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

Triangle Waveguide

\[ \mathbf{E}_1 = \mathbf{E}_{0,1}(x, y) e^{-j\beta z} \]
\[ \mathbf{H}_1 = \mathbf{H}_{0,1}(x, y) e^{-j\beta z} \]

Square Waveguide

\[ \mathbf{E}_2 = \mathbf{E}_{0,2}(x, y) e^{-j\beta z} \]
\[ \mathbf{H}_2 = \mathbf{H}_{0,2}(x, y) e^{-j\beta z} \]

Coupled Waveguides

\[ \mathbf{E} = A(z) \mathbf{E}_1 + B(z) \mathbf{E}_2 \]
\[ \mathbf{H} = A(z) \mathbf{H}_1 + B(z) \mathbf{H}_2 \]

Perturbation analysis

Modes unperturbed by other guide

supermodes
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

\[
\frac{dA}{dz} = -j\kappa_{12} Be^{-j(\beta_2 - \beta_1)z}
\]

\[
\frac{dB}{dz} = -j\kappa_{21} Ae^{+j(\beta_2 - \beta_1)z}
\]

Codirectional Coupling

\[
\tilde{P}_c(z) = \frac{|A(z)|^2}{|\kappa|} = 1 - F \sin^2(\psi z)
\]

Contradirectional Coupling

\[
\tilde{P}_s(z) = \frac{|B(z)|^2}{|\kappa|} = F \sin^2(\psi z)
\]

\[
F = \left( \frac{\kappa}{\psi} \right)^2 = \frac{1}{1 + (\delta/\kappa)^2}
\]
Codirectional Devices – The Directional Coupler

3 dB Directional Coupler
Microwave Bidirectional Coupler

100% 97%

3%

97% 100%

3%

http://paginas.fe.up.pt/~h.miranda/etele/microstrip/

Integrated Optical Directional Coupler

Laser Focus World, 2008
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 length $L$ where the input field is imaged $N$ times is given by

$$L_{N \times N} = \frac{3L}{4N}$$

and

$$L_\alpha = \frac{\pi}{\beta_0 - \beta_1}$$
Photonic Crystal MMI


Integrated Optical MMI’s


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

Long Period Gratings

Fiber Optic Long Period Gratings

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

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

- Conventional LPG using UV sensitive fiber.
- Higher index contrast LPG using etched fiber.
Fabrication of Fiber LPGs

Optical Fiber and Its Modes
Phase Matching Condition: \[ \beta_1 - \beta_2 = \frac{2\pi}{\Lambda} \]

Turn Around Point Long Period Gratings (TAP-LPG)

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

- Narrowband
- Wavelength shift
- Harder to detect.

- Broadband
- Dip fluctuation
- Easy to measure

Lecture 6

**Ionic Self-Assembled Multilayer (ISAM) Films**

**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.


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**Scanning Electron Microscope Image of ISAM on Fiber**

Cleaved cross-section of ISAM coated optical fiber
How to Make a Sensor

\[ \beta_1 - \beta_2 = \frac{2\pi}{\Lambda} \]

- Bare Fiber
- Etched Fiber
- Thin ISAM
- Thick ISAM

Measure Response of Fiber
TAP-LPG

Sensor Response During Bilayer Deposition

- 0 bilayers
- 15 bilayers

Increasing number of bilayers
Sensor Theory (3 of 6): Fiber optic sensor transduction

T = 1%
T = 3%
T = 10%
T = 30%
T = 100%

TAP-LPG Sensor Animation

Incident Light

Response
Medium Period Devices –

Grating Couplers

Grating Coupler Concept

Free space to waveguide grating coupler

Waveguide to free space grating coupler
Apodized Gratings

Energy escaping from the grating will have a non-uniform amplitude producing asymmetric beams. This is usually a bad thing because asymmetric beam 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.

<table>
<thead>
<tr>
<th>Grating Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d)</td>
<td>1.0 (\mu m)</td>
</tr>
<tr>
<td>(\Lambda_1)</td>
<td>400 nm</td>
</tr>
<tr>
<td>(\Lambda_2)</td>
<td>10 (\mu m)</td>
</tr>
<tr>
<td>(f_1)</td>
<td>0.4</td>
</tr>
<tr>
<td>(f_2)</td>
<td>0.5</td>
</tr>
<tr>
<td>(n_{eff})</td>
<td>2.90</td>
</tr>
<tr>
<td>(\varepsilon_{max})</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Waveguide-to-Waveguide Couplers


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

Optical Fiber to Integrated Circuit Coupling


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


Focusing Grating Coupler

Slotted Waveguide Antennas

Medium Period Devices – Guided-Mode Resonance Filters
The Slab Waveguide

If we “sandwich” a slab of material between two materials with lower refractive index, we form a slab waveguide.

Conditions

\[ n_2 > n_1 \]

and

\[ n_2 > n_3 \]

Grating Diffraction

\[ \tilde{k}_{inc} \quad \theta_{inc} \]

\[ +1 \quad +2 \quad +3 \quad +4 \]

\[ \theta_{ref} \]

\[ -1 \quad -2 \]

\[ 0 \]
Away from resonance, the GMR filter exhibits the “background” response of the multilayer structure.

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

The graph illustrates the resonance regions and trends with the following parameters:

- \( \lambda_0/A \)
- \( \theta \)
- \( \epsilon_1 \)
- \( \epsilon_2 \)

The graph is divided into regions marked as \(-3, -2, -1, +1, +2, +3\) indicating different resonance conditions and trends.
Contradirectional Devices –

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

Phase Matching Condition: $\beta_1 - \beta_2 = \frac{2\pi}{\Lambda}$
Dispersion Compensating Bragg Grating (Transmission Mode)

1. Schematic diagram of transmission dispersion compensator.

Dispersion Compensating Bragg Grating (Reflection Mode)

Typically, these are chirped Bragg gratings.

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

\[ \lambda_c \] = center wavelength  
\[ N \] = number of layers  
\[ i \] = layer number  
\[ n_1 \] = refractive index in reflection region  
\[ n_2 \] = refractive index in transmission region  

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

\[ \delta_i = 0.1 \left( \frac{N + 1}{N} \right) \sqrt{\frac{\lambda_c}{n_1 n_2}} \]

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