Advanced Electromagnetics:
21^{st} Century Electromagnetics

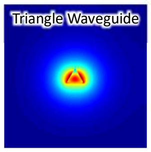
Coupled-Mode Devices

Lecture Outline

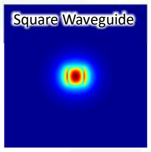
- Review
- Codirectional Devices
  - Directional couplers
  - Coupled-line filters
  - Multimode interference coupler
  - Long period gratings
- Medium-Period Grating Devices
  - Grating couplers
  - Guided-mode resonance filters
- Contradirectional Devices
  - Bragg gratings

Review

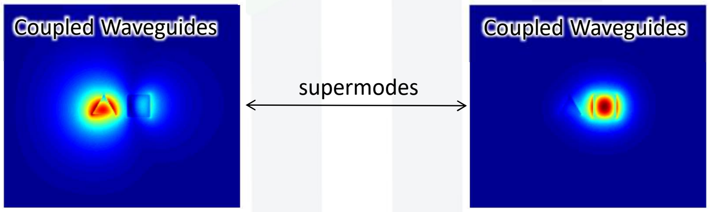
Waveguides in Proximity



$$\vec{E}_1 = \vec{E}_{0,1}(x,y)\,e^{-j\beta_1 z}$$
$$\vec{H}_1 = \vec{H}_{0,1}(x,y)\,e^{-j\beta_1 z}$$



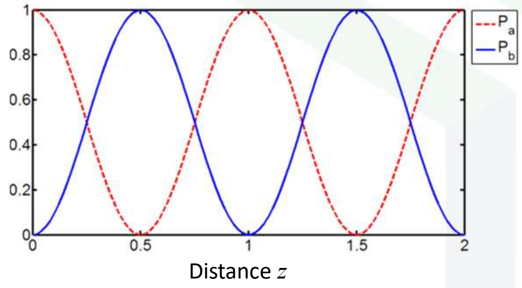
$$\vec{E}_2 = \vec{E}_{0,2}(x,y)\,e^{-j\beta_2 z}$$
$$\vec{H}_2 = \vec{H}_{0,2}(x,y)\,e^{-j\beta_2 z}$$

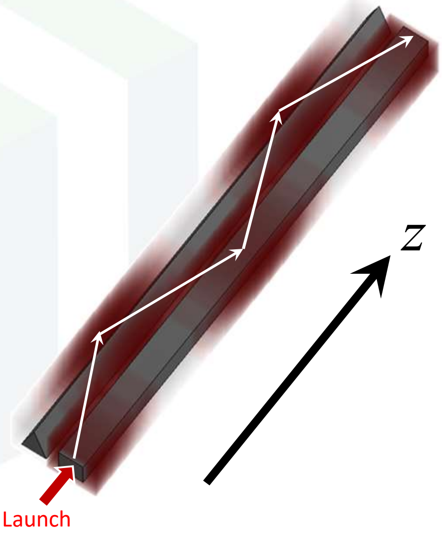


$$\vec{E} = A(z)\vec{E}_1 + B(z)\vec{E}_2$$
$$\vec{H} = A(z)\vec{H}_1 + B(z)\vec{H}_2$$

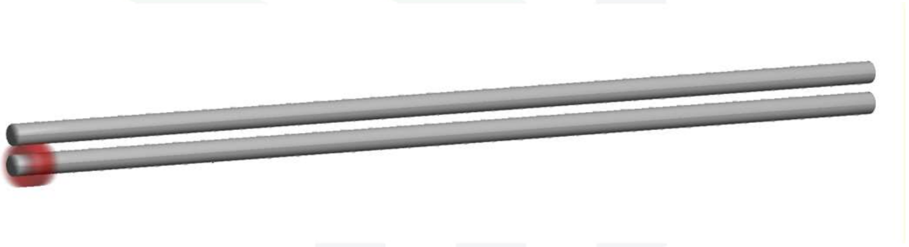
Perturbation analysis
→ Modes unperturbed by other guide

Visualization of Coupled-Modes

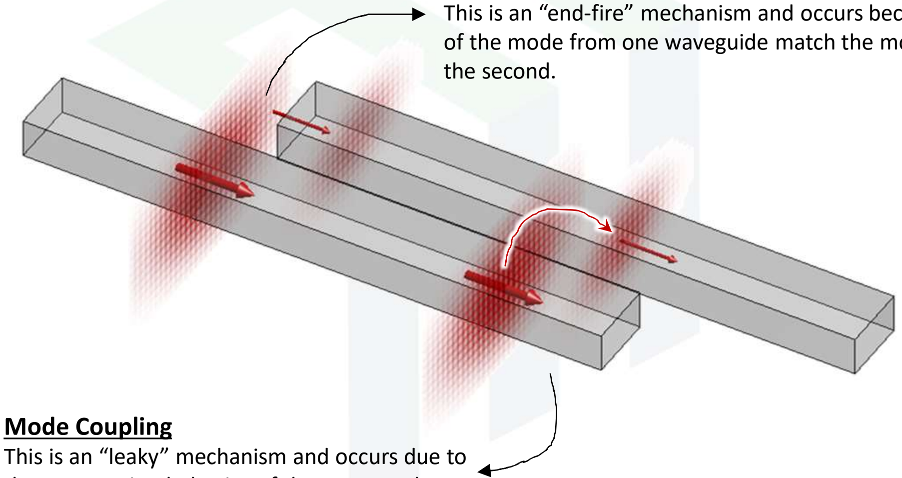




Animation of Directional Coupling



Mode-Coupling Vs. Butt Coupling



Butt Coupling
This is an "end-fire" mechanism and occurs because parts of the mode from one waveguide match the mode from the second.

Mode Coupling
This is an "leaky" mechanism and occurs due to the propagation behavior of the supermode.

Coupled-Mode Equations and Solutions

The simple coupled-mode equations were

$$\frac{dA}{dz} = -j\kappa_{12} B e^{-j(\beta_2-\beta_1)z}$$

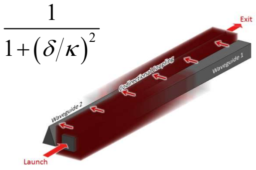
$$\frac{dB}{dz} = -j\kappa_{21} A e^{+j(\beta_2-\beta_1)z}$$

Codirectional Coupling

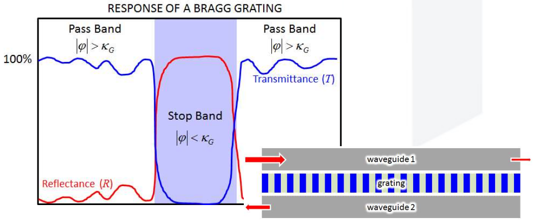
$$\tilde{P}_a(z) = \frac{|A(z)|^2}{|A_0|^2} = 1 - F\sin^2(\psi z)$$

$$\tilde{P}_b(z) = \frac{|B(z)|^2}{|A_0|^2} = F\sin^2(\psi z)$$

$$F = \left(\frac{\kappa}{\psi}\right)^2 = \frac{1}{1+(\delta/\kappa)^2}$$



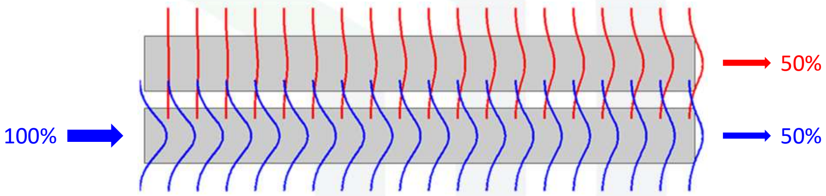
Contradirectional Coupling



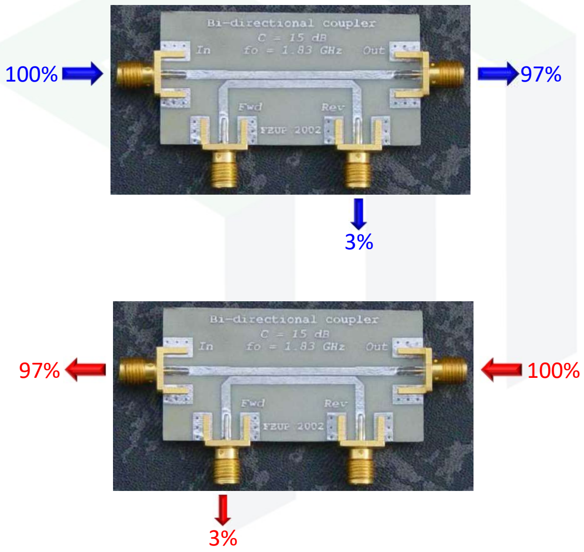
Codirectional Devices –

The Directional Coupler

3 dB Directional Coupler

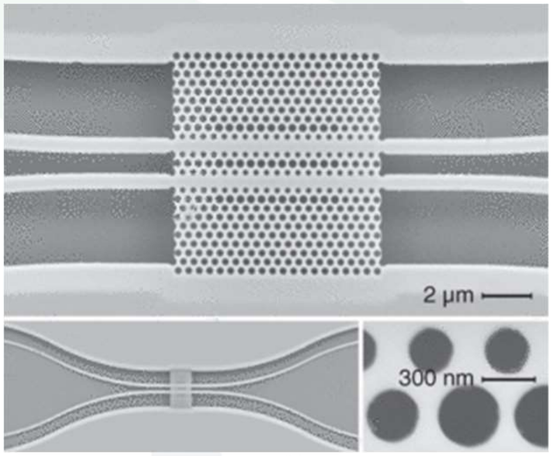


Microwave Bidirectional Coupler

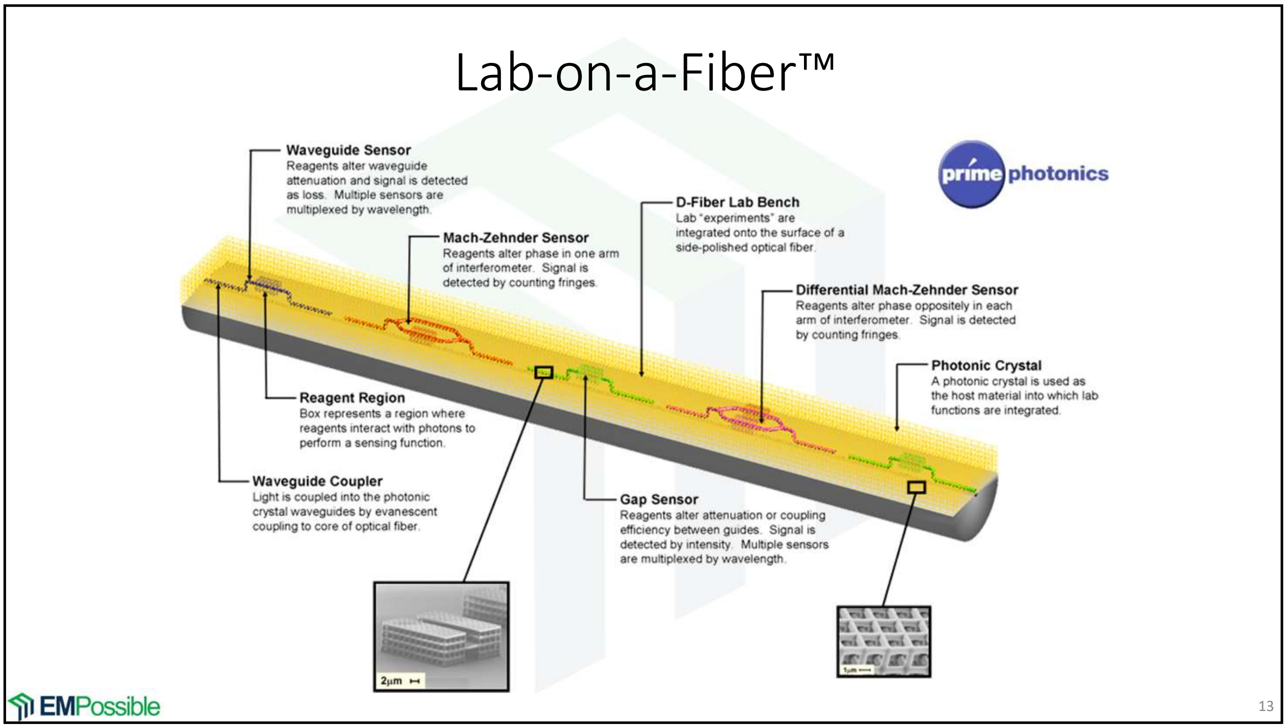


http://paginas.fe.up.pt/~hmiranda/etele/microstrip/

Integrated Optical Directional Coupler



Laser Focus World, 2008



Lab-on-a-Fiber™

Waveguide Sensor
Reagents alter waveguide attenuation and signal is detected as loss. Multiple sensors are multiplexed by wavelength.

Mach-Zehnder Sensor
Reagents alter phase in one arm of interferometer. Signal is detected by counting fringes.

D-Fiber Lab Bench
Lab "experiments" are integrated onto the surface of a side-polished optical fiber.

Differential Mach-Zehnder Sensor
Reagents alter phase oppositely in each arm of interferometer. Signal is detected by counting fringes.

Photonic Crystal
A photonic crystal is used as the host material into which lab functions are integrated.

Reagent Region
Box represents a region where reagents interact with photons to perform a sensing function.

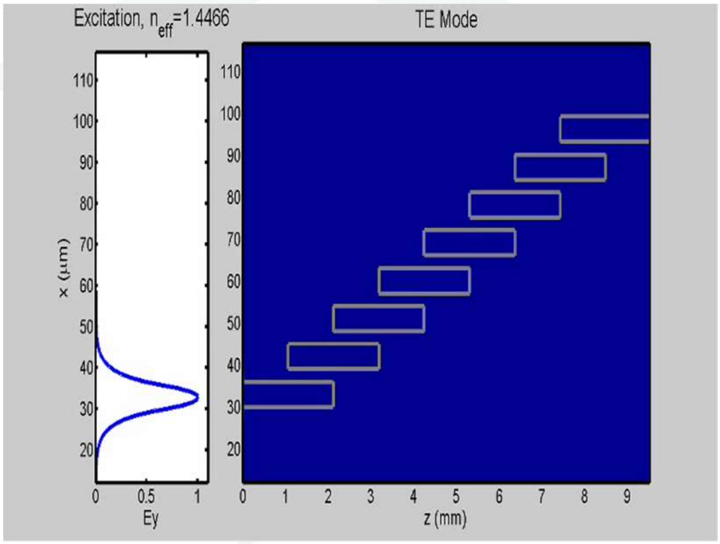
Waveguide Coupler
Light is coupled into the photonic crystal waveguides by evanescent coupling to core of optical fiber.

Gap Sensor
Reagents alter attenuation or coupling efficiency between guides. Signal is detected by intensity. Multiple sensors are multiplexed by wavelength.

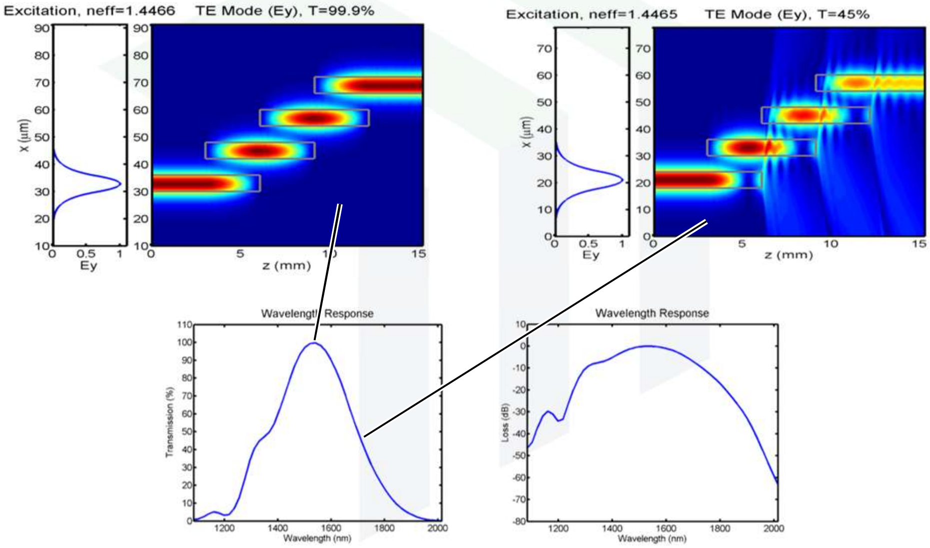
Codirectional Devices –

Coupled-Line Filters

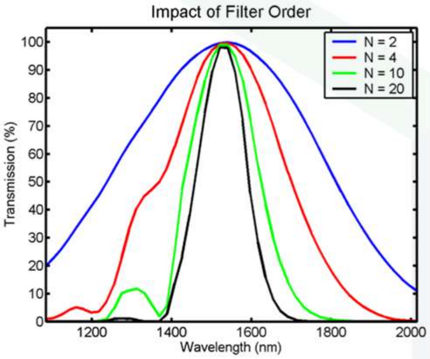
BPM Simulation of a Coupled-Line Filter

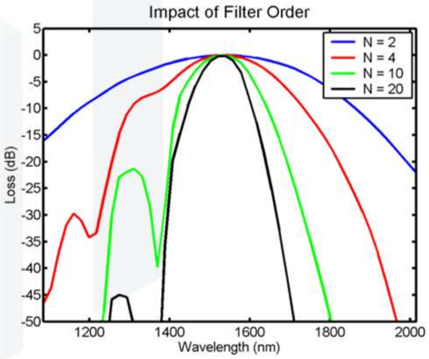


Third-Order Coupled-Line Filter



Impact of Filter Order

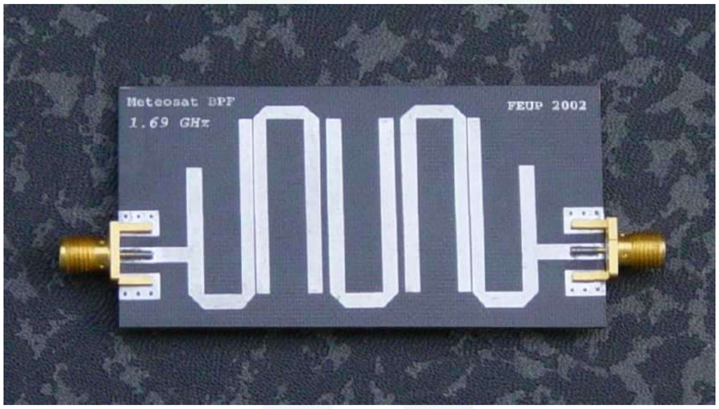




Microwave Coupled-Line Bandpass Filter

http://paginas.fe.up.pt/~hmiranda/etele/microstrip/

Microwave Hairpin Bandpass Filter

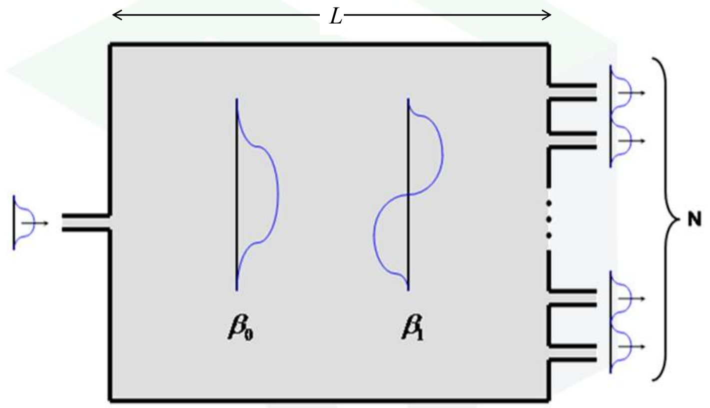


http://paginas.fe.up.pt/~hmiranda/etele/microstrip/

Codirectional Devices –

Multimode Interference (MMI) Coupler

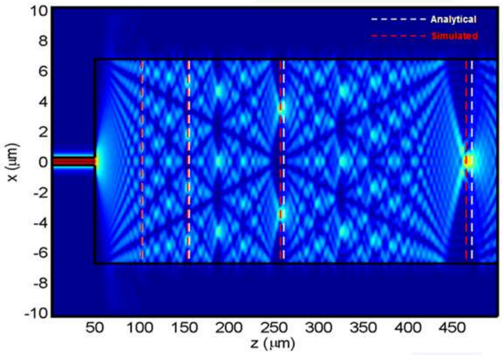
The Multimode Interference Coupler

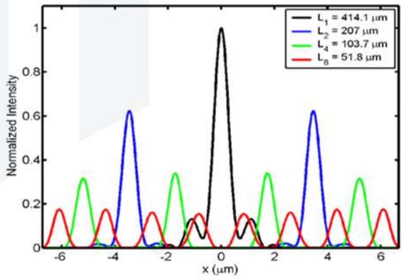


The length L where the input field is imaged N times is given by

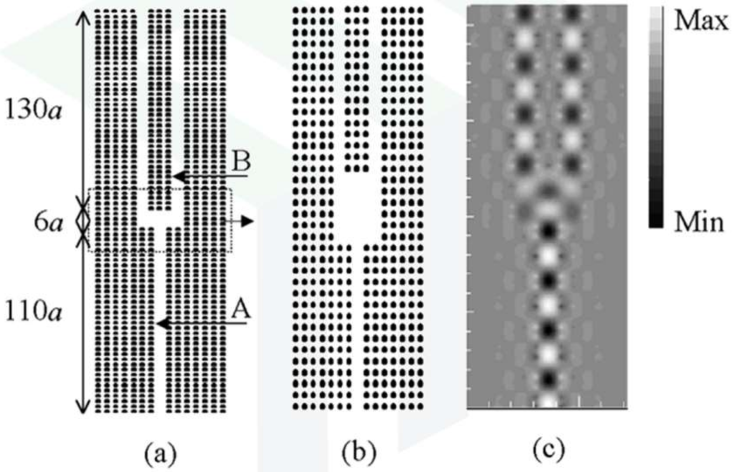
$$L_{1\times N} = \frac{3L_\pi}{4N} \qquad L_\pi = \frac{\pi}{\beta_0 - \beta_1}$$

The Multimode Interference Coupler



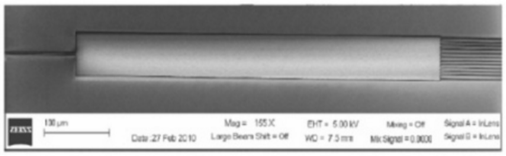


Photonic Crystal MMI

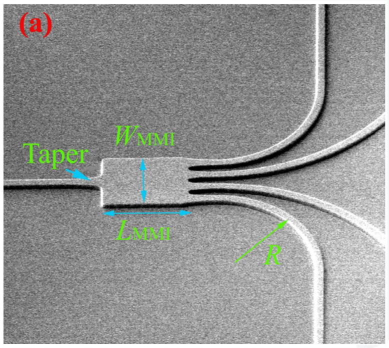


Tao Lui, et al, "Multimode Interference-Based Photonic Crystal Waveguide Power Splitter," JLT, Vol. 22, No. 12, pp. 2842-2846, 2004.

Integrated Optical MMI's

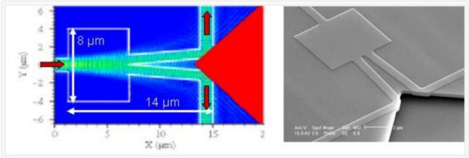


Afshin, Ghaffair, et al, "Transfer of micro and nano-photonic silicon nanomembrane waveguide devices on flexible substrates," Opt. Exp 18(19), pp. 20086-20095, 2010.



Haifeng, Zhou, et al, "A compact thermo-optical multimode-interference silicon-based 1×4 nano-photonic switch," Opt. Exp 21(18), pp. 21403-21413, 2013.

http://silicon-photonics.ief.u-psud.fr/?page_id=286



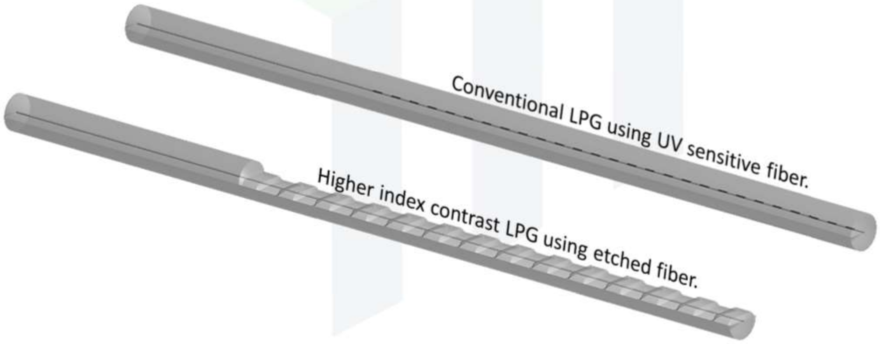
Codirectional Devices –

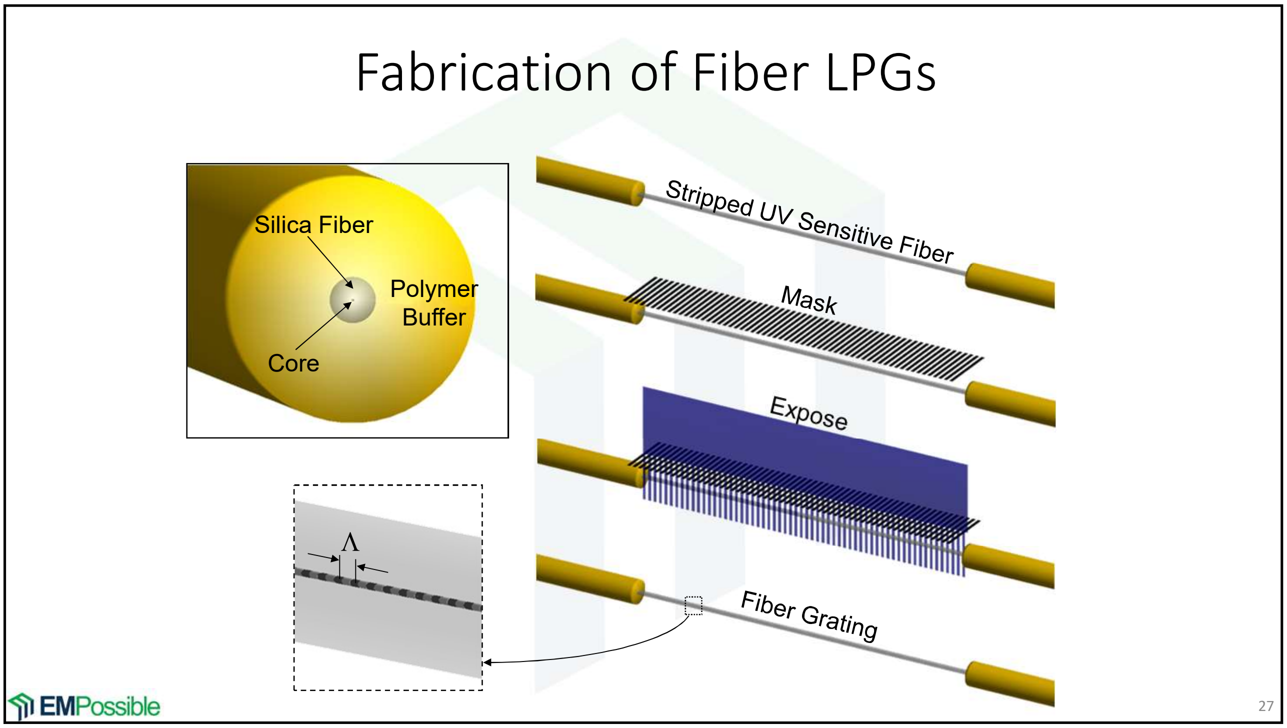
Long Period Gratings

Fiber Optic Long Period Gratings

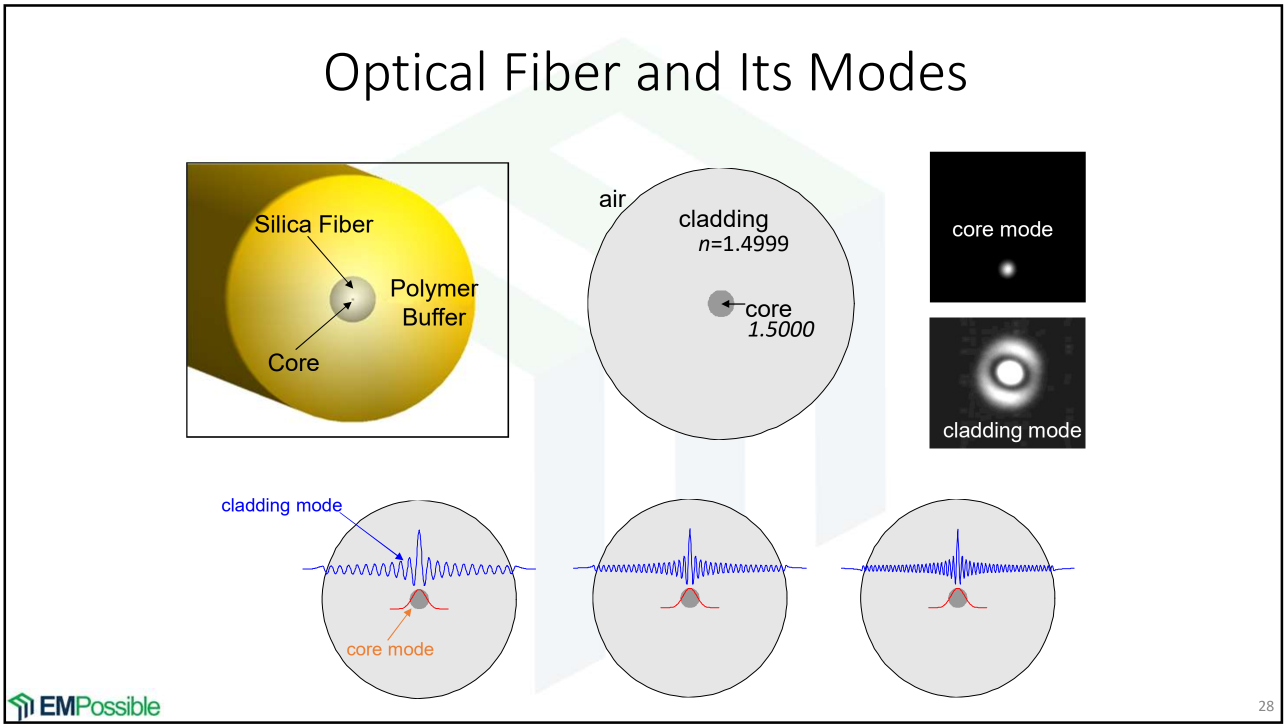
Long period gratings are most commonly found in fiber optic devices where the scales are more easily realized. The wavelength is usually 1.5 μm and the period of the gratings are on the order of 100's μm.

Here are two possible realizations of LPG gratings in optical fibers.





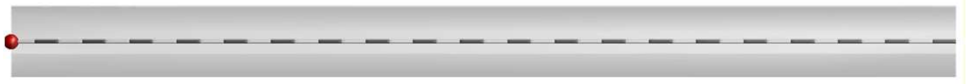
Fabrication of Fiber LPGs



Optical Fiber and Its Modes

Animation of LPG Operation

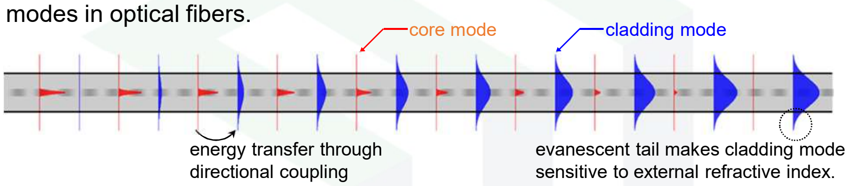
Incident Light ● **Back-Scattered Light** ● **Forward-Scattered Light**



Phase Matching Condition: $\beta_1 - \beta_2 = \dfrac{2\pi}{\Lambda}$

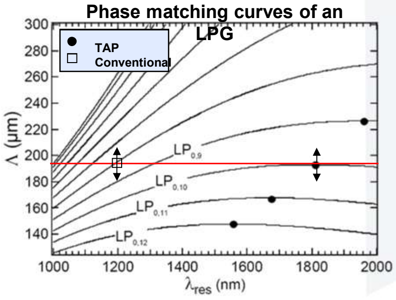
Turn Around Point Long Period Gratings (TAP-LPG)

Long period gratings (LPG) can transfer energy from core to cladding modes in optical fibers.



energy transfer through directional coupling

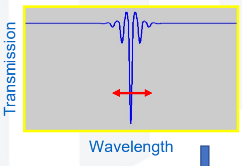
evanescent tail makes cladding mode sensitive to external refractive index.



Phase matching curves of an LPG

Z. Wang, Ph.D. dissertation, Virginia Tech, pp. 35, 2005

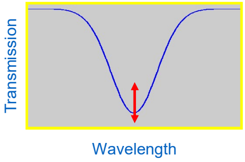
Conventional LPG



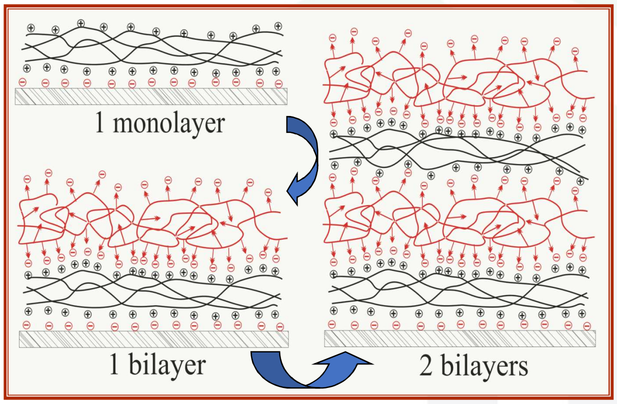
- Narrowband
- Wavelength shift
- Harder to detect.

- Broadband
- Dip fluctuation
- Easy to measure

TAP-LPG



Ionic Self-Assembled Multilayer (ISAM) Films



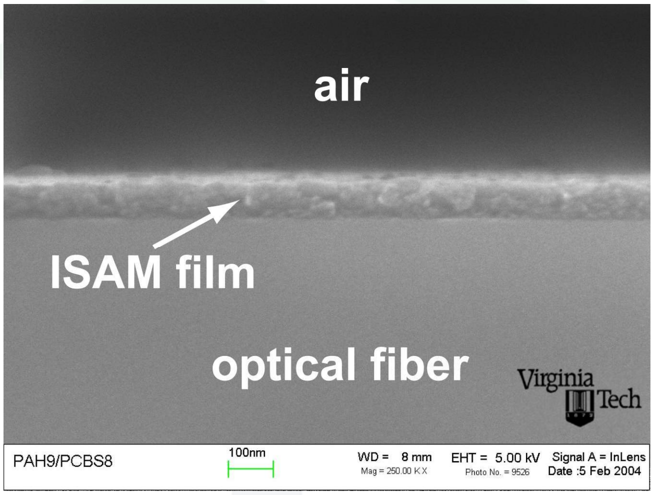
G. Decher *et al.*, Makromol. Chem., Makromol. Symp. **46**, 321 (1991); Thin Solid Films **210/211**, 831 (1992)

ISAM Process:

1. Immersion of charged substrate in aqueous solution of oppositely charged polyelectrolyte.
2. Immersion in polyelectrolyte of opposite charge to first.
3. Repeat to desired number of bilayers.

Yields exceptionally uniform, homogeneous thin films with structural and thickness control at the molecular (monolayer) level. Simple, rapid, inexpensive self-assembly process

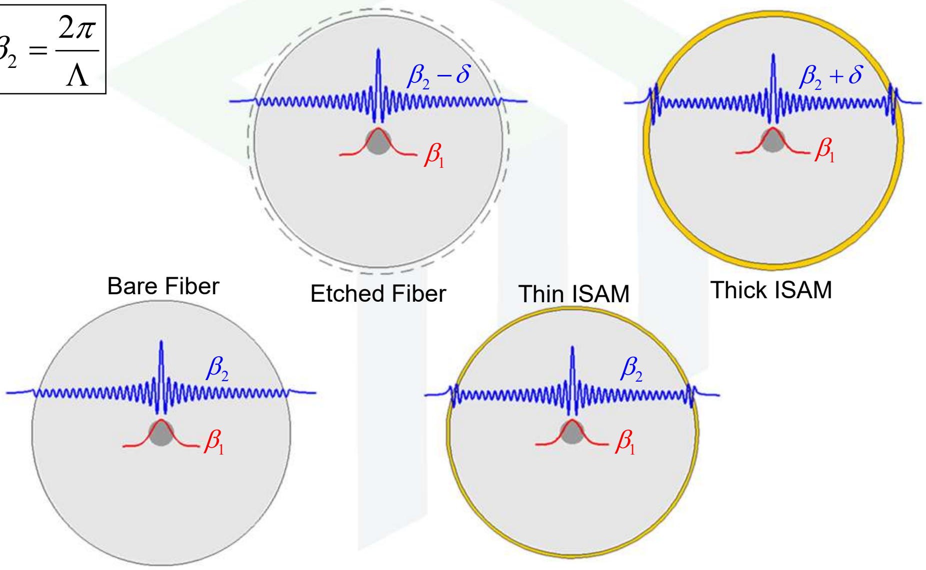
Scanning Electron Microscope Image of ISAM on Fiber



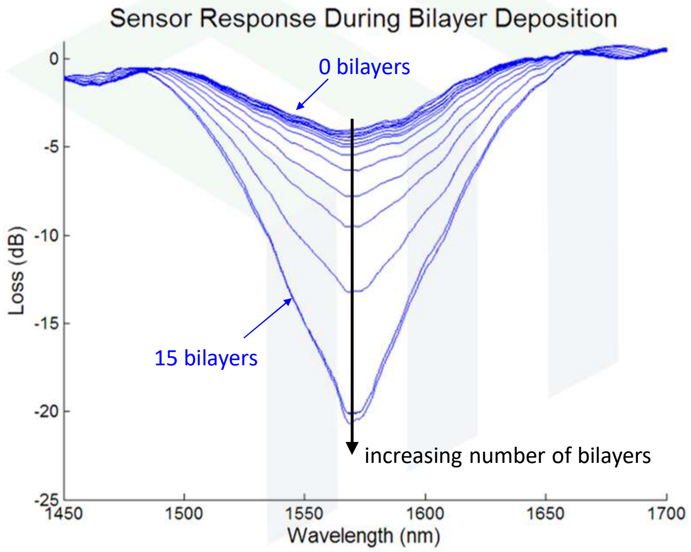
Cleaved cross-section of ISAM coated optical fiber

How to Make a Sensor

$$\boxed{\beta_1-\beta_2=\frac{2\pi}{\Lambda}}$$

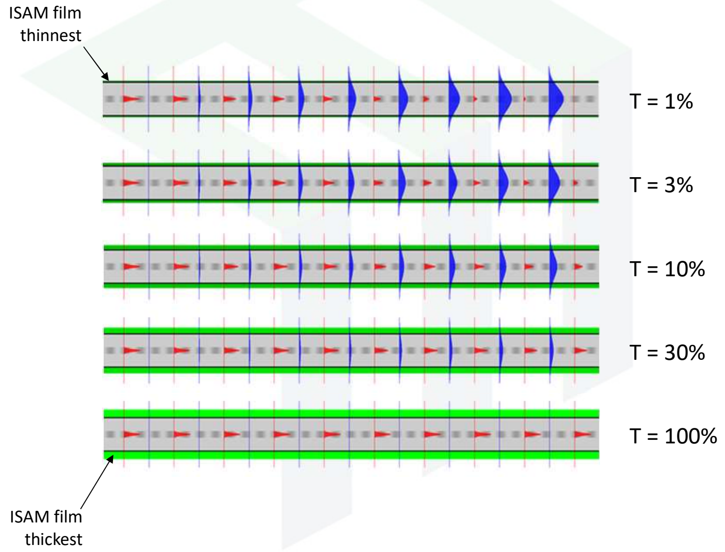


Measure Response of Fiber TAP-LPG



Sensor Theory (3 of 6):

Fiber optic sensor transduction



ISAM film thinnest

T = 1%

T = 3%

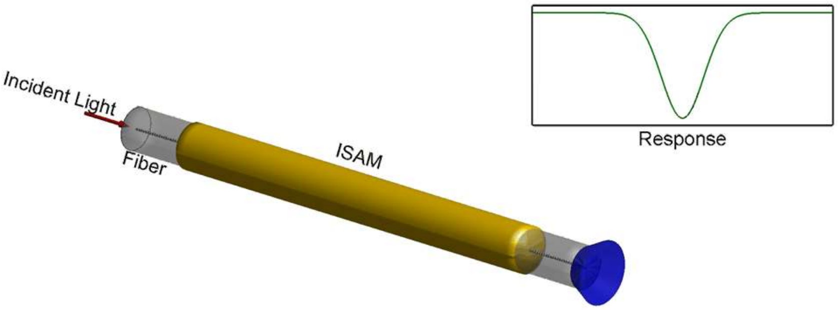
T = 10%

T = 30%

T = 100%

ISAM film thickest

TAP-LPG Sensor Animation

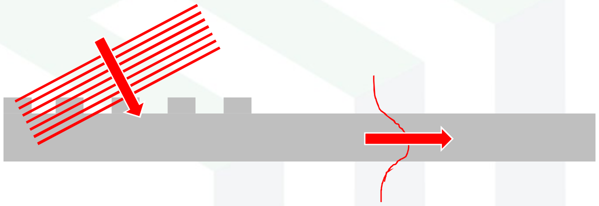


Medium Period Devices –

Grating Couplers

Grating Coupler Concept

Free space to waveguide grating coupler



Waveguide to free space grating coupler

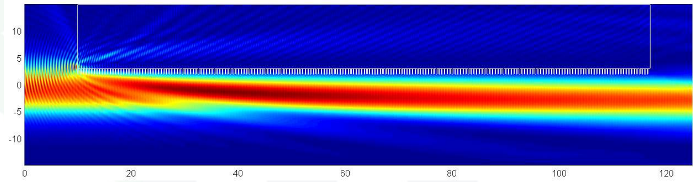
Apodized Gratings

Power escaping from the grating will have a non-uniform amplitude producing asymmetric beams. This is usually a bad thing because asymmetric beams do not behave well and are hard to control.

This can be very effectively mitigated using apodized gratings.

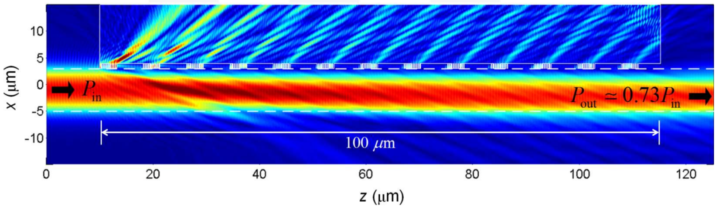
Fast Fiber Grating Coupler

Introduction of the grating shifts the mode away from the grating so coupling is weakened.



A solution was to implement a doubly-periodic grating. This provided around 10× faster outcoupling than any other published results.

Grating Parameter	Value
d	1.0 µm
Λ_1	400 nm
Λ_2	10 µm
f_1	0.4
f_2	0.5
n_{grat}	2.00
n_{epoxy}	1.46



R. C. Rumpf, "Optowireless Final Report," National Science Foundation.

Waveguide-to-Waveguide Couplers

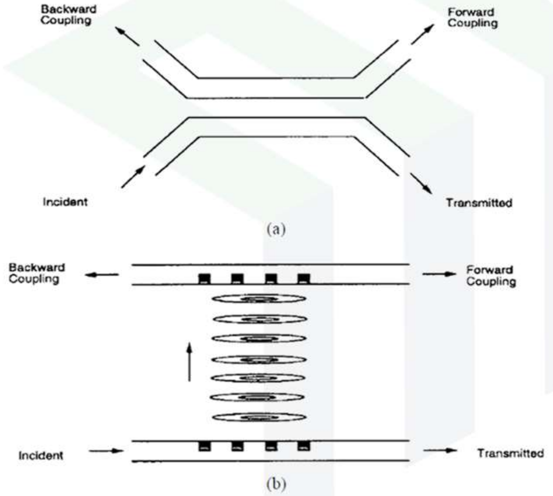


Fig. 1. Two kinds of waveguide-to-waveguide couplers. (a) Hybrid mode coupler. (b) Radiation mode coupler.

T. Liang et at, "Grating Assisted Waveguide-to-Waveguide Couplers," IEEE Phot. Technol. Lett., Vol. 10, No. 5, 693-695, 1998.

Optical Fiber to Integrated Circuit Coupling

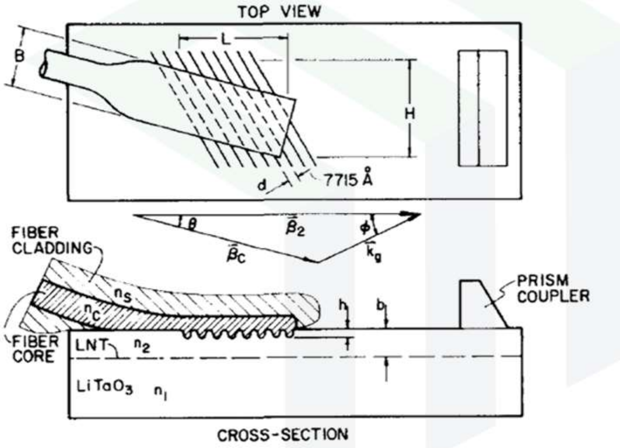
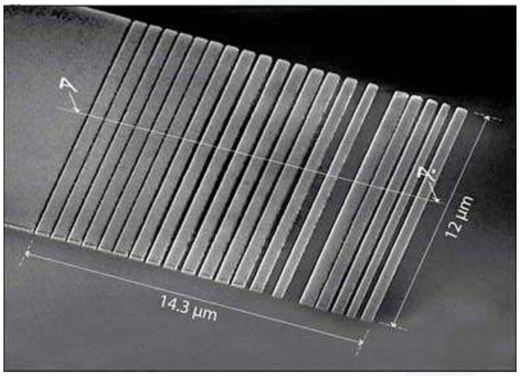
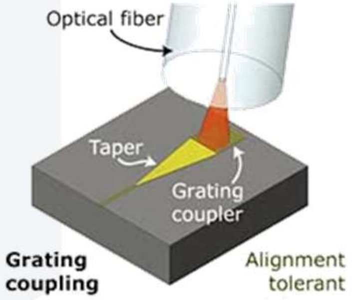


FIG. 1. Schematic representation of coupling between fiber and film waveguide.

J. M. Hammer et al, "Optical grating coupling between low-index fibers and high-index film waveguides," Appl. Phys. Lett., Vol. 28, No. 4, pp. 192-194, 1976.

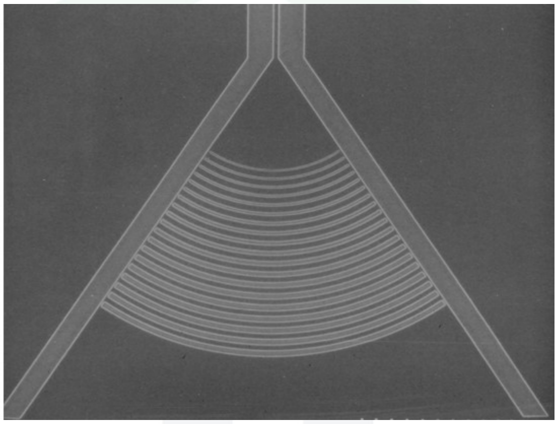
Apodized Grating Coupler





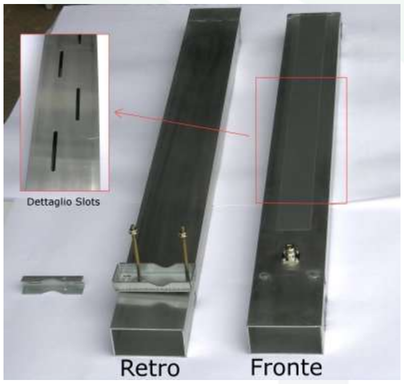
https://www.kth.se/en/ees/omskolan/organisation/avdelningar/mst/research/optics/apodized-waveguide-to-fiber-surface-grating-couplers-1.315473

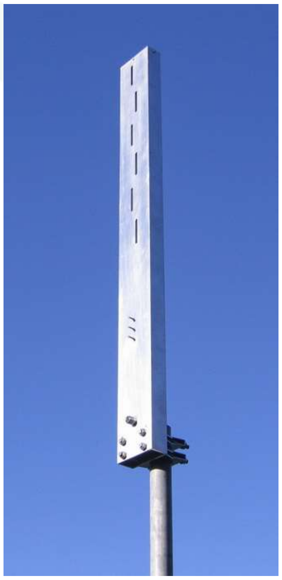
Focusing Grating Coupler



http://www.google.com/imgres?q=focusing+grating+coupler&um=1&hl=en&sa=N&rls=com.microsoft:en-us:IE-SearchBox&rlz=1I7GGIE_enUS400&biw=1680&bih=811&tbm=isch&tbnid=iM1DpXz57v1YbM:&imgrefurl=http://www.iph.rwth-aachen.de/%3Fpage_id%3D40&docid=dWmB1Q4-ItjZWM&imgurl=http://www.iph.rwth-aachen.de/wp-content/uploads/3_4.jpg&w=1128&h=410&ei=tC0rT8bNG-rE2wXOzMzwDg&zoom=1&iact=rc&dur=138&sig=110124736558651623808&page=1&tbnh=68&tbnw=187&start=0&ndsp=35&ved=1t:429,r:0,s:0&tx=9&ty=29

Slotted Waveguide Antennas



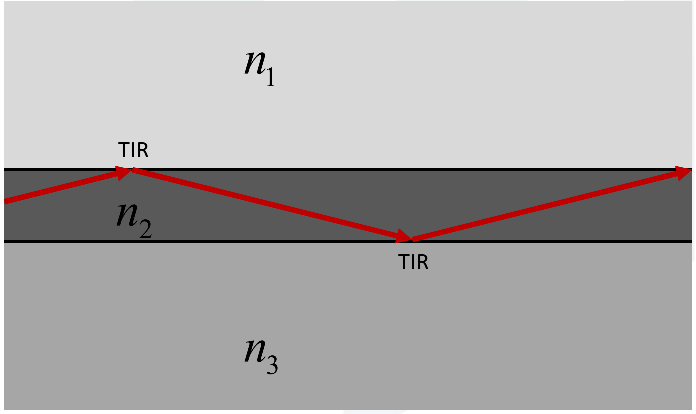


Medium Period Devices –

Guided-Mode Resonance Filters

The Slab Waveguide

If a slab of material is placed between two materials with lower refractive index, a slab waveguide is formed.

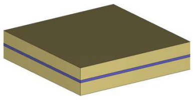


Conditions

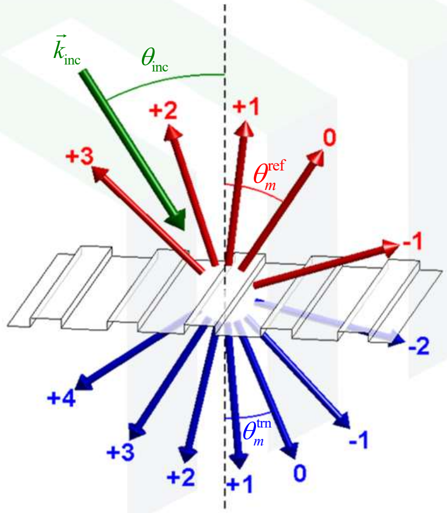
$n_2 > n_1$

and

$n_2 > n_3$

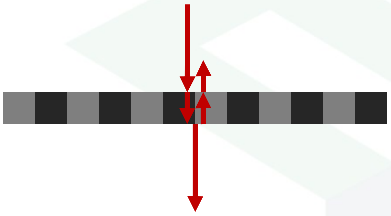


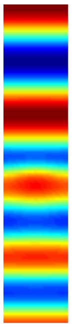
Grating Diffraction



Qualitative Description of the GMR Response

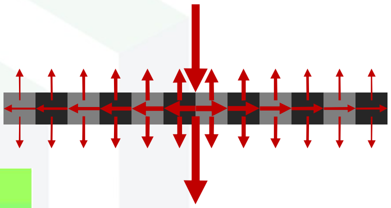
Away From Resonance

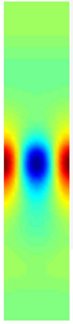




Away from resonance, the GMR filter exhibits the “background” response of the multilayer structure.

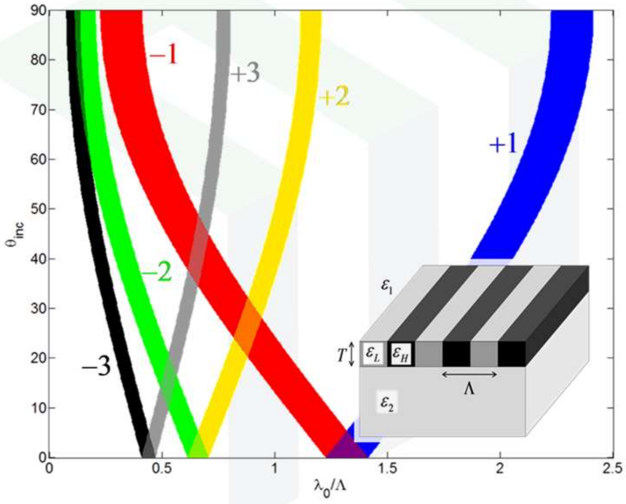
At Resonance



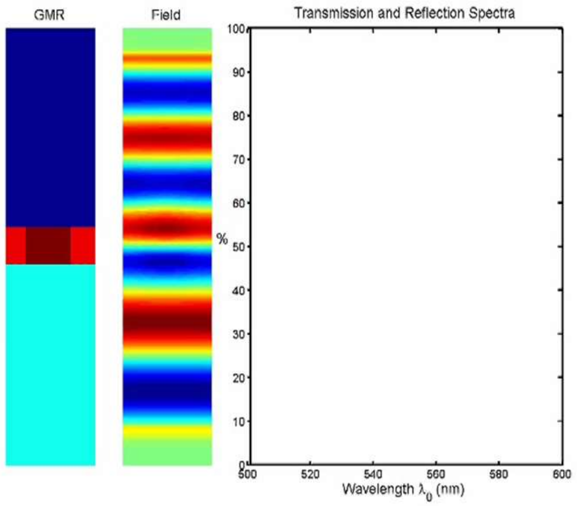


At resonance, part of the applied wave is coupled into a guided mode. The guided mode slowly “leaks” out from the waveguide. The “leaked” wave interferes with the applied wave to produce the GMR filter response.

Resonance Regions and Trends

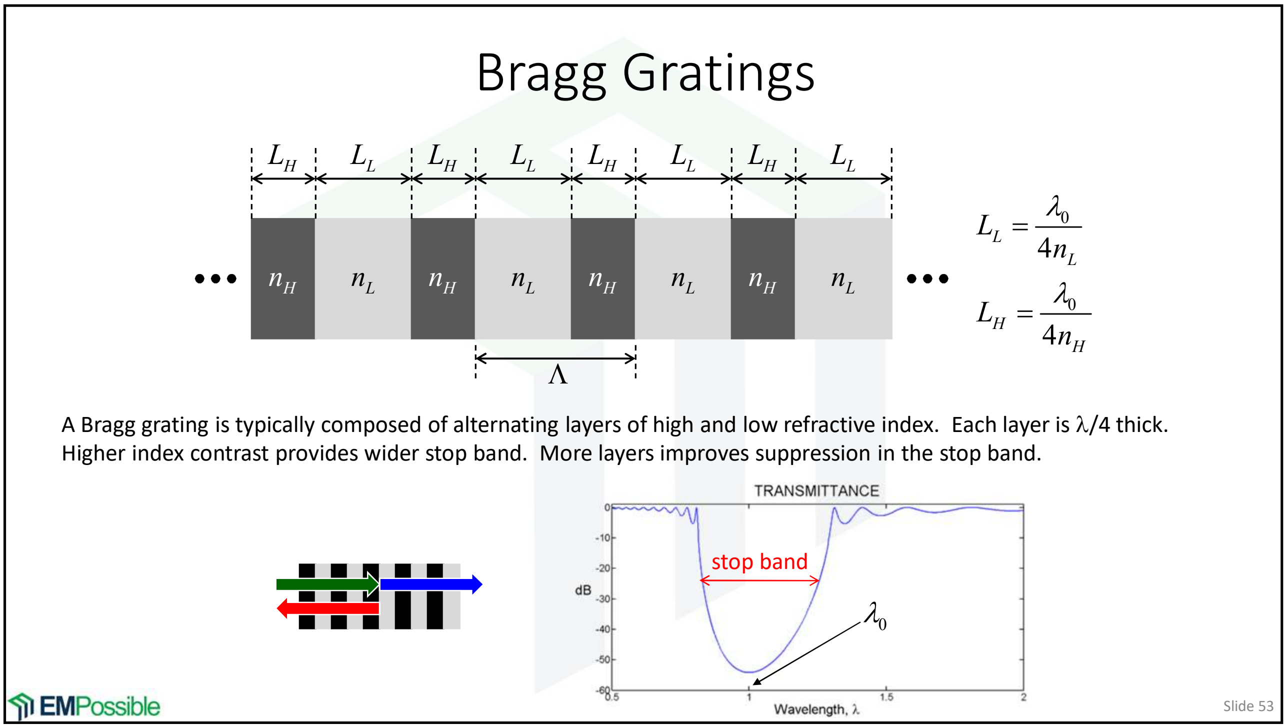


Animation of FDFD Simulation of a Guided-Mode Resonance Filter



Contradirectional Devices –

Bragg Gratings

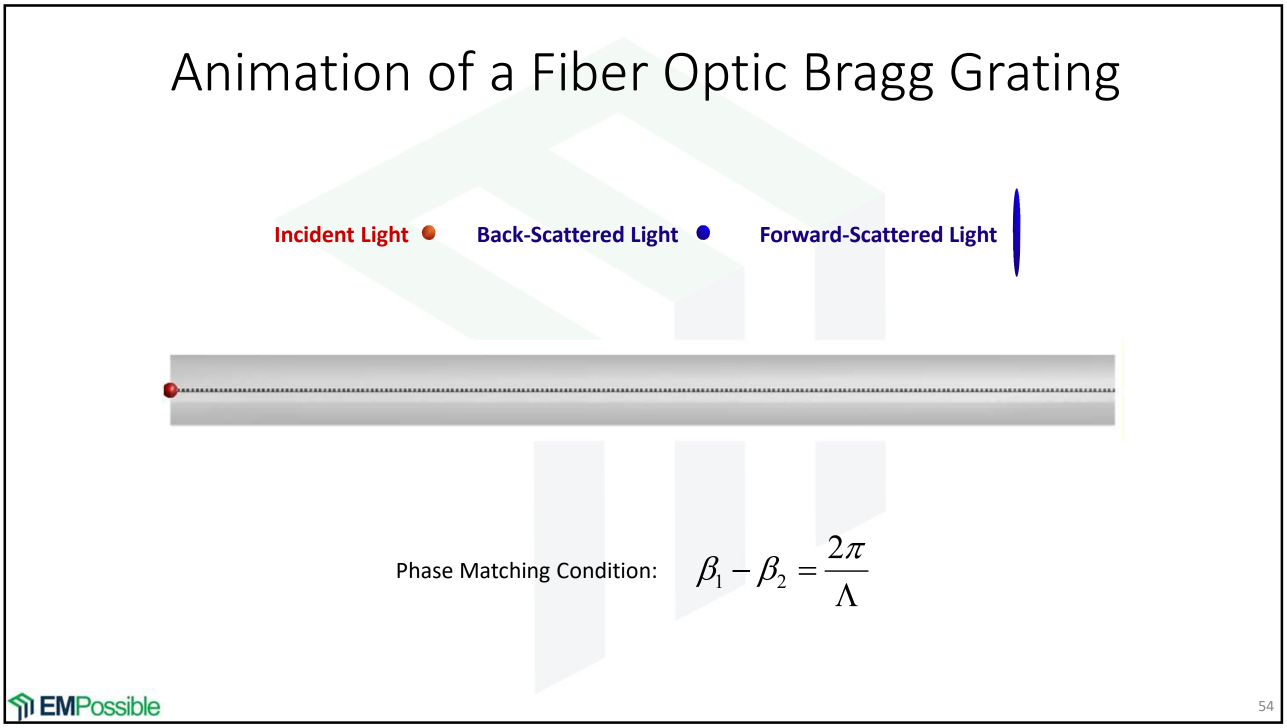


Bragg Gratings

$$L_L = \frac{\lambda_0}{4n_L}$$

$$L_H = \frac{\lambda_0}{4n_H}$$

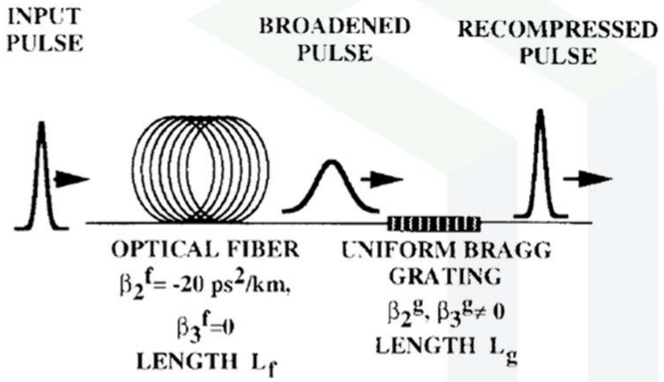
A Bragg grating is typically composed of alternating layers of high and low refractive index. Each layer is λ/4 thick. Higher index contrast provides wider stop band. More layers improves suppression in the stop band.



Animation of a Fiber Optic Bragg Grating

Phase Matching Condition: $\beta_1 - \beta_2 = \dfrac{2\pi}{\Lambda}$

Dispersion Compensating Bragg Grating (Transmission Mode)



1. Schematic diagram of transmission dispersion compensator.

N. M. Litchinitser et al, “Fiber Bragg Gratings for Dispersion Compensation in Transmission: Theoretical Model and Design Criteria for Nearly Ideal Pulse Recompression,” J. Lightwave Technol., Vol. 15, No. 8, pp. 1303-1313, 1997.

Dispersion Compensating Bragg Grating (Reflection Mode)

D. Borne et al, “Fiber Bragg Gratings for In-Line Dispersion Compensation in Cost-effective 10.7-Gbit/s Long-Haul Transmission,” Proc. IEEE/LEOS Benelux Chapter, pp. 177-180, 2006.

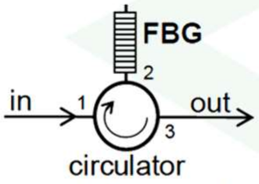
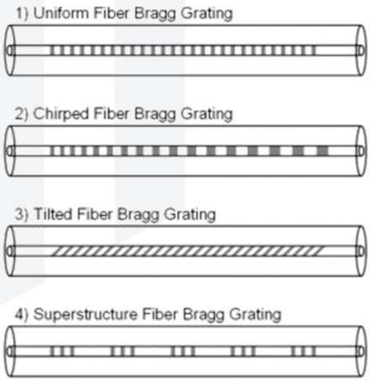


Fig. 1: Layout of the FGB-based DCMs

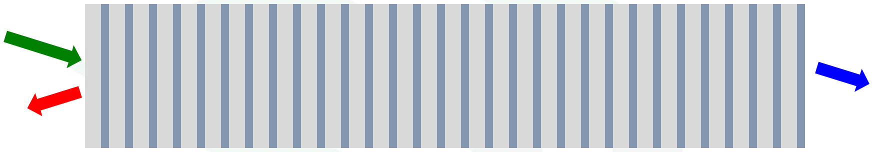


Typically, these are chirped Bragg gratings.

Contradirectional Devices –

Thin Film Optical Filters

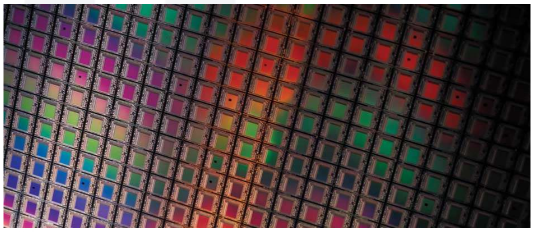
What is a Thin Film Optical Filter?



Thin film optical filters often contain dozens of alternating layers of different dielectrics.

Amazing filter properties can be realized because there are so many degrees of freedom.

- Wideband
- Wide FOV
- Multi-line
- Dispersion compensation
- Etc.



Multilayer Antireflection Coatings

$\lambda_c \equiv$ center wavelength

$N \equiv$ number of layers

$i \equiv$ layer number

$n_1 \equiv$ refractive index in reflection region

$n_2 \equiv$ refractive index in transmission region

$$n_i = n_1 + i\left(\frac{n_2 - n_1}{N+1}\right)$$

$$d_i \cong 0.1\left(\frac{N+1}{N}\right)\frac{\lambda_c}{\sqrt{n_1 n_2}}$$

Multilayer filters are an optimization problem.
This page represents only a good first guess.