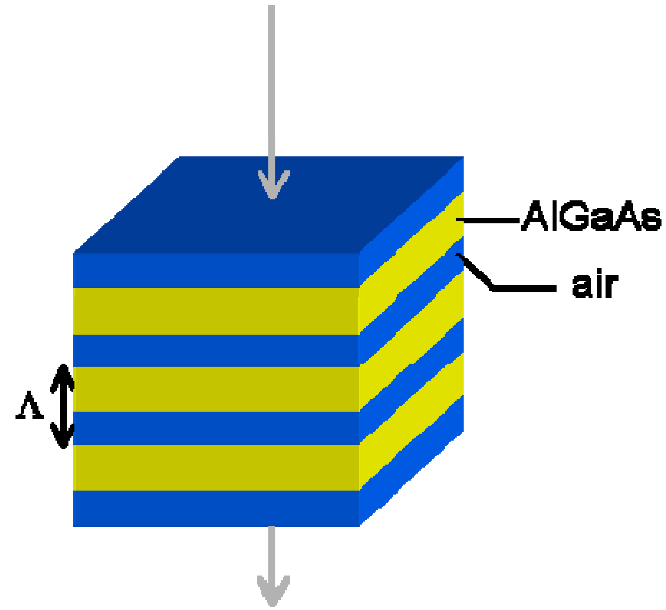




This reduced range of wave vectors is called the "Brillouin zone"

Photonic Band Gaps (PBG)





Standing wave

v_{group}=0

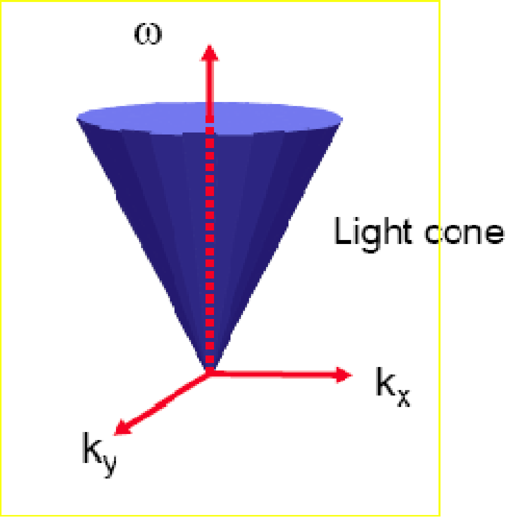
Long wavelength limit: effective index

Visualization of the vacuum band structure (2d)

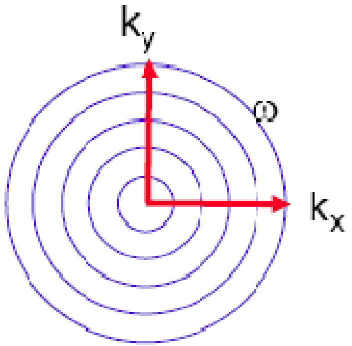
For a two-dimensional system:

$$\omega = c\sqrt{k_x^2 + k_y^2}$$

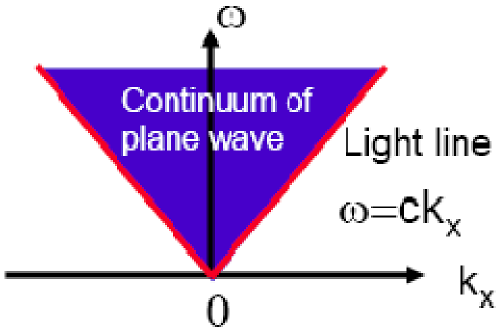
This function depicts a cone: light cone.



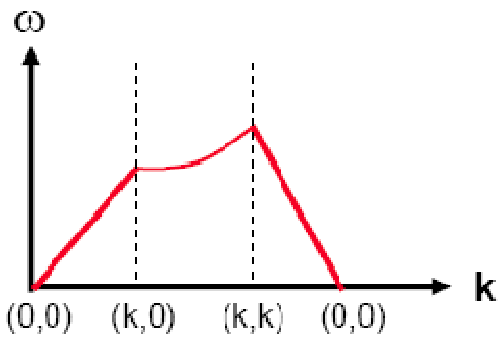
A few ways to visualize this band structure :



Constant frequency contour



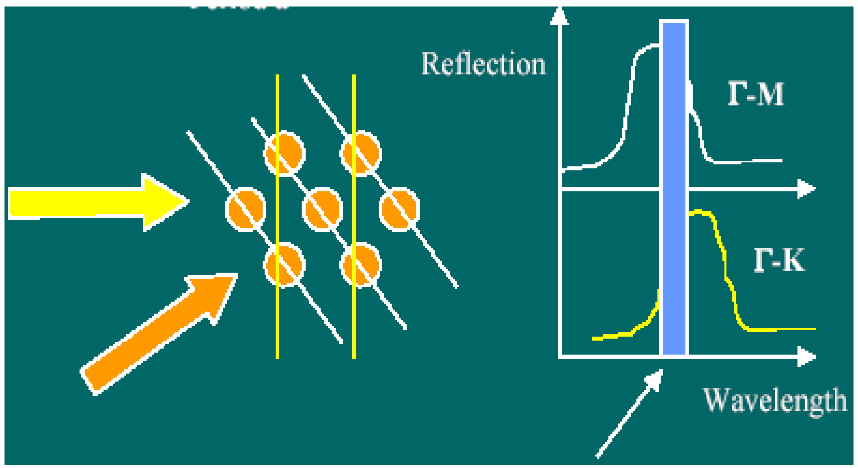
Projected band diagram



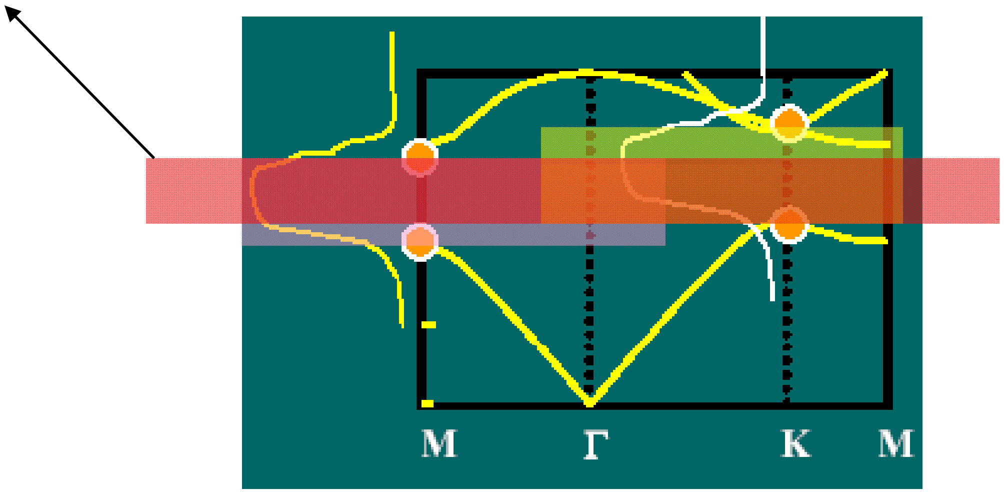
Band diagram along several "special" directions

2-D Photonic Crystals

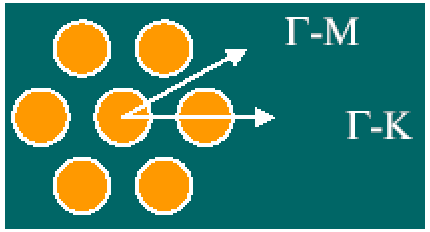
1. In 2-D PBG, different layer spacing, *a*, can be met along different direction. Strong interaction occurs when $\lambda/2 = a$.

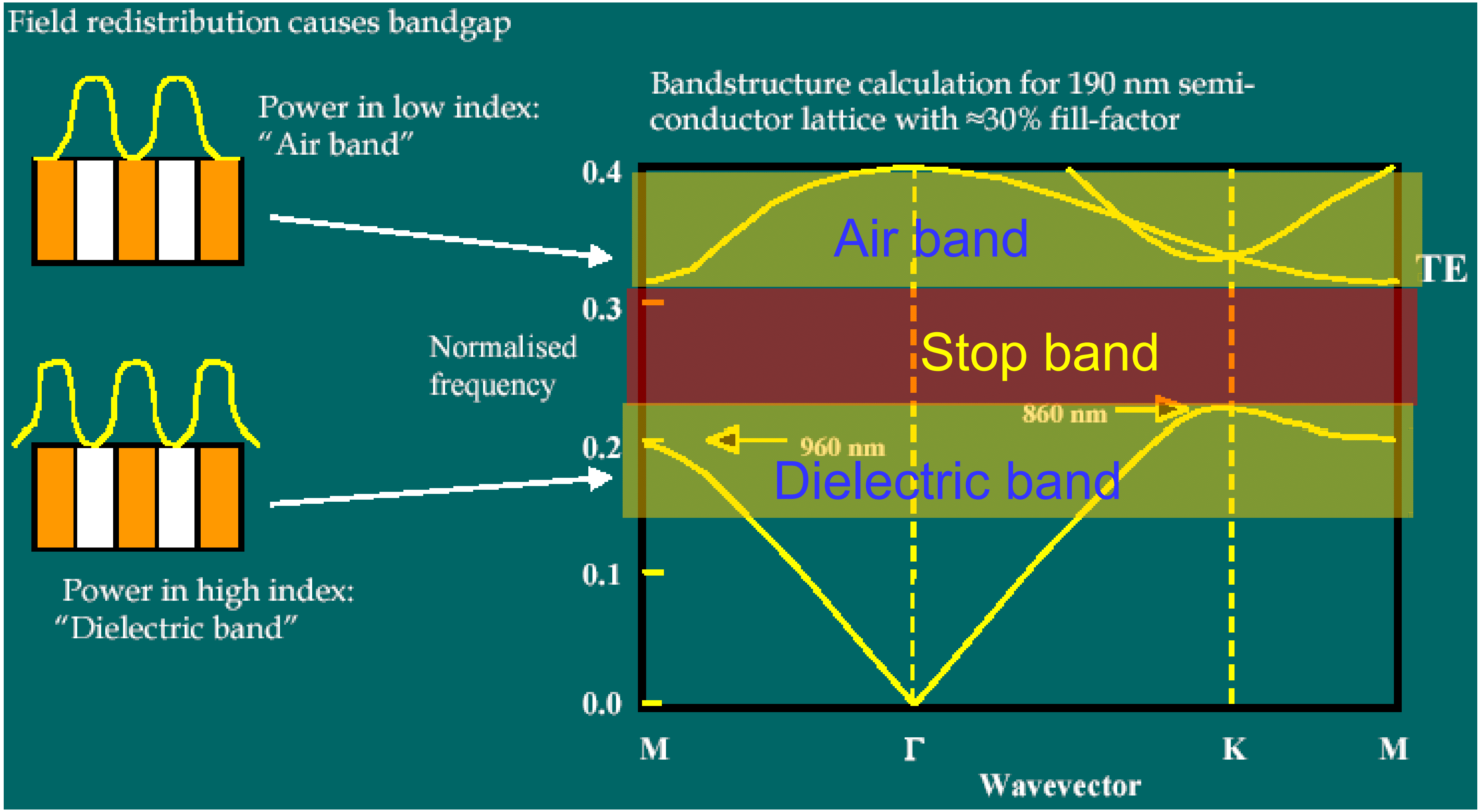


2. PBG (Photonic band gap) = stop bands overlap in all directions

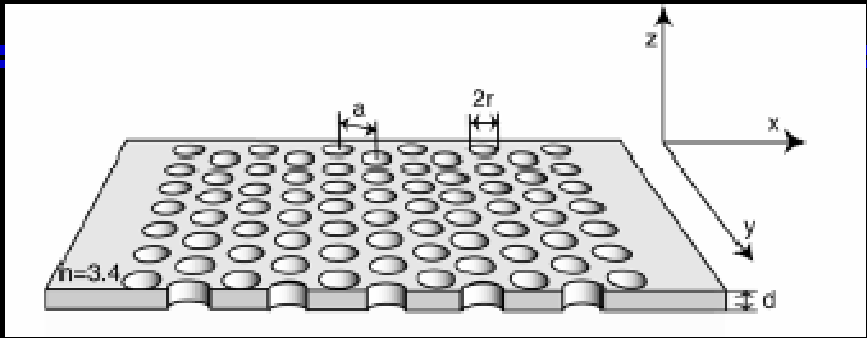


Band Diagram



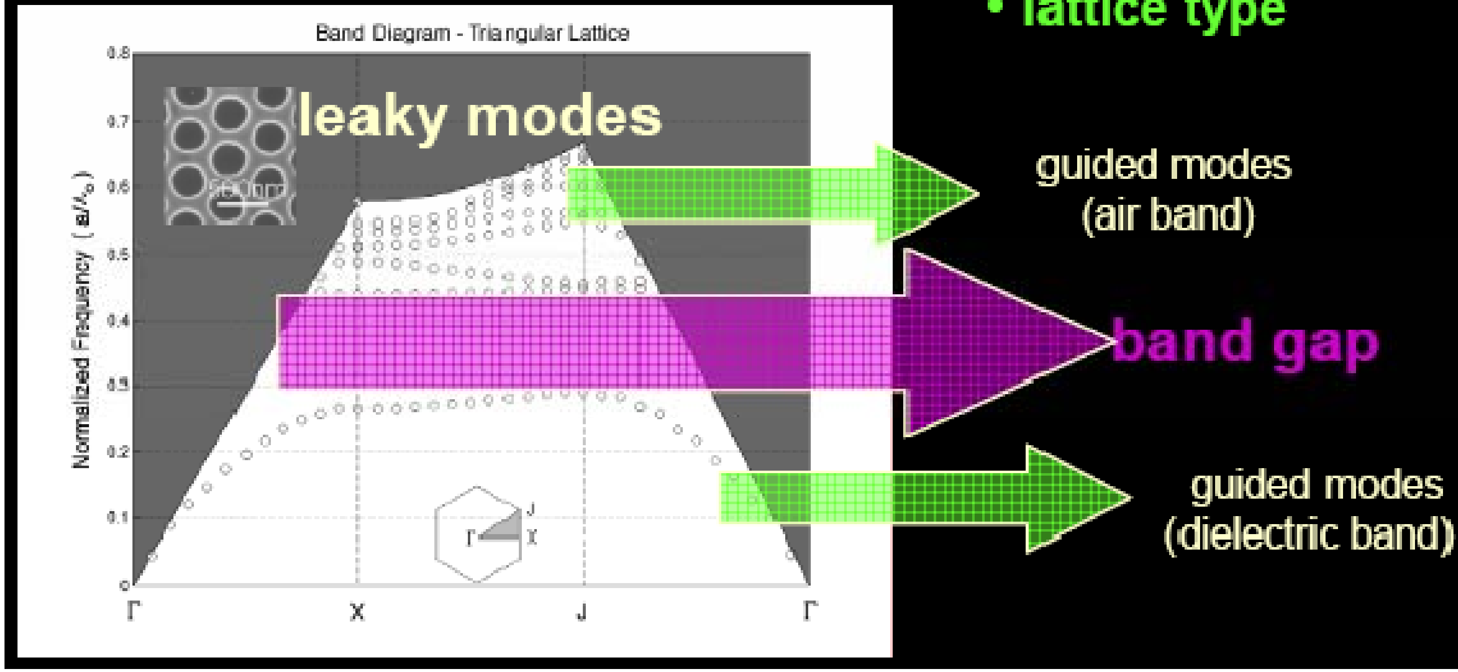


Band structure of a two-dimensional crystal



Dispersion diagram is determined by:

- **r** (hole radius)
- **a** (periodicity of lattice)
- **d** (slab thickness)
- **n** (refractive index: 3.4<n<3.5)
- **lattice type**



Contrast dependent band gap

Magnitude of the bandgap depends on index contrast

No contrast, no reflections, no gap

Weak contrast, reflected beam only enhanced if many interfaces contribute with *exactly the correct phase*: highly frequency selective: small gap

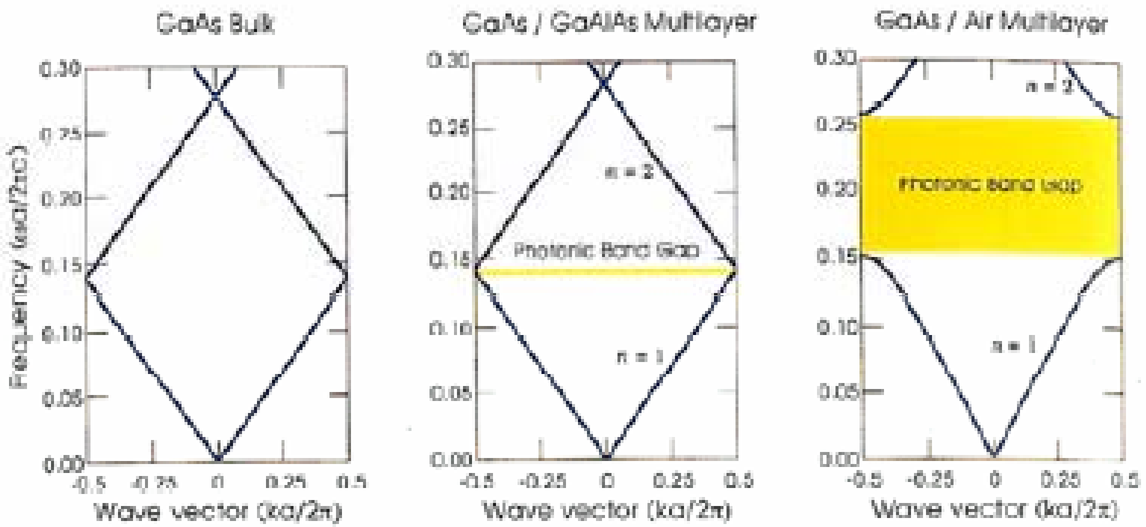


Figure 2 The photonic band structures for on-axis propagation, shown for three different multilayer films, all of which have layers of width 0.5*a*. *Left:* each layer has the same dielectric constant $\varepsilon = 13$. *Center:* layers alternate between $\varepsilon = 13$ and $\varepsilon = 12$. *Right:* layers alternate between $\varepsilon = 13$ and $\varepsilon = 1$.

From: *Photonic Crystals – Molding the flow of light*, Joannopoulos, Meade, and Winn

Angular dependence vs. photonic crystal lattice

2D structures: dispersion relation angle dependent
Similar to phonons in atomic lattices or electrons in periodic potentials
(but without exclusion principle!)

Joannopoulos, JD, Villeneuve, PR & Fan, S. Photonic crystals: putting a new twist on light. Nature 386, 143-149 (1997)

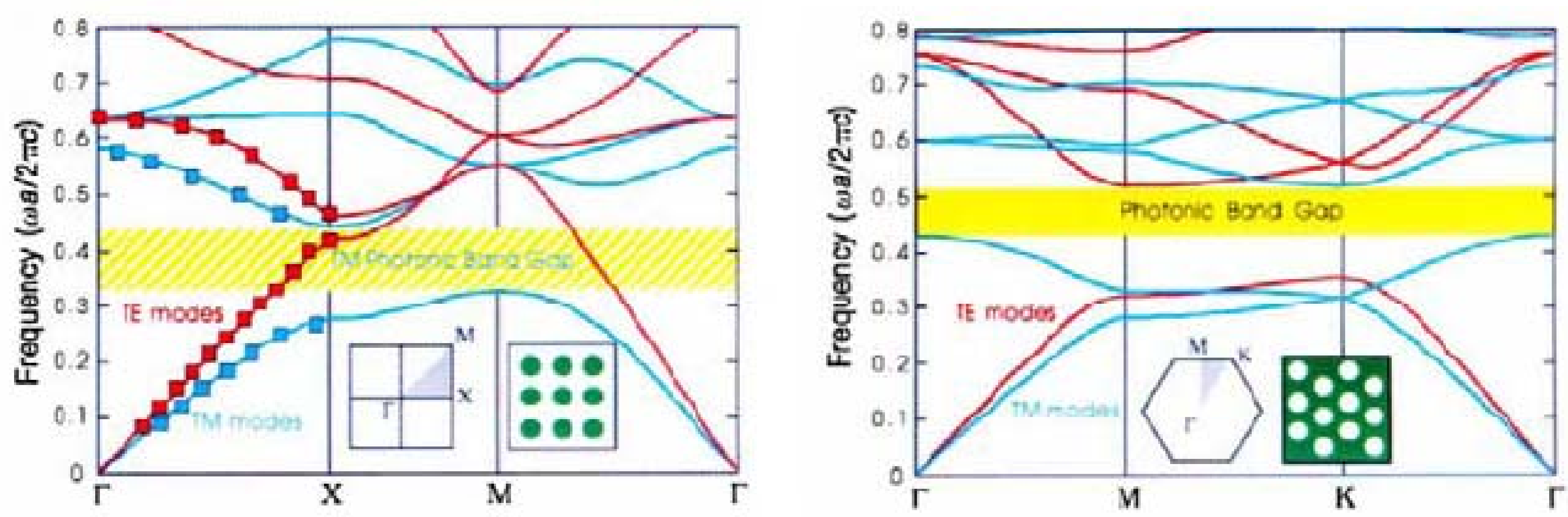
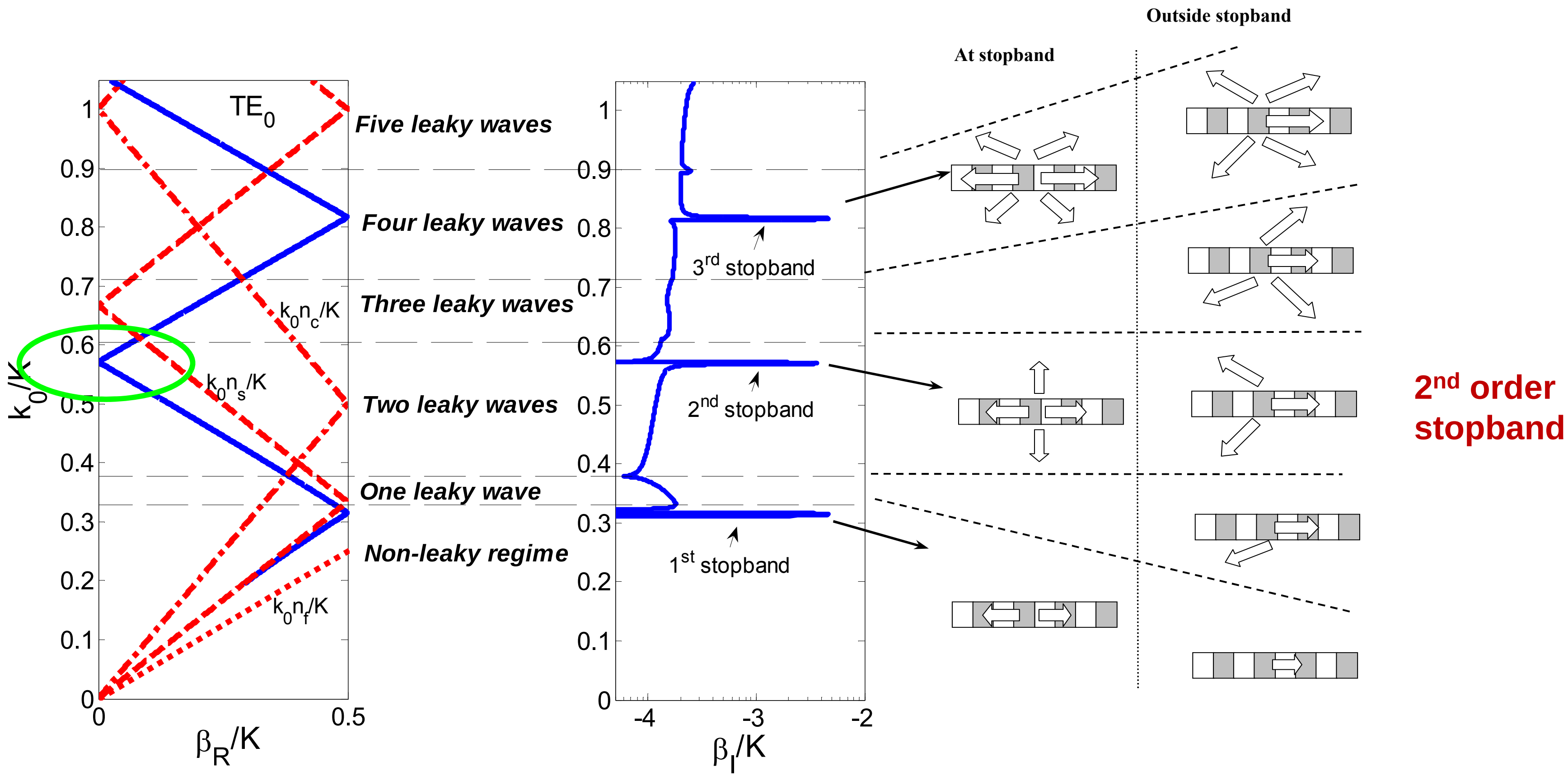


Figure 1 Top, photonic band structure for a square lattice of dielectric (ϵ = 8.9) rods in air with radius r = 0.2a, where a is the lattice constant. TM modes are shown in blue and TE modes in red. The solid lines are from theory and the squares represent experimental measurements along Γ to X from Robertson *et al.*[8] Bottom, photonic band structure for a triangular lattice of air cylinders (r = 0.48a) in dielectric (ϵ = 13). Note the presence of a complete photonic bandgap for both TE and TM polarizations in this case as shown by a solid yellow bar. In both panels high-dielectric material is indicated in green in the insets.

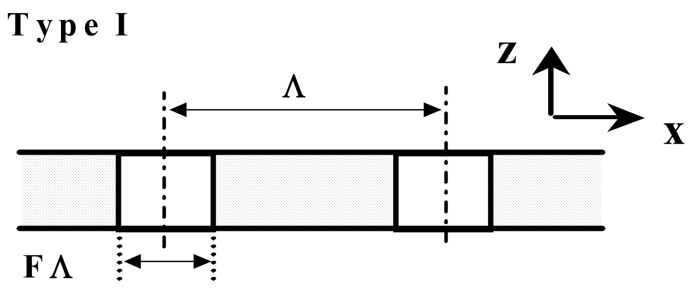
Photonic bandgaps (stop bands) in GMR gratings



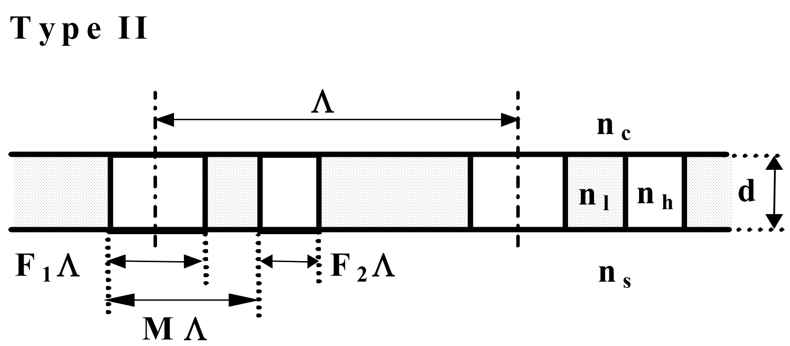
Complex propagation constant of leaky mode $\beta=\beta_R+j\ \beta_I$

Symmetry in grating profile of GMR elements

(a) Grating with symmetric profile



(b) Grating with asymmetric profile



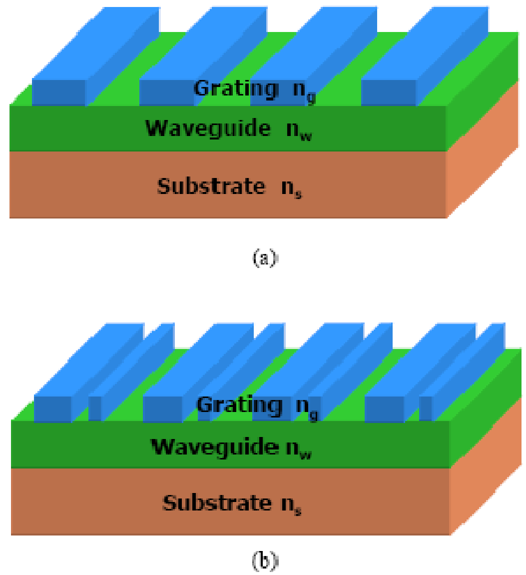
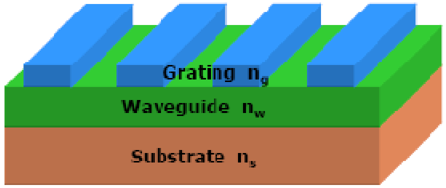


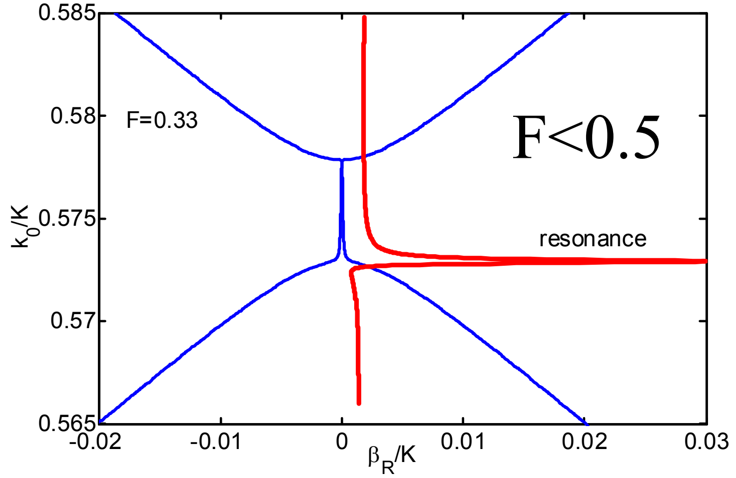
Fig. 1. Illustration of basic GMR filters associated with (a) symmetric and (b) asymmetric grating structures on a planar waveguide constructed on a transparent substrate.

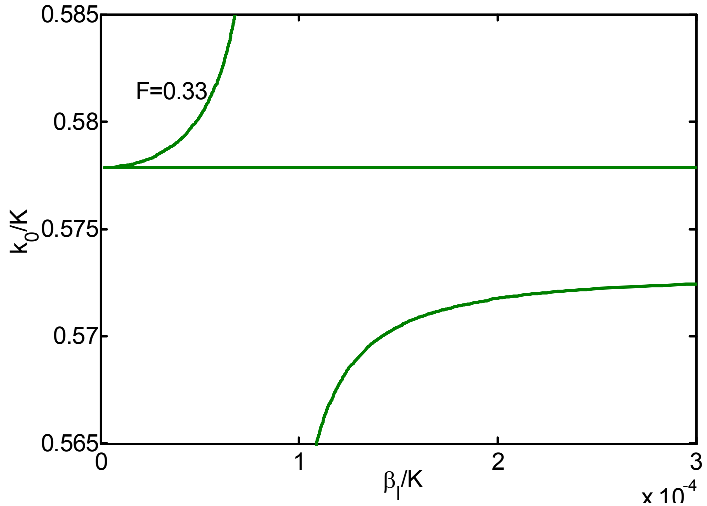
Details: Y. Ding and R. Magnusson, "Use of nondegenerate resonant leaky modes to fashion diverse optical spectra," Optics Express, May 3, 2004

Symmetric profile band diagram

Complex propagation constant of leaky mode $\beta=\beta_R+j\,\beta_I$







β_I=0, no leakage

Reduced BZ notation

Vincent/Neviere 1979: Asymmetry "defeats selection rule"

P. Vincent and M. Neviere, "Corrugated dielectric waveguides: A numerical study of the second-order stop bands," Appl. Phys. **20**, 345-351 (1979).

Perturbation model: 0,π phase differences of radiated fields (symmetric profile)

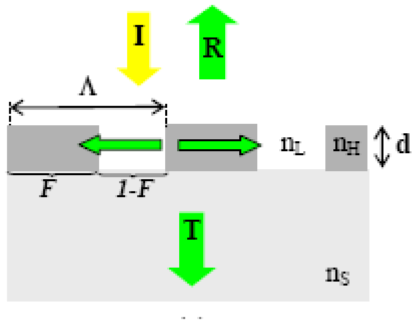
R. F. Kazarinov and C. H. Henry, "Second-order distributed feedback lasers with mode selection provided by first-order radiation loss," IEEE J. Quant. Elect. **QE-21**, 144-150 (1985).

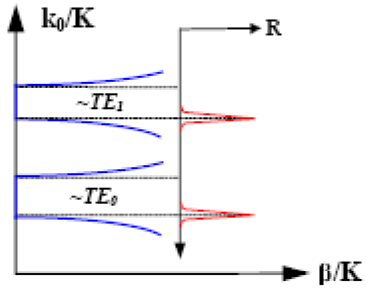
Numerical calculations of resonance at edges (symmetric profile)

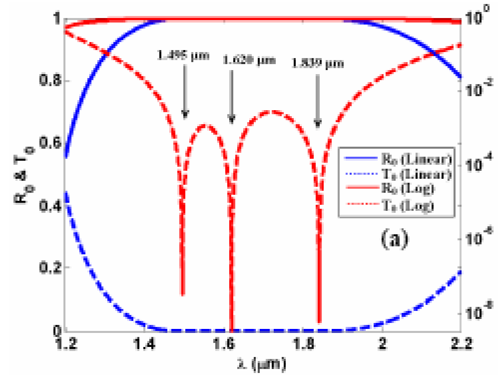
D. L. Brundrett, E. N. Glytsis, T. K. Gaylord, and J. M. Bendickson, "Effects of modulation strength in guided-mode resonant subwavelength gratings at normal incidence," J. Opt. Soc. Am. A. **17**, 1221-1230 (2000).

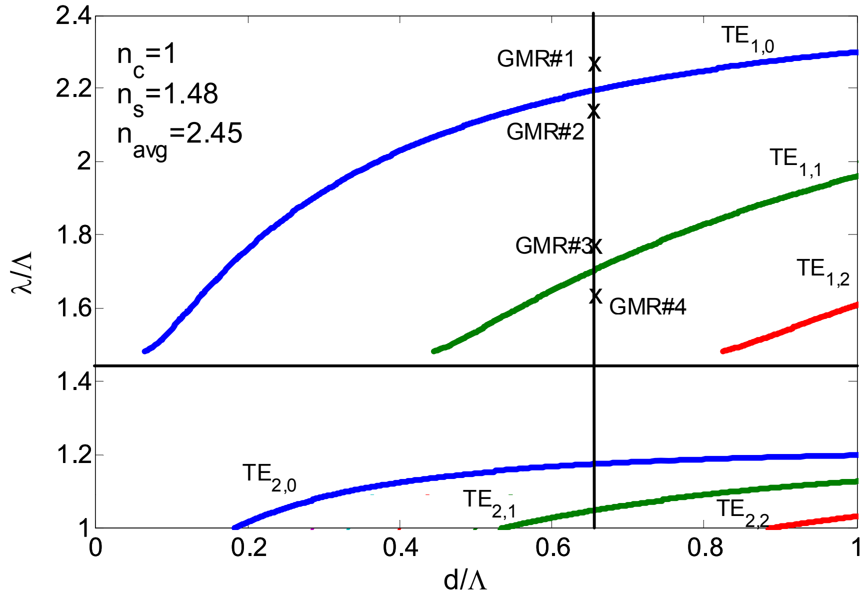
Design of multi-resonance elements

- Resonance locations are estimated with the eigenfunction of homogeneous waveguide (modulation~0)
- Numerical RCWA computations







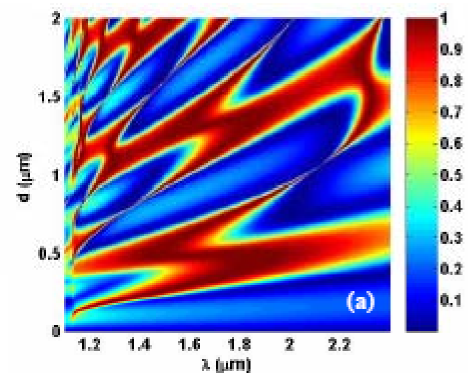


Notation:

$TE_{m,\nu}$

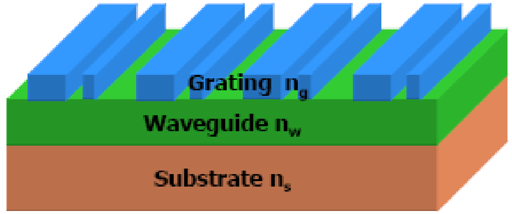
m represents the evanescent diffraction order exciting the ν-th mode

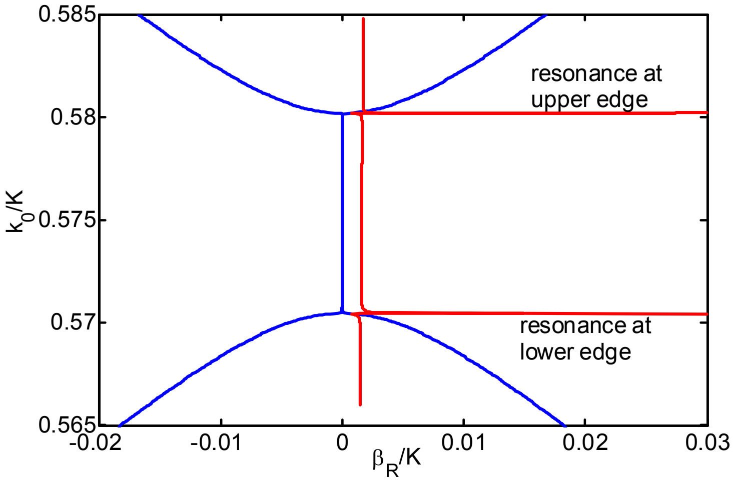
Reflectance map

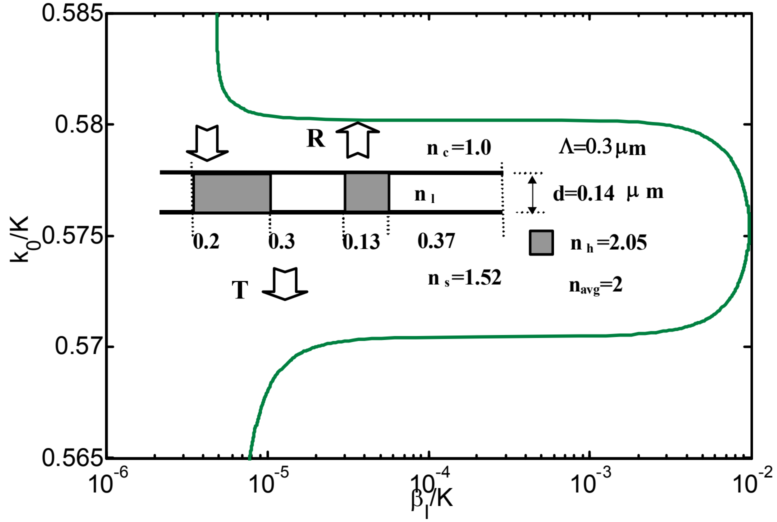


Band diagram of asymmetric profile

Weak modulation



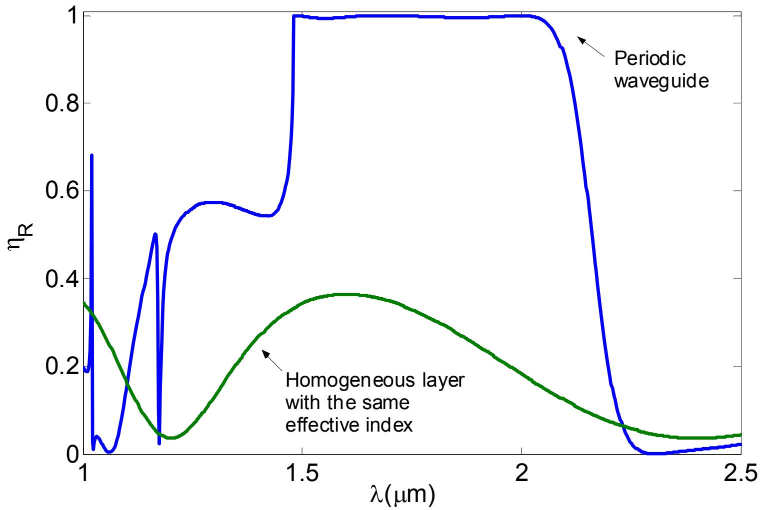


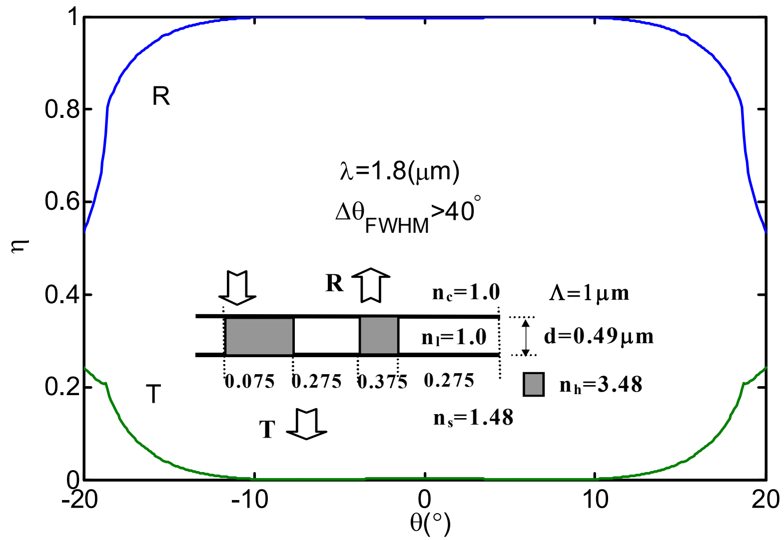


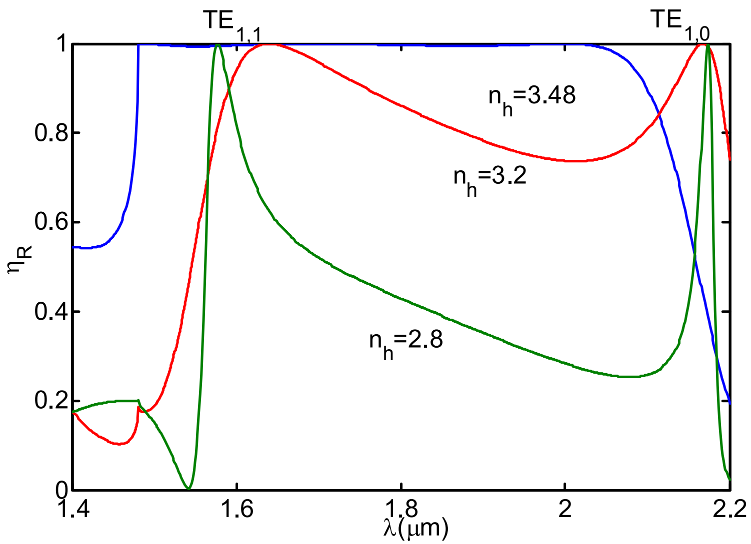
- Both edges are lossy
- GMRs appear at both edges
- Resonance separation depends on size of bandgap
- Resonance degeneracy of symmetric case removed

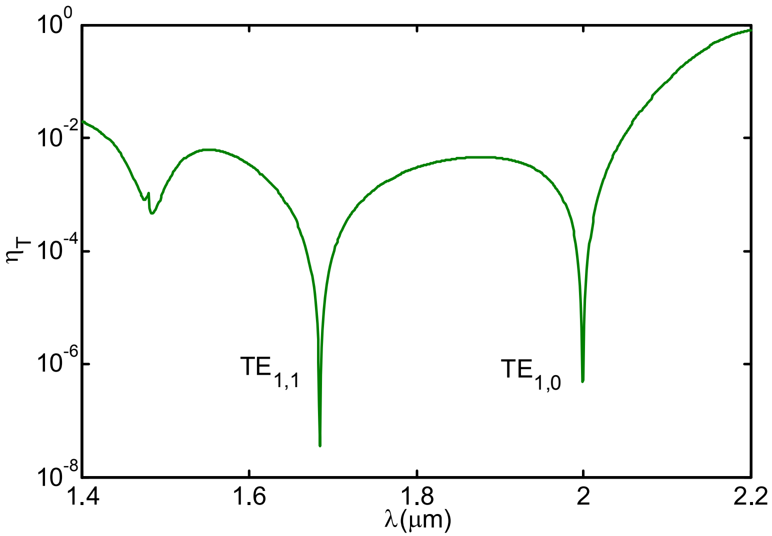
Resonant SOI leaky-mode reflector

Single layer, TE polarization, 2 resonance peaks



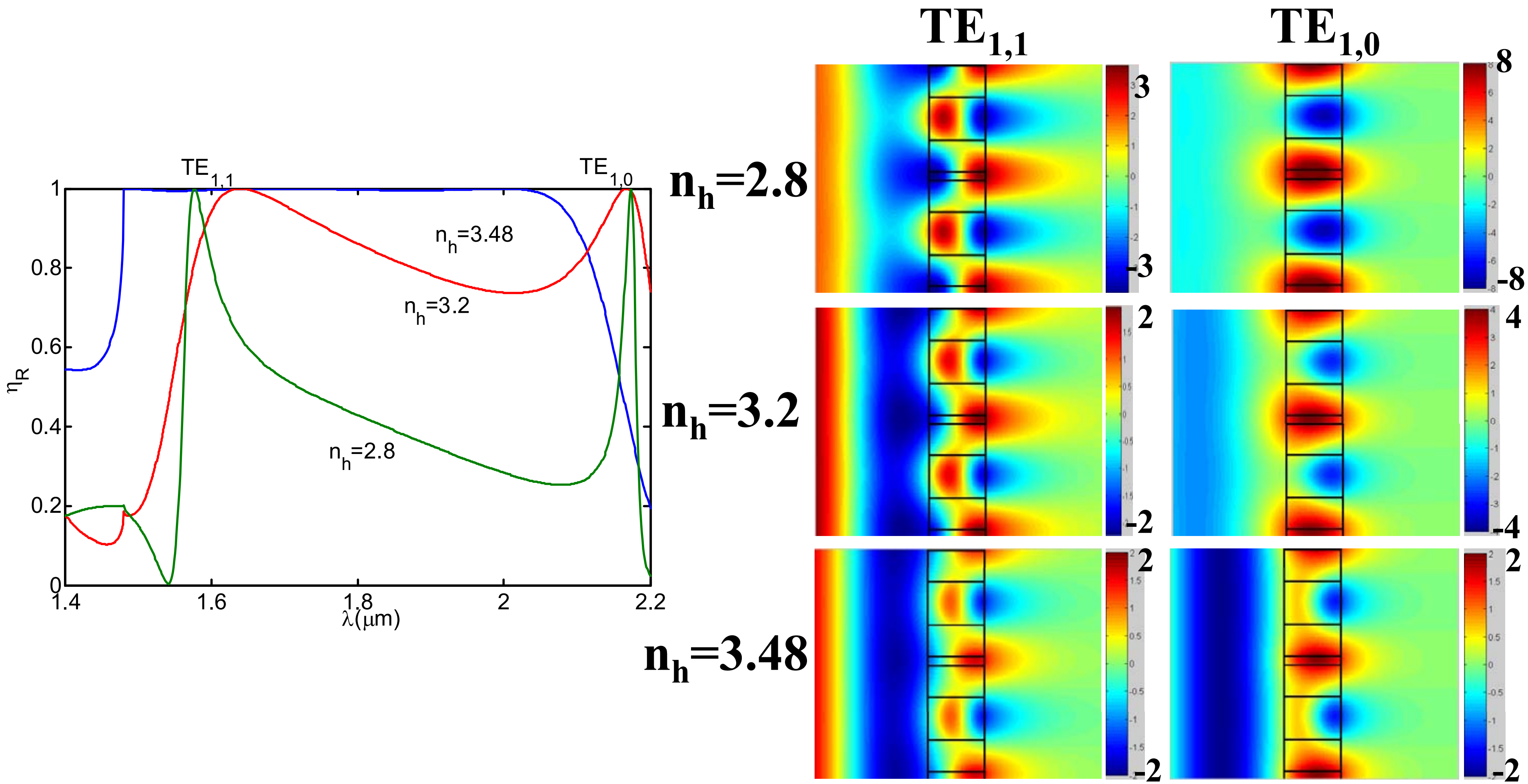




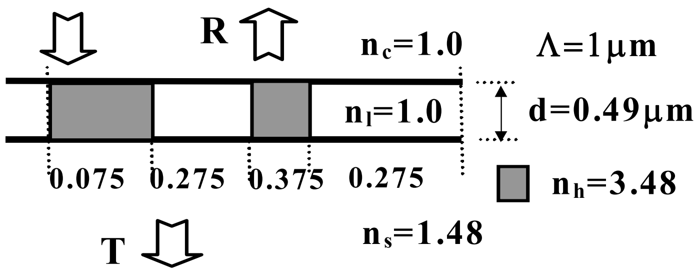


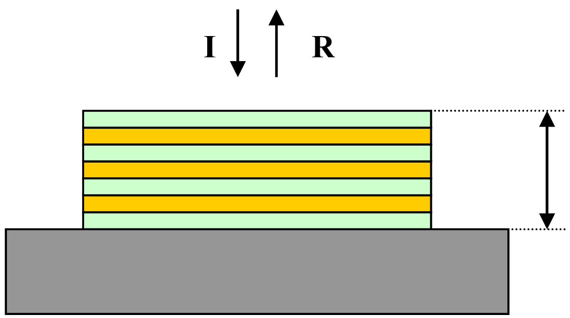
Resonant leaky-mode reflector: E-fields

Single layer, TE polarization, 2 resonance peaks



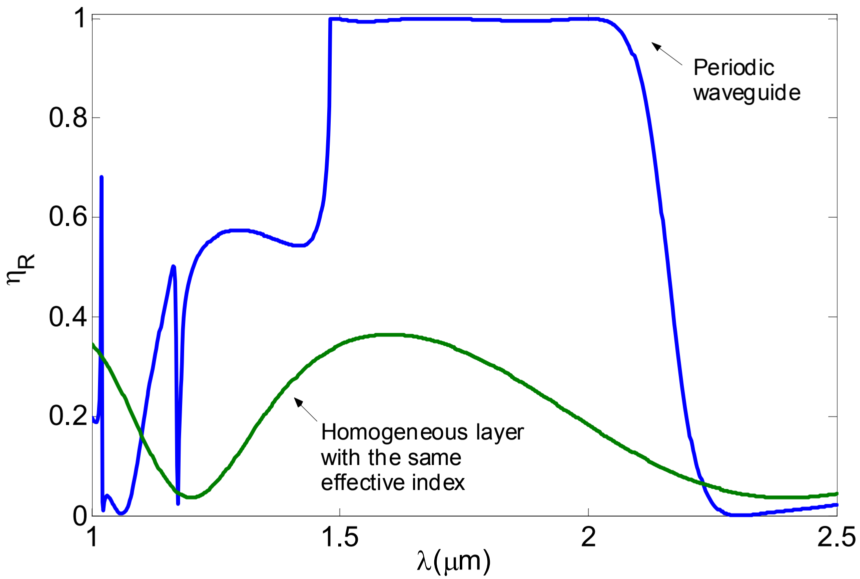
GMR reflectors vs Bragg stacks

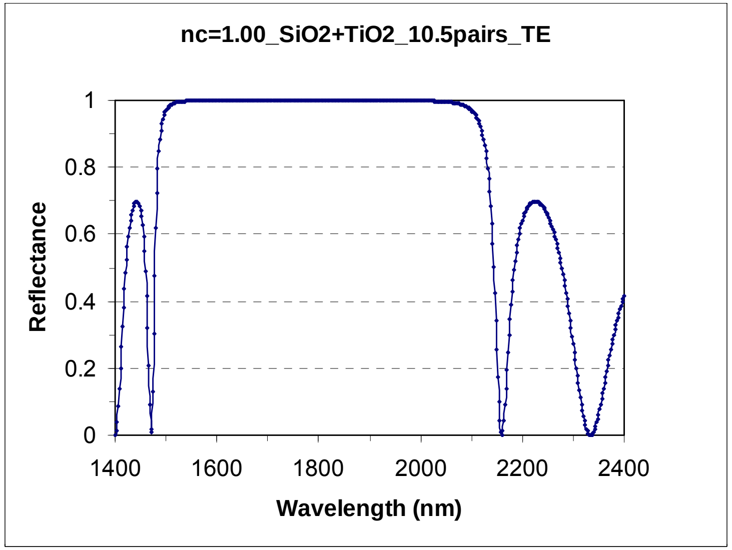




Single-layer SOI resonance device

21-layer SiO_2/TiO_2 Bragg stack

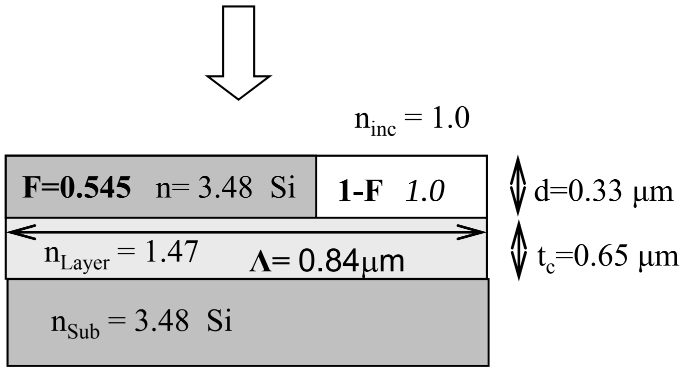


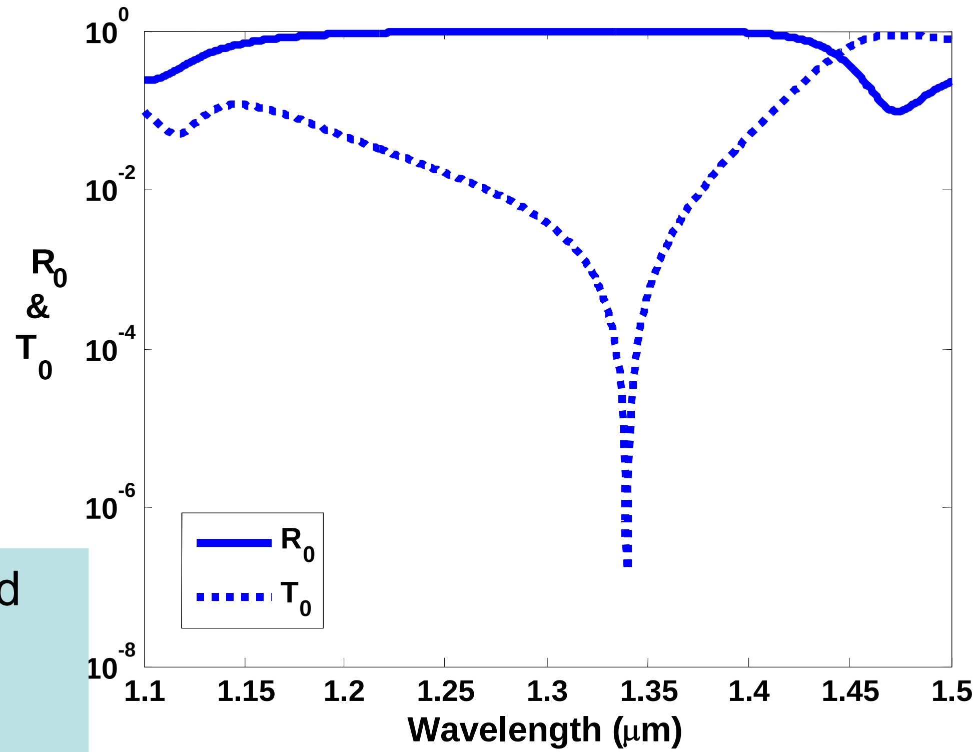


~600 nm wide reflection band in each case

Wideband SOI reflector

Single resonance, TE polz



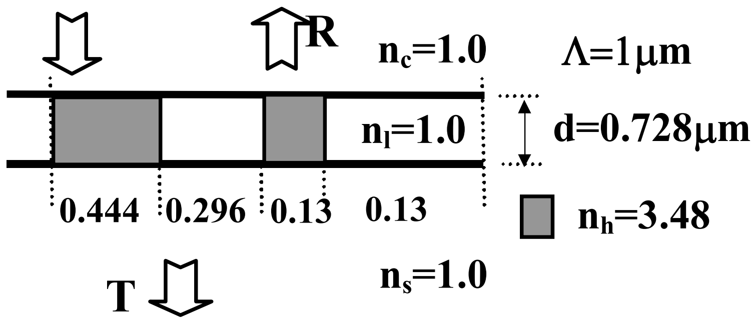


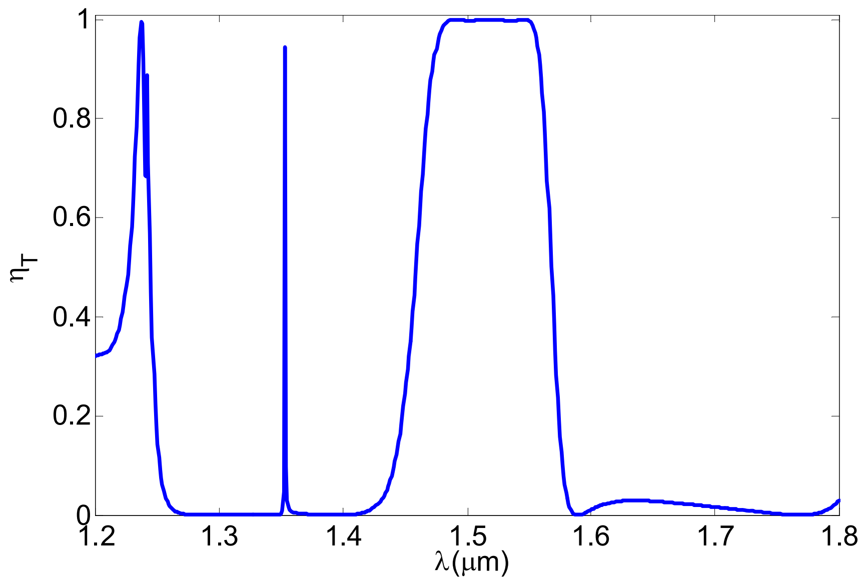
Single-resonance TM-polz wideband reflector experiment reported in:

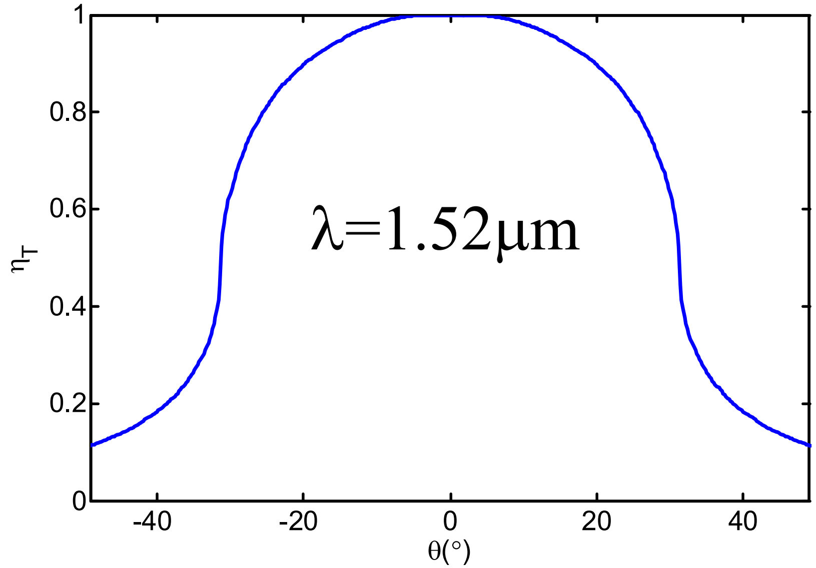
Mateus et al, IEEE PTL, July 2004.

Resonant SOI leaky-mode transmission element

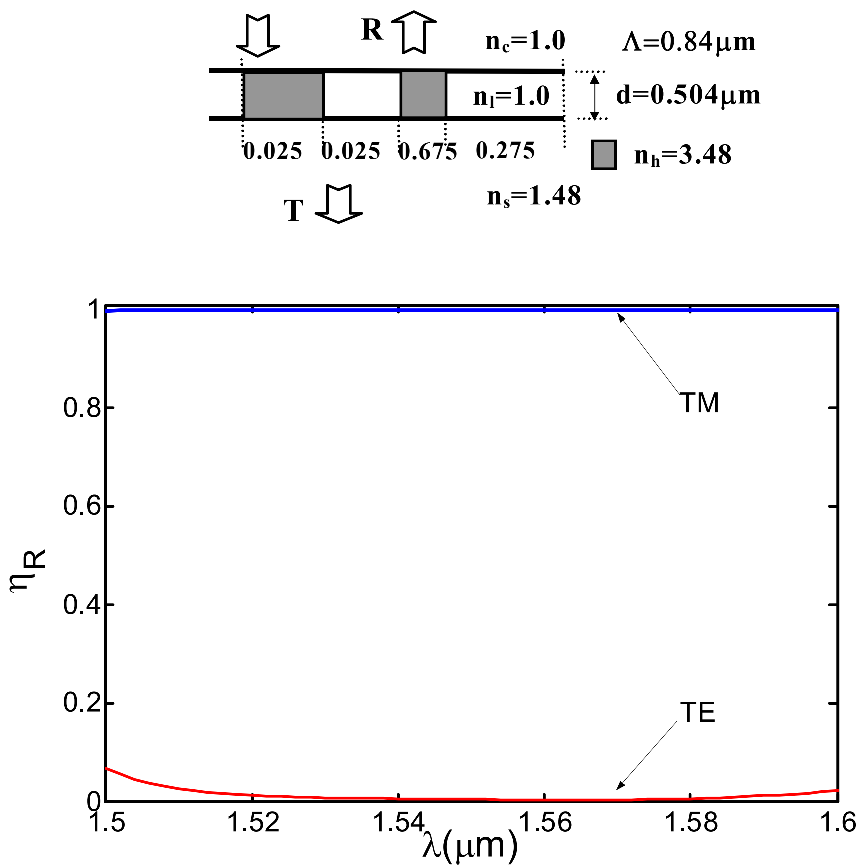
Single layer, TE polarization, ~100 nm flattop

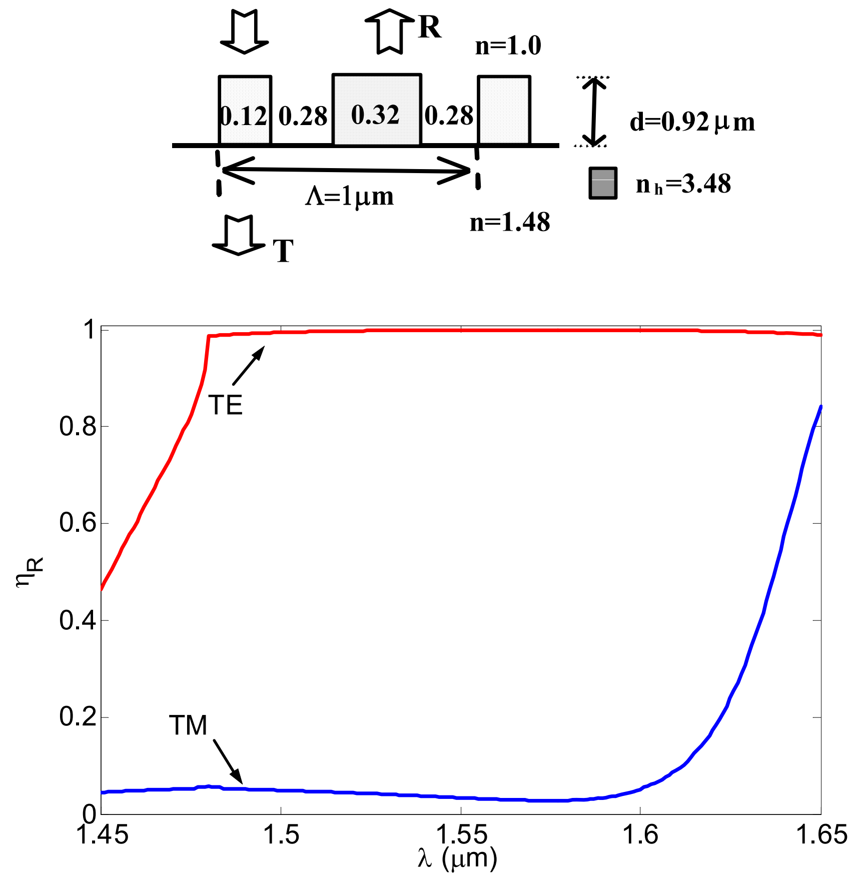






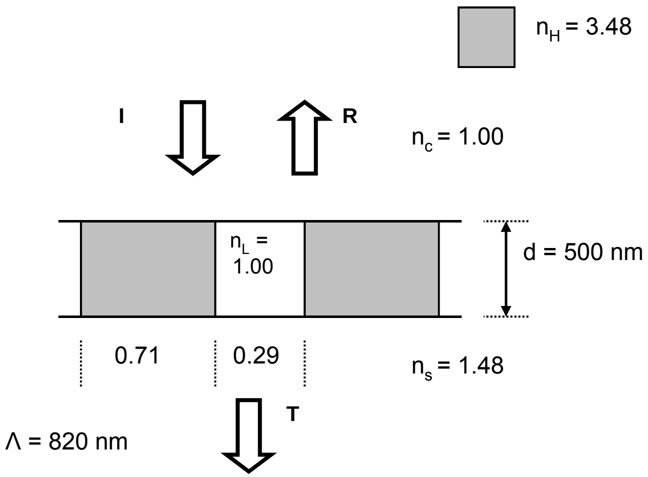
Resonant SOI leaky mode polarizers

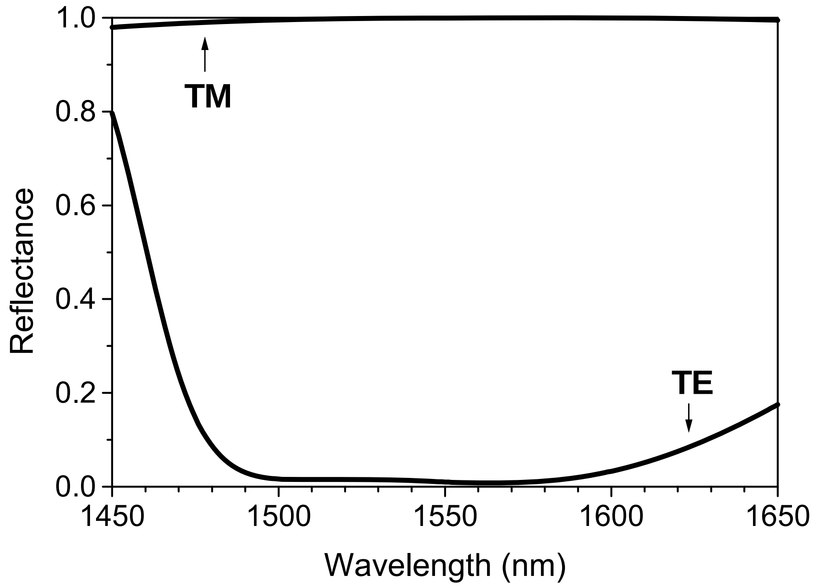




Y. Ding and R. Magnusson, "Resonant leaky-mode spectral-band engineering and device applications," *Optics Express,* vol. 12, 5661-5674 (2004).

Fabricated SOI single-layer ~100 nm polarizer

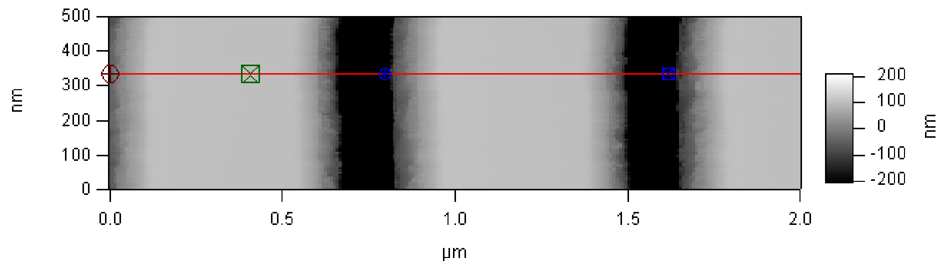


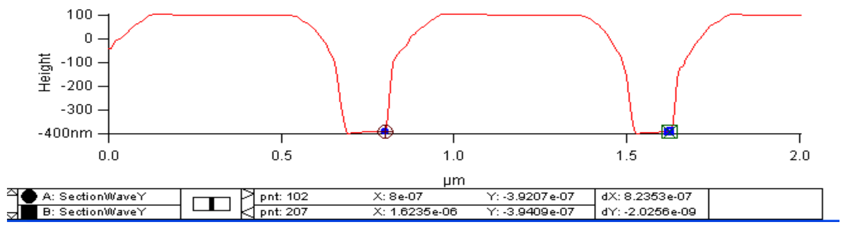


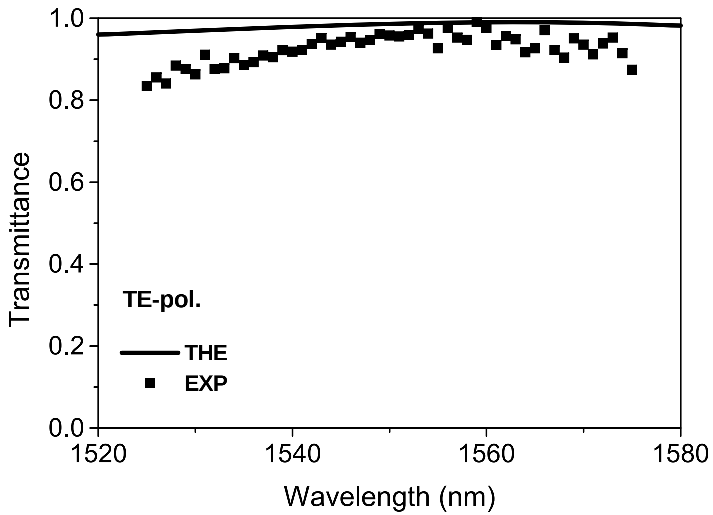
Goal: Simple fab; higher quality via more complex distribution within period

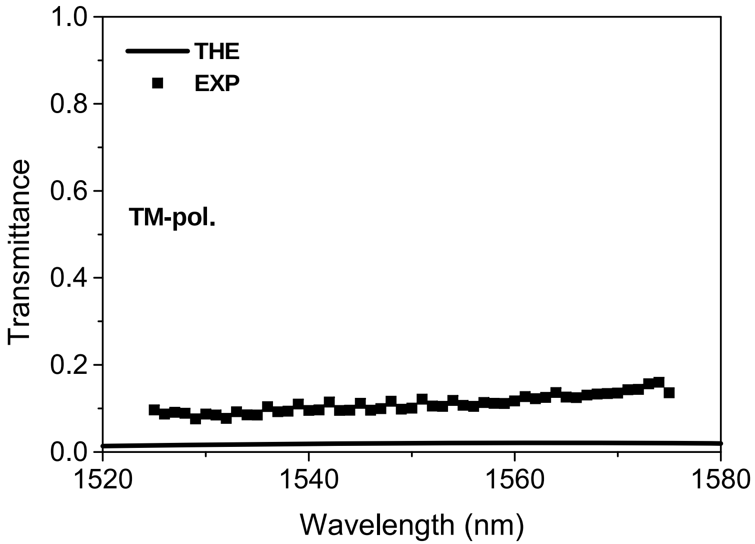
AFM image and preliminary polarizer data

Electron-beam writing with reactive ion etching









Leaky-mode resonance technology: Application summary

- Narrow-band reflection (bandstop)/transmission (bandpass) filters ($\Delta\lambda$~sub nm)
- Wide-band reflection (bandstop)/transmission (bandpass) filters ($\Delta\lambda$~100's nm)
- Tunable filters, EO modulators, and switches
- Mirrors for vertical cavity lasers
- Wavelength division multiplexing (WDM)
- Polzarization independent elements
- Reflectors
- Polarizers
- Security devices
- Laser resonator frequency selective mirrors
- Non-Brewster polarizing mirrors
- Laser cavity tuning elements
- Spectroscopic biosensors
- Tunable display pixels

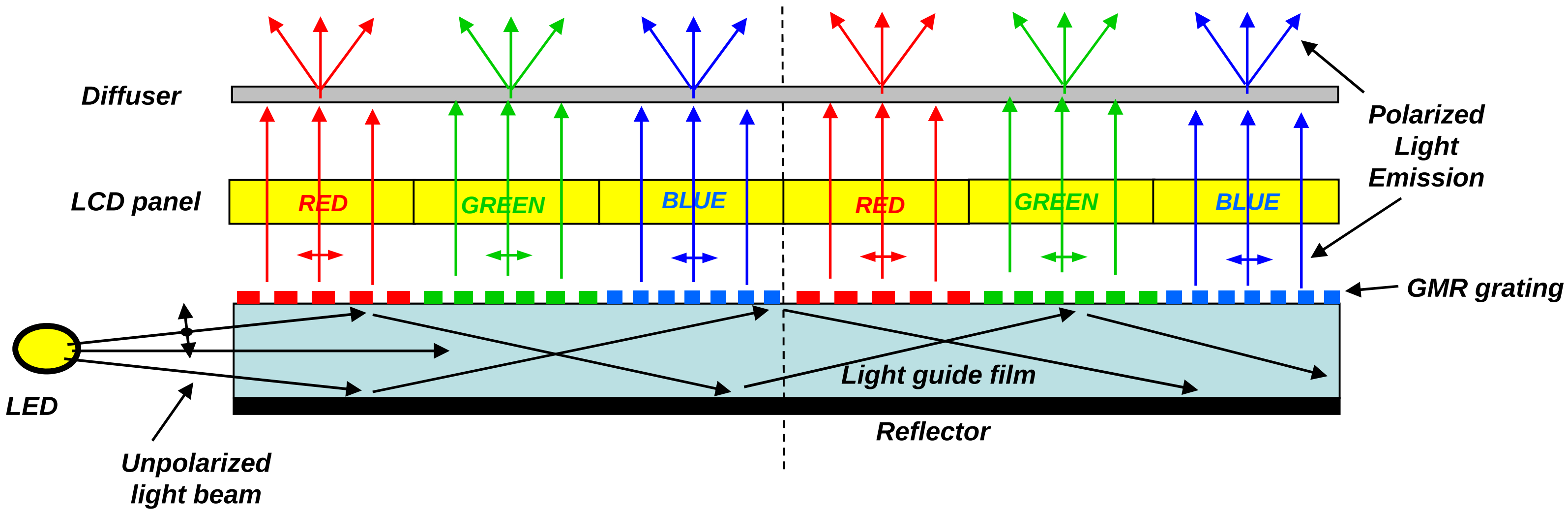
Leaky-mode resonance photonics: An enabling technology platform

- Interesting physics
- Complex, interacting resonant leaky modes
- Remaining challenges in analysis
- Remaining challenges in fabrication
- Many potential application fields
- Applications emerging
- Favorable area for R&D&A

In summary

Key notes

1. What is the GMR effect of waveguide gratings?
2. What is the photonic band structure (or, dispersion relation)?
3. What can we play with GMR filters for display?
4. What is the practical difficulties to be solved in GMR applications?



Next lecture at 07/07

(06/23)	Introduction: Micro- and nano-optics based on diffraction effect for next generation technologies
(06/30)	Guided-mode resonance (GMR) effect for filtering devices in LCD display panels
(07/07)	**Surface-plasmons: A basic**
(07/14)	Surface-plasmon waveguides for biosensor applications
(07/21)	Efficient light emission from LED, OLED, and nanolasers by surface-plasmon resonance