UNIVERSITY OF CALIFORNIA SANTA BARBARA
ELECTRICAL AND COMPUTER ENGINEERING

Multimode Interference Waveguides

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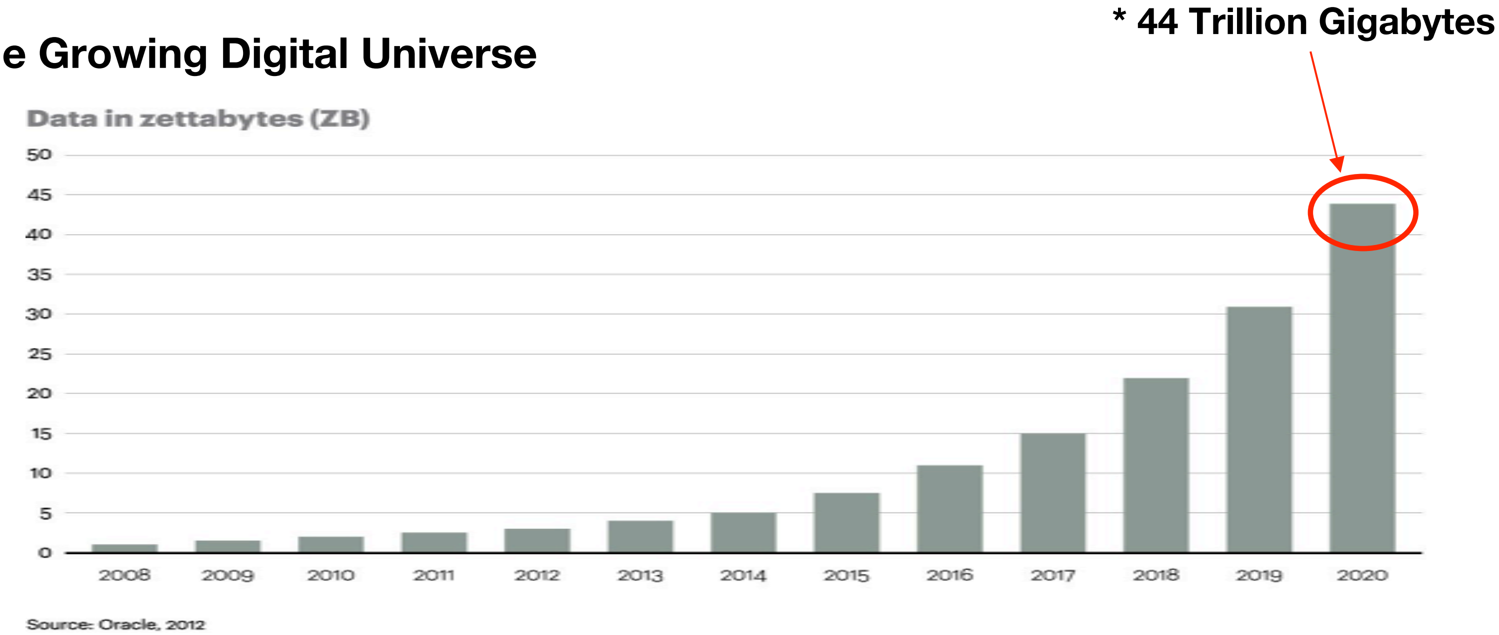
Why Integrated Photonics?

- **Vast potential in integrated optical circuits**

  - Larger bandwidth, faster speeds, lower energy consumption

- **The Growing Digital Universe**

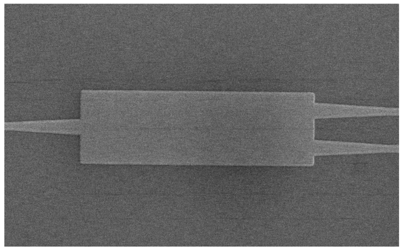


Source: Oracle, 2012

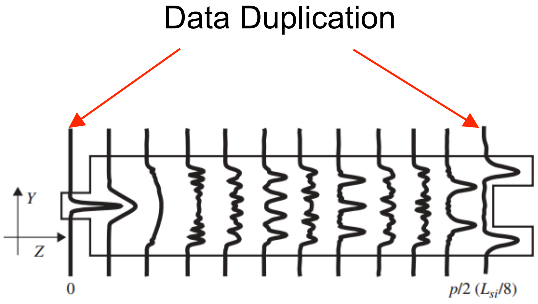
- **American Institute for Manufactoring Integrated Photonics (AIM)**
  - Develop process flows that permit the re-use of the current electronic fabrication infrastructure
  - High performance hardware requires optimal efficiency in every component
  - Multimode interference proves to be a vital technique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

Splitting and Combining Mid- Infared Lightwaves

- **Generating multiple images of input field :**



Source: http://www.electronics.dit.ie



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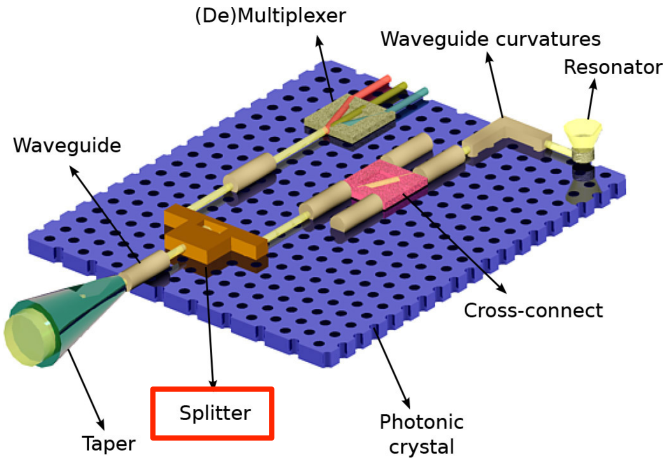
- **For various applications in photonic circuits:**
  - 2x2 Mach-Zehnder Switch
  - Polarization- insensitive photodetectors
  - Power splitters and combiners

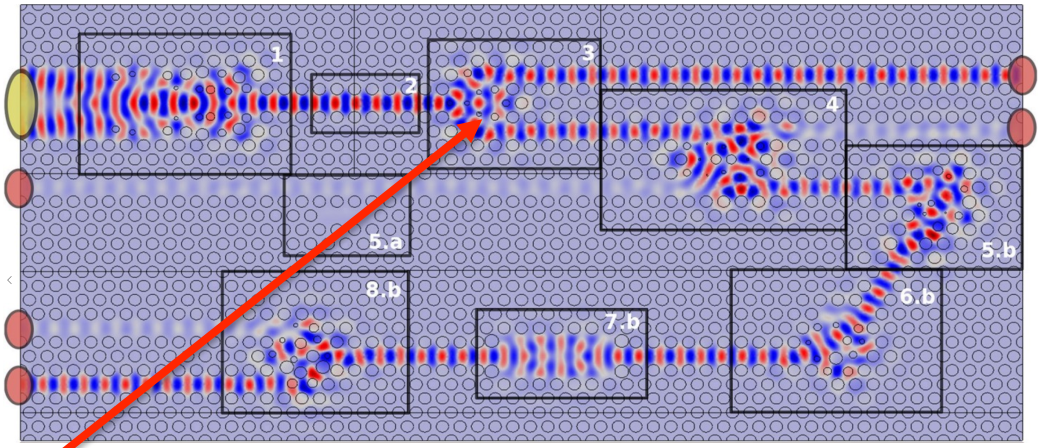


http://spie.org/Images/Graphics/Newsroom/Imported-2013/005035/005035_10_fig1.jpg

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



http://spie.org/newsroom/5035-designing-integrated-circuitry-in-nanoscale-photonic-crystals

- 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" :

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

3) Inserting propagation constant :

- Modal excitation factor

$$E(x,z) = \boxed{e^{-jk_0 n_l z}} \cdot \sum_{m=0}^{M-1} \boxed{a_m} U_m(x) \boxed{e^{j2\pi(m+1)^2(z/L_{si})}}$$

- Phase of lateral plane wave
- Mode phase factor

4) Self-imaging distance : L_{si}

* Inserting for "z" we get self-image

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General Interference for 2x2 MMI waveguides

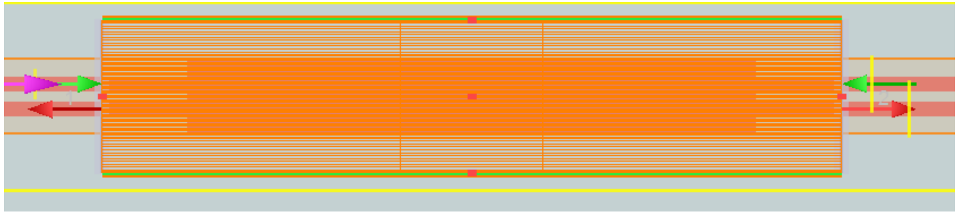
- **Inserting** $\frac{L_{si}}{4}$ **for “z” :** $$e^{j(\pi/2)(m+1)^2} = \begin{cases} j & \text{(even m)} \\ 1 & \text{(odd m)} \end{cases}$$

- **Separating into even and odd modes :** $$e^{-jk_0 n_l L_{si}/4}\left(\frac{1+j}{2}\boxed{E(x,0)} - \frac{1-j}{2}\boxed{E(-x,0)}\right)$$

  - Input Field
  - Mirrored Input Field

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

- **2x2 MMI Waveguide :**



Lumerical MODE Solutions

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Restricted Interference for 1x2 MMI Waveguides

- **For *general* interference, compacted with stepping integer *p* :**

$$\frac{j^p}{2}\boxed{[E(x,0)+E(-x,0)]}+\frac{1}{2}\boxed{[E(x,0)-E(-x,0)]}$$

- Even/ symmetric
- Odd/ antisymmetric

- **Using Fourier Analysis :**

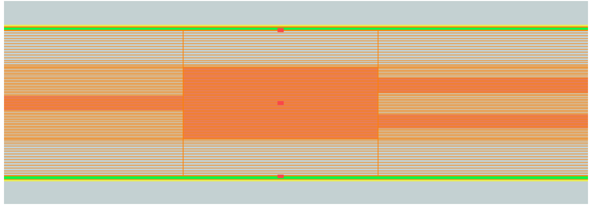
$$L=\frac{p}{N}\left(\frac{L_{si}}{2}\right)$$

- **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 :**



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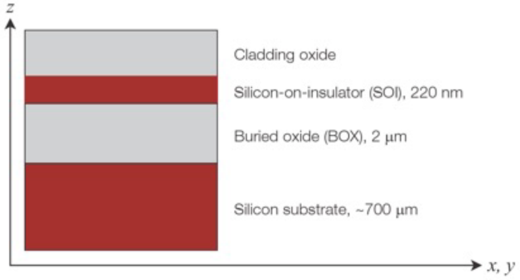
Designing Multimode Interference Couplers

- **[1x2] Restricted MMI Waveguide**



1) Normalized frequency : $V \equiv k_0\, d \left(\boxed{n_{\mathrm{II}}^2} - \boxed{n_{\mathrm{III}}^2}\right)^{1/2}$

Waveguide (Si)

Cladding (SiO2)

2) Propagation Parameter : $b \equiv \dfrac{\bar{n}^2 - n_{\mathrm{III}}^2}{n_{\mathrm{II}}^2 - n_{\mathrm{III}}^2} \equiv 1 - \dfrac{\ln\left(1 + \frac{V^2}{2}\right)}{\frac{V^2}{2}}$

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

4) Self- imaging length : $L_{si} = \frac{\lambda}{(\bar{n}_l - \bar{n}_0)}$

5) Applying previous restricted length for restricted propagation : $L = \dfrac{p}{N}\left(\dfrac{L_{si}}{8}\right)$

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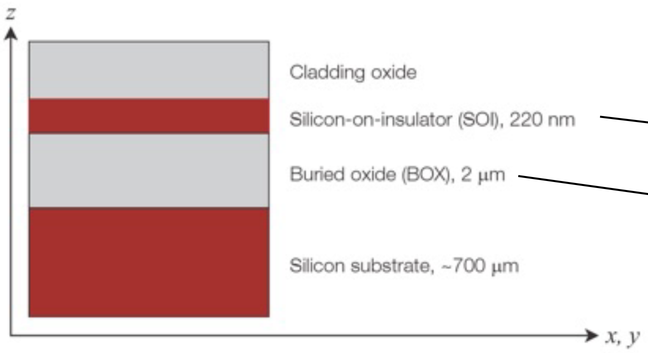
Lumerical MODE Solutions

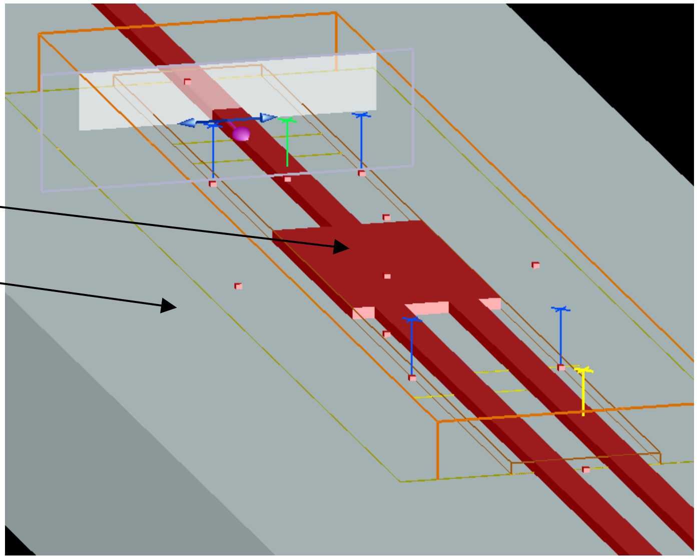
- **Design Model**
  - Specific material
  - Calculated dimensions
  - Add signal source (1.55 microns)
  - Monitors

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

- **Cross Sectional View**



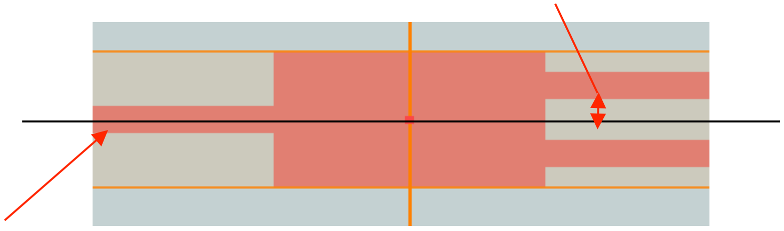
- **1x2 MMI Waveguide (Perspective)**



Lumerical MODE Solutions

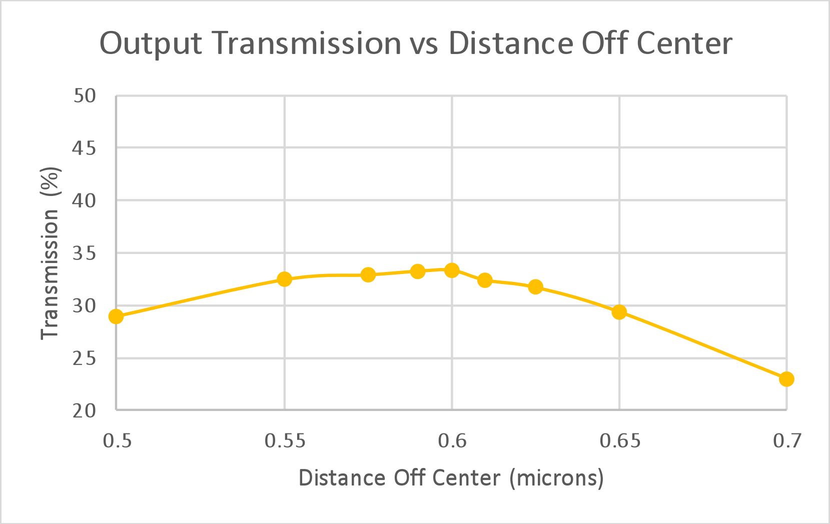
Optimization and Simulation

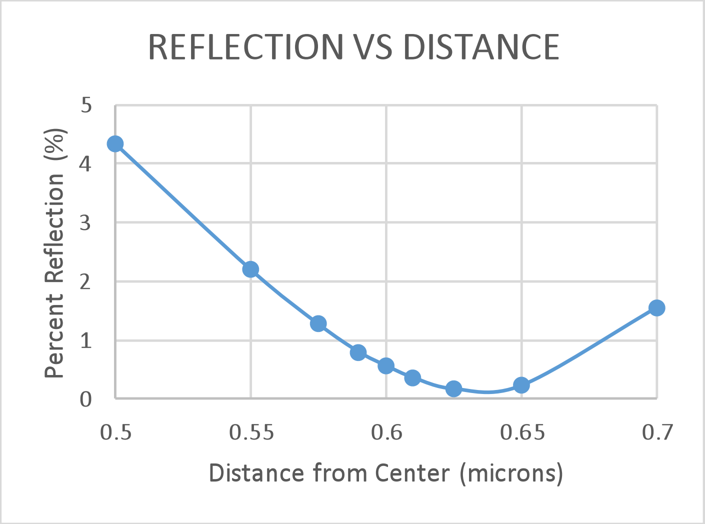
- **Adjusting Output Waveguide Position**
  - - Optimize transmission of fundamental mode
  - - Reduce back reflection into input



- Distance from center
- Input

Lumerical MODE Solutions

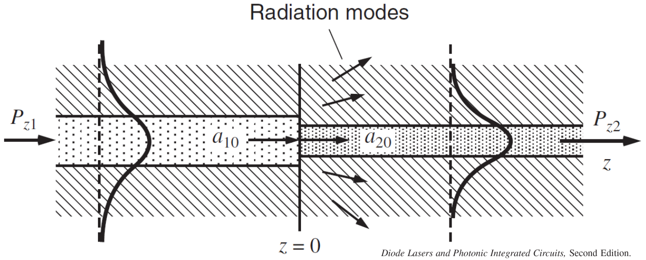




- 28.9% to 33.3 % increase in transmission
- 4.34% to 0.36% % decrease in back reflection

Optimization and Simulation

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



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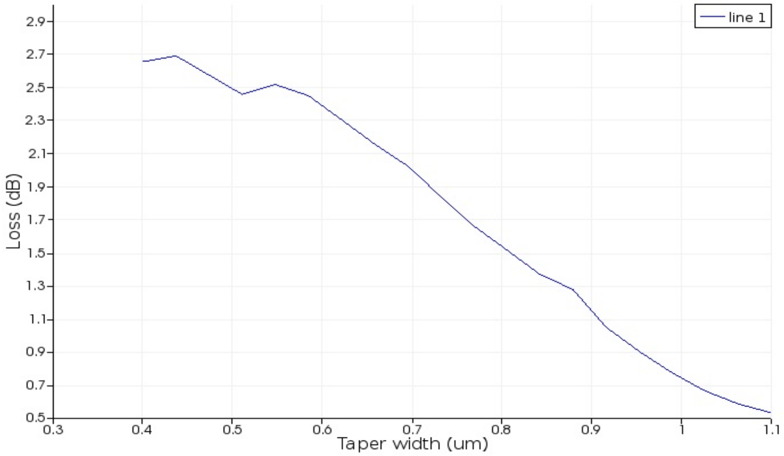
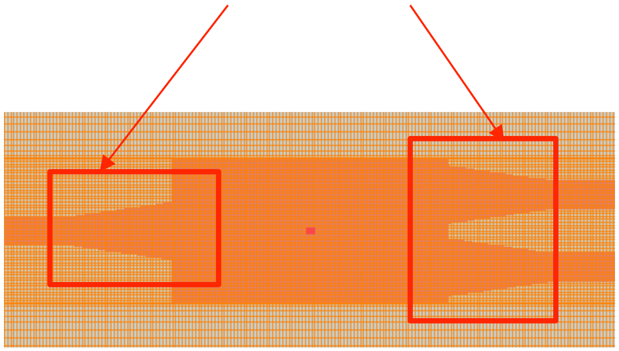
- **Loss vs Taper Width**



Lumerical MODE Solutions

- Increased width, decreased loss
- Limited width increase

- **Introduce tapered inputs/ outputs**



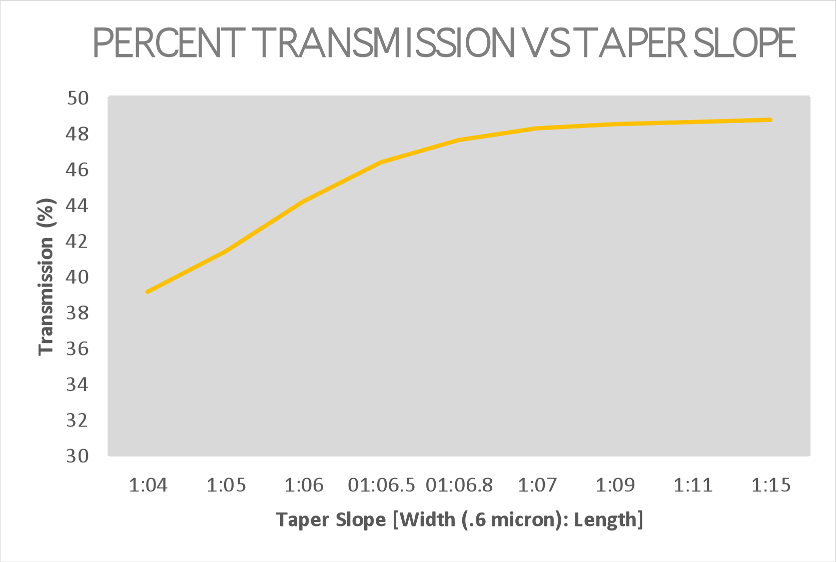
Lumerical MODE Solutions

Finalizing 1x2 MMI waveguide

- **Introduced taper transmission :**

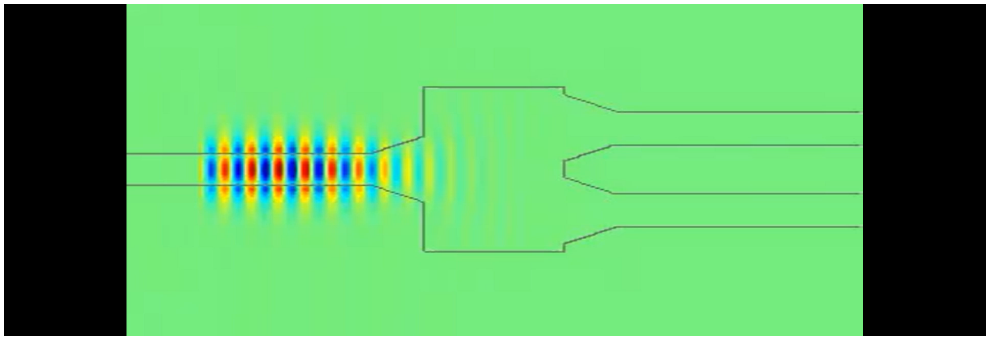
  - Increased length, increased transmission

  - Limited length increase



- **FDTD Simulation of a Input :**

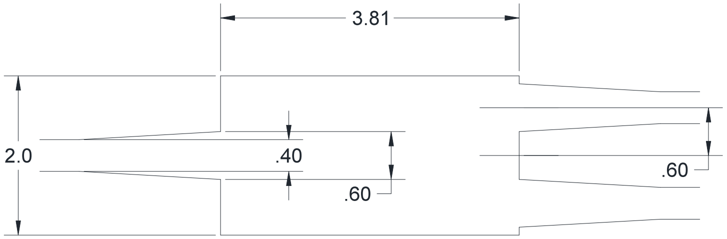
  - Pulse input @ 1.55 microns



Lumerical MODE Solutions

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

Acknowledgements

- **Mentor:** Akhilesh Knope
- **Faculty Advisor:** John Bowers
- **Program Director:** Wendy Ibsen
- **SBCC Advisor:** Jens- Uwe Kuhn
- **CSEP Program Coordinator:** Stephanie Mendes
- AIM interns and mentors