Multimode Interference Waveguides

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Why Integrated Photonics?

• **Vast potential in integrated optical circuits**
  - Larger bandwidth, faster speeds, lower energy consumption

• **The Growing Digital Universe**
  * 44 Trillion Gigabytes

  ![Graph showing data growth from 2008 to 2020](chart)

  Sources: Oracle, 2012

• **American Institute for Manufacturing Integrated Photonics (AIM)**
  - Develop process flows that permit the re-use of the current electronic fabrication infrastructure
  - High performance hardware requires optimal efficiency in every component
  - Multimode interference proves to be a vital technique in high performance
Splitting and Combining Mid-Infared Lightwaves

- Generating multiple images of input field:

  ![Image](http://www.electronics.dit.ie)

- For various applications in photonic circuits:
  - 2x2 Mach-Zehnder Switch
  - Polarization-insensitive photodetectors
  - Power splitters and combiners

![Diagram](http://spie.org/Images/Graphics/Newsroom/Imported-2013/005035/005035_10_fig1.jpg)
Why Multimode Interference Waveguides?

- Higher tolerance to dimension changes in fabrication process
- Easier fabrication process than other couplers
  - Do not require submicron gaps found in directional couplers
- Low inherent losses
  - Loss depends on the quality of the input
- Large optical bandwidth
- Low polarization dependence

Optical Circuit for Telecommunication Application

- Input light is split, sending it through an optical cross-connect and output port

Principles of Guided Mode Propagation

1) Input field profile at distance “z = 0”:

\[ E(x, 0) = \sum_{m=0}^{M-1} a_m U_m(x). \]

2) Superposition of individual modes at propagation distance “z”:

\[ E(x, z) = \sum_{m=0}^{M-1} a_m U_m(x) \cdot e^{-j\beta_m z}. \]

- Modal excitation factor

3) Inserting propagation constant:

\[ E(x, z) = e^{-j\kappa n_1 z} \sum_{m=0}^{M-1} a_m J_m(x) \cdot e^{j2\pi (m+1)^2(z/L_{si})}. \]

- Phase of lateral plane wave
- Mode phase factor

4) Self-imaging distance: \( L_{si} \) * Inserting for “z” we get self-image
General Interference for 2x2 MMI waveguides

- Inserting $\frac{L_{si}}{4}$ for “z”:

$$e^{j(\pi/2)(m+1)^2} = \begin{cases} j & \text{(even m)} \\ 1 & \text{(odd m)} \end{cases}$$

- Separating into even and odd modes:

$$e^{-jk_{0}n_{s}L_{si}/4} \left( \frac{1+j}{2} E(x,0) - \frac{1-j}{2} E(-x,0) \right)$$

- Input Field
- Mirrored Input Field

* We can use this length to produce an efficient 2x2 MMI coupler

- 2x2 MMI Waveguide:
Restricted Interference for 1x2 MMI Waveguides

- For general interference, compacted with stepping integer $p$:
  \[
  \frac{j^p}{2} E(x,0) + E(-x,0) + \frac{1}{2} E(x,0) - E(-x,0)
  \]
  - Even/ symmetric
  - Odd/ antisymmetric

- Using Fourier Analysis:
  \[
  L = \frac{p}{N} \left( \frac{L_{si}}{2} \right)
  \]

- For symmetric interference, odd term disappears:
  \[
  L = \frac{p}{N} \left( \frac{L_{si}}{8} \right)
  \]
  - Self-image now appears at quarter of the distance

- 1x2 MMI Waveguide:

Lumerical MODE Solutions
Designing Multimode Interference Couplers

- [1x2] Restricted MMI Waveguide

1) Normalized frequency: \[ V = k_0 d \left( n_{\text{II}}^2 - n_{\text{III}}^2 \right)^{1/2} \]

2) Propagation Parameter: \[ b = \frac{\bar{n}_{\text{II}}^2 - n_{\text{III}}^2}{n_{\text{II}}^2 - n_{\text{III}}^2} \equiv 1 - \frac{\ln \left( 1 + \frac{V^2}{2} \right)}{\frac{V^2}{2}} \]

3) Effective Index: \[ \bar{n}_0 = \sqrt{b (n_{\text{II}}^2 - n_{\text{III}}^2) + n_{\text{III}}^2} \]

4) Self-imaging length: \[ L_{si} = \frac{\lambda}{(n_{\text{II}} - \bar{n}_0)} \]

5) Applying previous restricted length for restricted propagation: \[ L = \frac{p}{N} \left( \frac{L_{si}}{8} \right) \]
Lumerical MODE Solutions

- **Design Model**
  - Specific material
  - Calculated dimensions
  - Add signal source (1.55 microns)
  - Monitors

- **Simulation**
  - EME (Eigen Mode Expansion)
  - FDTD (Finite Difference Time Domain)

- **Cross Sectional View**

- **1x2 MMI Waveguide (Perspective)**
Optimization and Simulation

- Adjusting Output Waveguide Position
  - Optimize transmission of fundamental mode
  - Reduce back reflection into input

- Distance from center

- Input

28.9% to 33.3% increase in transmission

4.34% to 0.36% decrease in back reflection
Optimization and Simulation

- Accounting for radiation mode loss
  - Transmission loss through change in width:

- Introduce tapered inputs/outputs

- Loss vs Taper Width
  - Increased width, decreased loss
  - Limited width increase
Finalizing 1x2 MMI waveguide

- **Introduced taper transmission**:
  - Increased length, increased transmission
  - Limited length increase

- **FDTD Simulation of a Input**:
  - Pulse input @ 1.55 microns
Final Dimensions and Future Application

- **MMI Length**
  - Calculated optimal length for modal splitting

- **Output Positioning**
  - 28.9% to 33.3% increase in transmission
  - 4.34% to 0.36% decrease in back reflection

- **Taper Introduction**
  - 33.3% to 48.3% increase in transmission
  - 0.36% to 0.32% decrease in back reflection

- **Application**
  - Use techniques for 2x2 MMI waveguides
  - Increase efficiency in future optical circuits

- **Final Dimensions**

1x2 MMI Waveguide
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