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SMR 1829 - 15

Winter College on Fibre Optics, Fibre Lasers and Sensors

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Passive Fibre Components

(PART I)

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Passive Fibre Components

Walter Margulis

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CV

Walter Margulis

Brazilian
(Swedish)
Old: 30 years in lasers, 22 years in fibres
Main area: Active fibre components
Main interests: samba, football
Sports: jogging slowly, volleyball, skiing

Acreo

Bridge between University and Industry

Non-profit institute
Owned by government and pool of industries
150 researchers

Departments: Nanoelectronics (III-V, IR)
Electronics on Paper

Photonics:
- Fiberlab
- Components
- Transmission } BB testbed
- Network } BB testbed

"Passive" components

Some facts (informative)
Some principles (make you think)
Some research (fun)

Passive fiber components

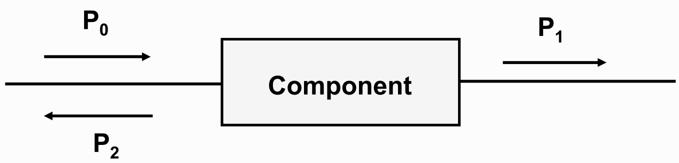
Used where fibers are used
Telecom
Sensing
Fibre lasers
Medicine
Industry

Examples discussed

Couplers/Splitters
Optical Taps
Multiplexers/Combiners
De-multiplexers/Splitters
Fixed Add/drop Multiplexers
Interleavers
Photonic Lightwave Circuits [AWG]
Twin Core Fibers
Connectors

Isolators
Circulators
Optical Attenuators
Polarisation Related Components
Polarization related problems
Tunable Filters
Interferometers
Polarization control (active)
Polarization switch
Electrooptical fibers

Loss and the dB scale



Insertion loss $\alpha_I\,[dB] = -10 \log\,(P_1 / P_0)$

Return loss $\alpha_R\,[dB] = -10 \log\,(P_2 / P_0)$

3 dB loss ⟷ 50% loss
10 dB loss ⟷ 90% loss
30 dB loss ⟷ 99.9 % loss

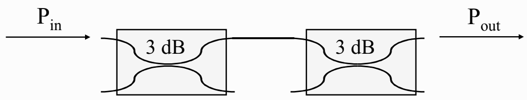
Examples

Two components in series:
Just add the losses in dB to get the combined loss

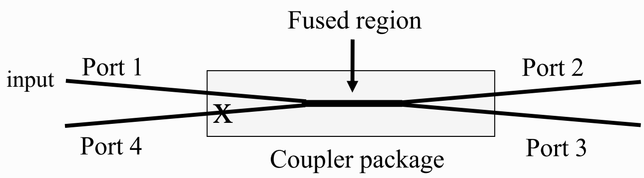
Examples:

1) A fiber has a propagation loss 0.2 dB/km. What fraction of the optical power reaches the fiber end at 15 km (i.e., 15 pieces of 1 km in series)?

2) Two 50% (i.e., 3 dB) fiber couplers are connected in series as shown.
What is the power loss of the combination?



Fiber couplers



$CR(percent) = 100P_3/(P_2 + P_3)$ — CR: coupling ratio (e.g., 70/30)

$EL(dB) = -10\log((P_2 + P_3)/P_1)$ — EL: excess loss (e.g., 0.2 dB)

$IL_2(dB) = -10\log(P_2/P_1)$ — IL2: insertion loss from port 1 to port 2

$IL_3(dB) = -10\log(P_3/P_1)$ — IL3: insertion loss from port 1 to port 3

Pn: optical power at nth port

Acknowledgement: David W. Stowe – Stowaway@attbi.com

Technologies available

Fused: Fibres are fused along their length

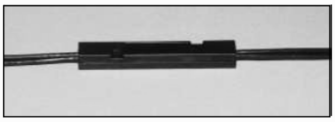
Planar: Fibres are pigtailed to a silica-on-silica or silica-on-silicon structure. Advantageous only for large number of channels (N>4)

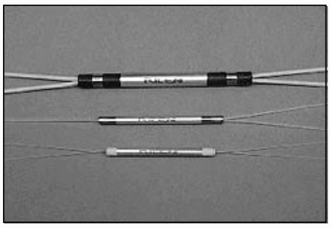
Micro-optics: Fibres are pigtailed to components such as MEMS, micro-mirrors, beam-splitters, etc

Side-polished: Evanescent field couples from fibre to fibre. Usually expensive and adjustable.

Fused couplers

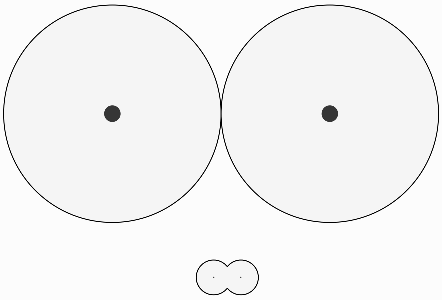
Fiber beam splitters





Fiber Coupler: before and after fusion

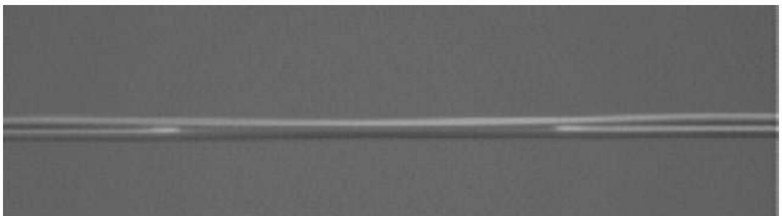
Coupler cross-section



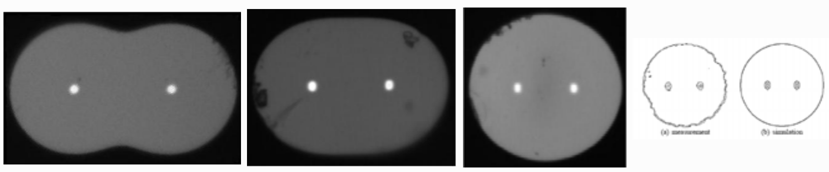
Before fusion
125 µm + 125 µm

After fusion
~35 µm

Fiber Coupler

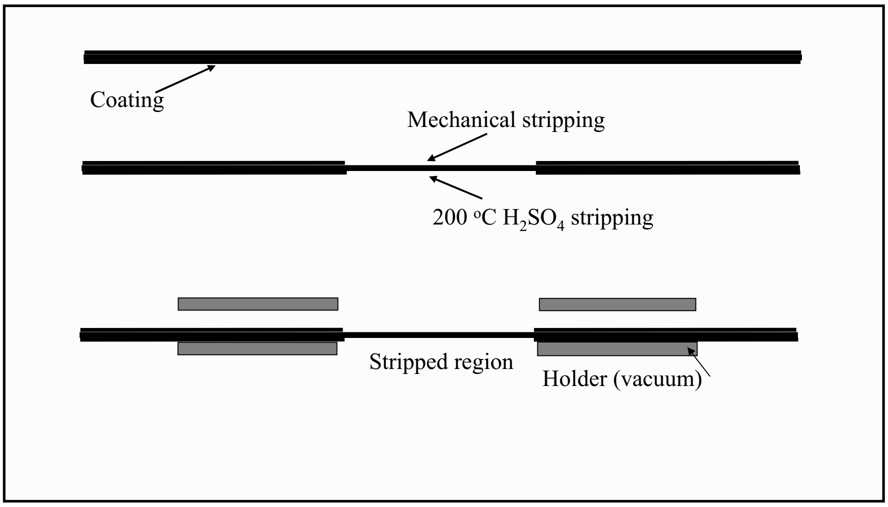


E. Pone et al, 12, 2909 (2004)

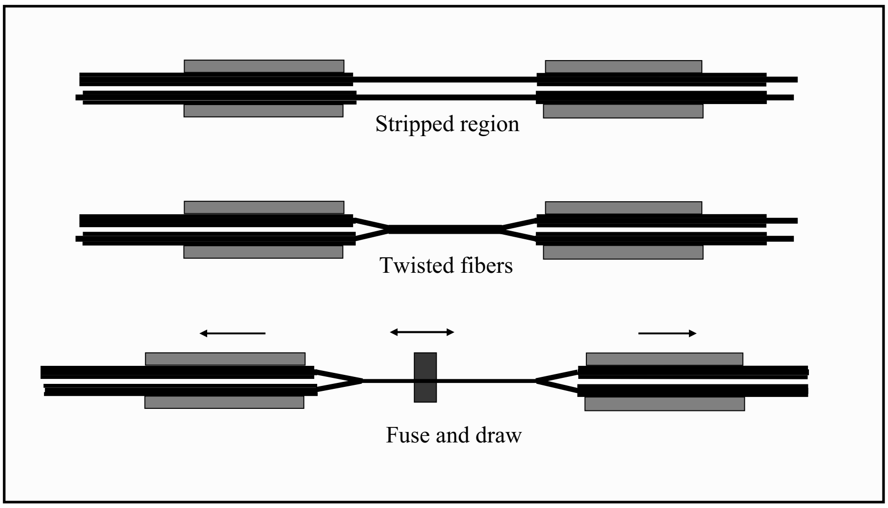


E. Pone et al, 12, 1036 (2004)

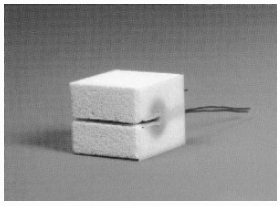
Fabrication of fused couplers



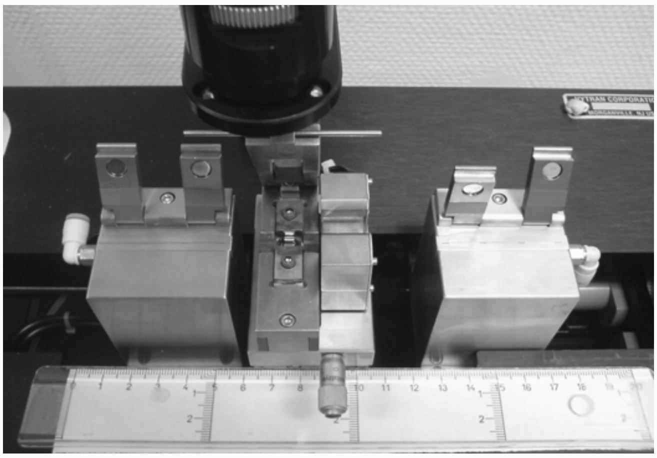
Fabrication of fused couplers



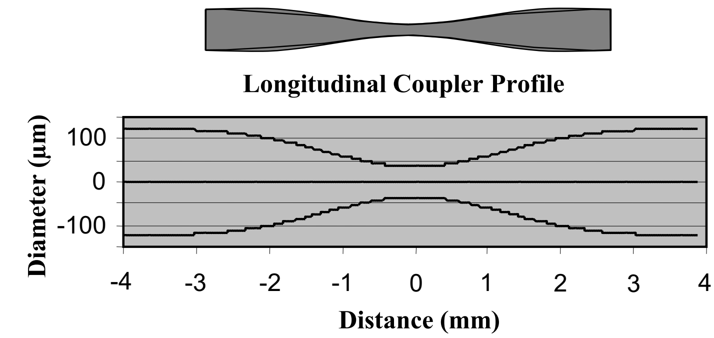
Fiber Coupler Fabrication



Fiber Coupler Fabrication



Cross-section after fabrication



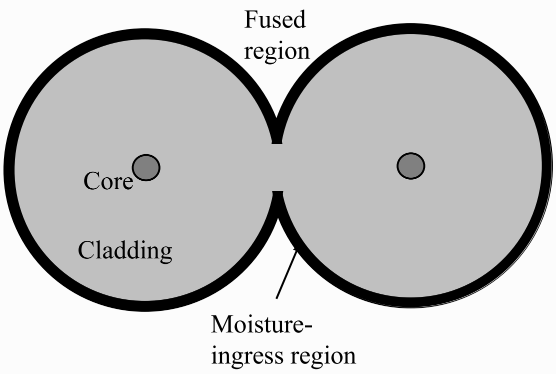
$D = D_0 - \Delta \exp(-x^2 / 2\sigma^2)$

Couplers: properties and issues

Fused devices:
- Low insertion loss
- Simple construction (light never leaves the fibre, no pigtailing)
- Lower cost than alternatives
  (e.g., 3 dB coupler from Asia costs ~ €10 and from Europe ~€70)
- Environmental stable

Material issues:
- Additional processing of fibre
- Weakening due to coating removal and cleaning
- Weakening due to heating and material diffusion
- Hydrogen and moisture
- Fictive temperature changes in coupler region
- Coupler depends on outer regions of fibre (contamination, purity, rugosity)
- Moisture drift in time

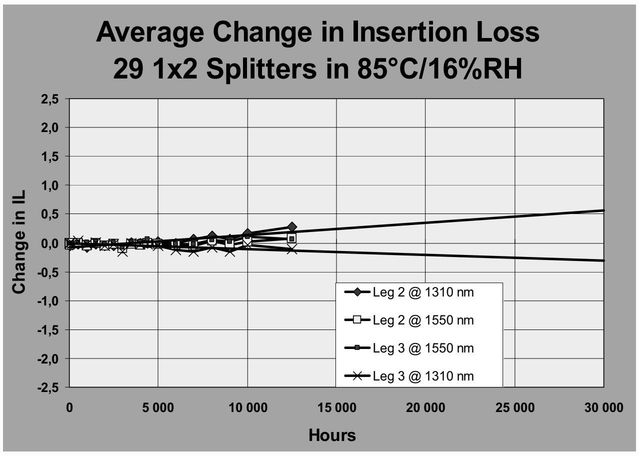
Typical Splitter Cross-section



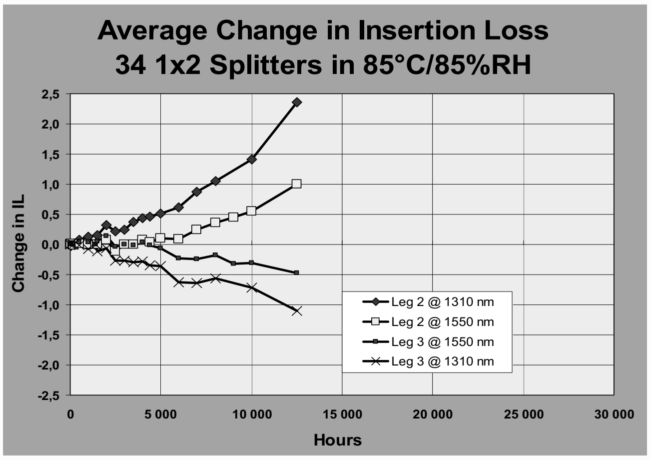
Loss and drift mechanisms

- Contaminants
- H_2 diffusion
- Epoxy degradation
- Water diffusion

Long-term effect of humidity



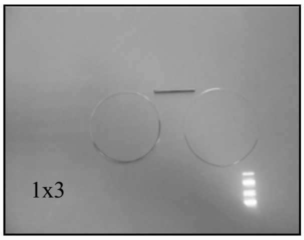
Long-term effect of humidity



More legs

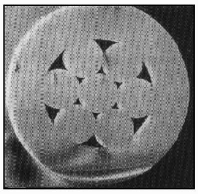

1x4


3x3

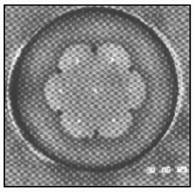

1x3


3x3

Fabrication of 1xN



Lightly fused



Highly fused

Energy transfer: ~100% for N=6 outer fibers

Technique: low index capillary tube and distortion allows for phase matching between outer fibers and central fiber

D Mortimore & J. Arkwright
"Monolithic wavelength-flattened fused fiber couplers: theory, fabrication and analysis", Appl. Opt 30, 650 (1991).
Theory and fabrication of wavelength-flattened 1XN single-mode couplers", Appl. Opt. 29, 1814-1818 (1990).

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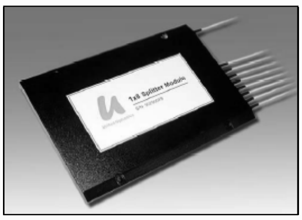
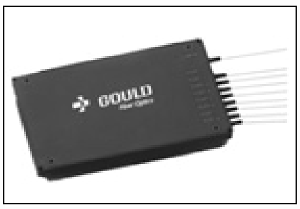
Photonic Lightwave Circuits (PLC): 1xN couplers

1x8 couplers





When N is large
Multimode Interference (MMI)
couplers can be used
(not fiber)

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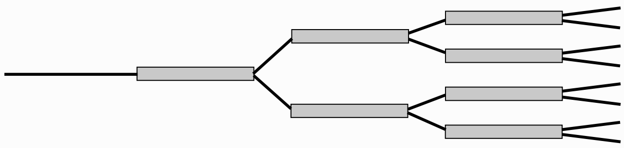
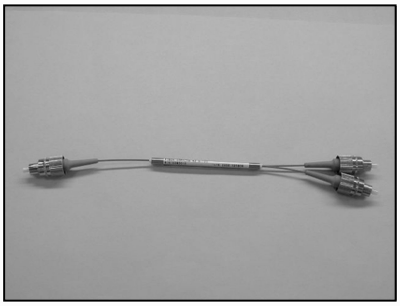
Concatenated splitters

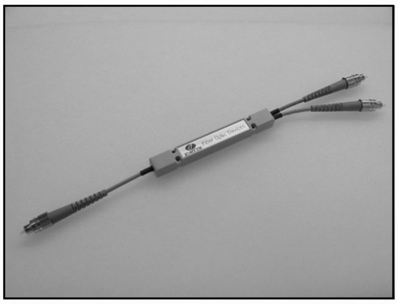
1x8 tree splitter fabricated by concatenating 1x2 splitters



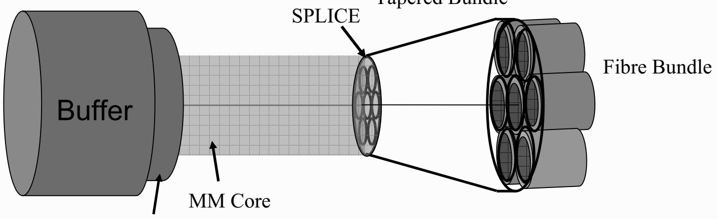
Useful in passive optical networks

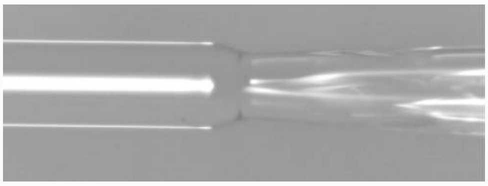
Multimode couplers





High-power: tapered fiber bundles





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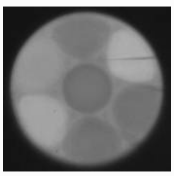
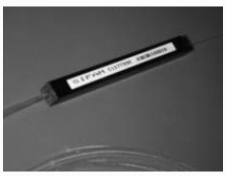
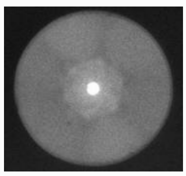
High-power: multimode combiners

7x1 MM combiner
MM: 94% transmission





Corning HI1060nm signal input
105/125um 0.22NA pump input
5/125um DCF (0.46 NA)
MM transmission: 93%
Signal transmission: 87%



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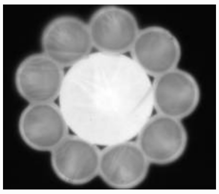
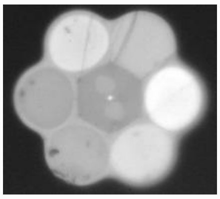
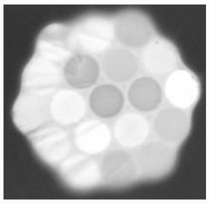
Novel designs

Novel designs	PM Combiners	Higher port count
		
10x1	PM 6+1x1	19x1

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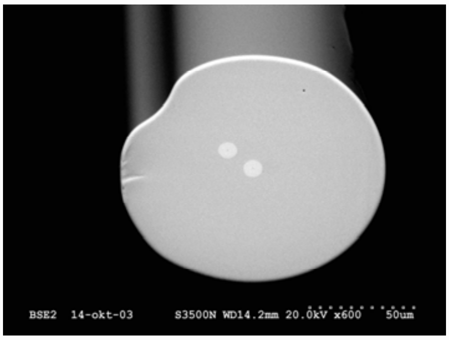
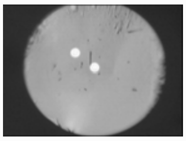
Power coupling between two parallel WG

Twin-core fiber





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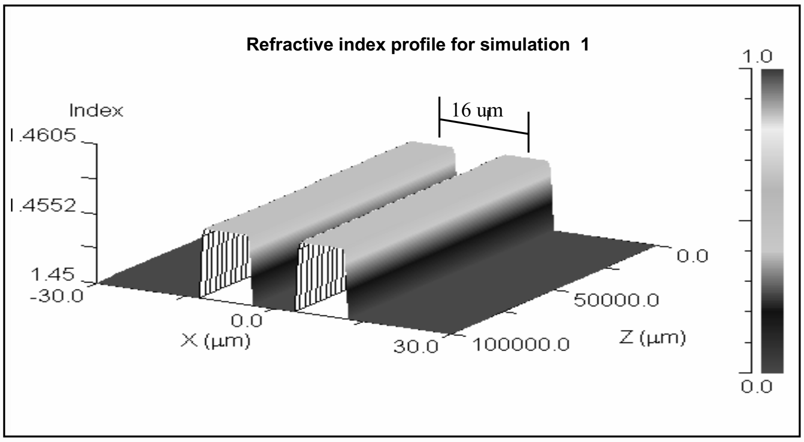
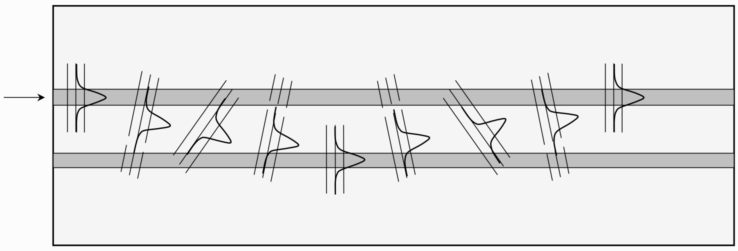
Power coupling between two parallel WG

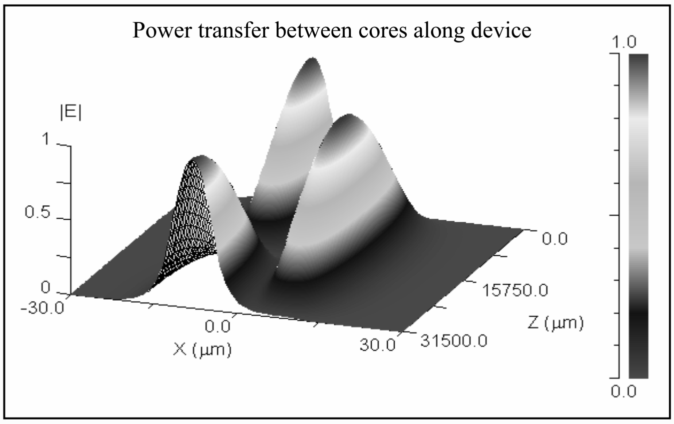


Qualitative - Do not quote me!

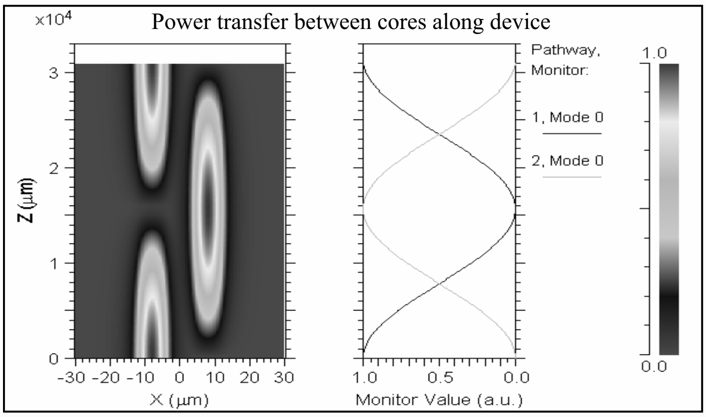


The wavefront propagates slower in the region of higher average index.
This changes the propagation direction.
Energy is coupled into the second waveguide.

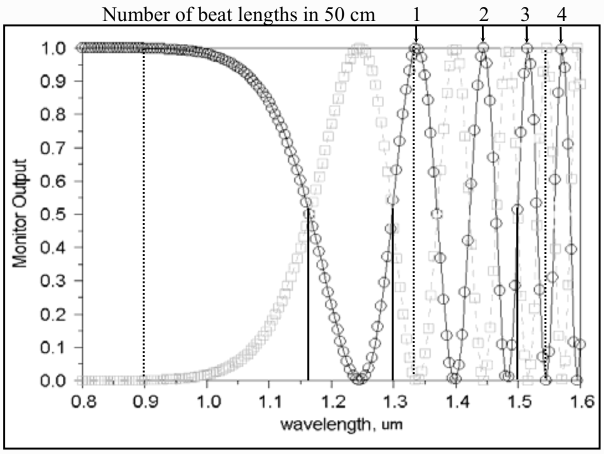
Beam propagation simulation



Beam propagation simulation



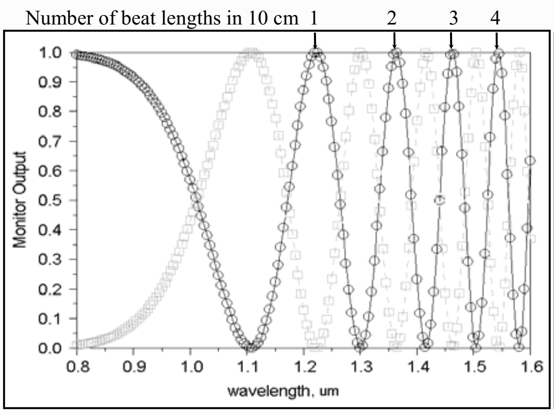
Power at the end of the device



Parameters:
Core distance: 21 µm
Fiber length: 50 cm
Core 1: o
Core 2: o

3 dB coupling:
λ=1.16 µm
1.3 µm
….
1.5 µm
Dual band (1.3-1.5)

Power at the end of the device

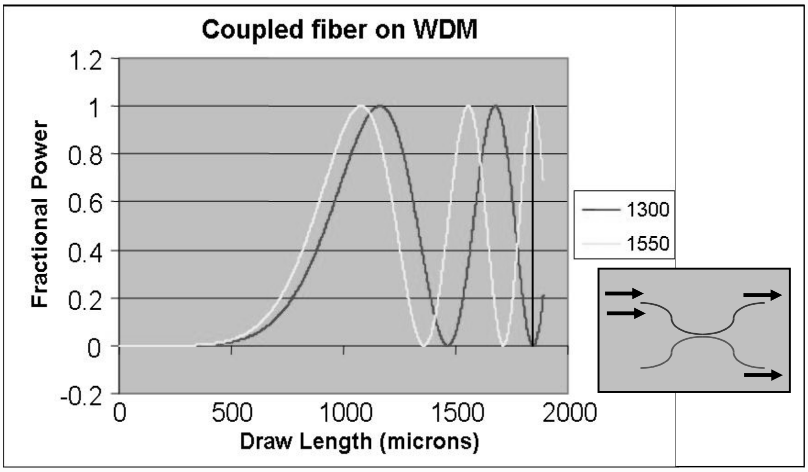


Parameters:
Core distance: 16 µm
Fiber length: 10 cm
Core 1: o
Core 2: o

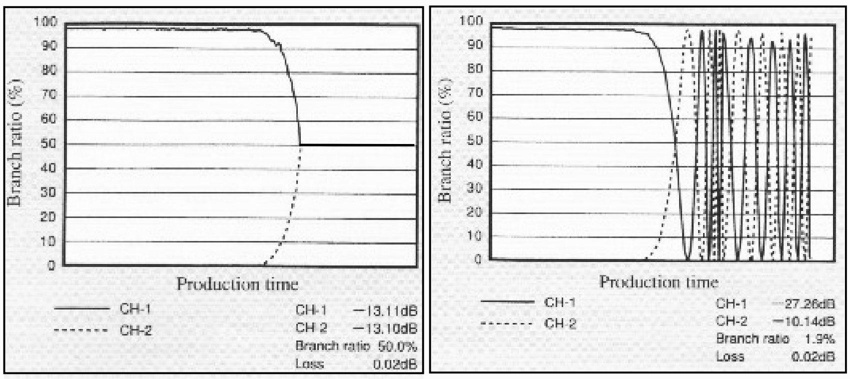
Computational domain:
30x30 µm
Step along z axis: 20 µm

Smaller core distance,
huge effect in coupling

Power coupling between ports vs length



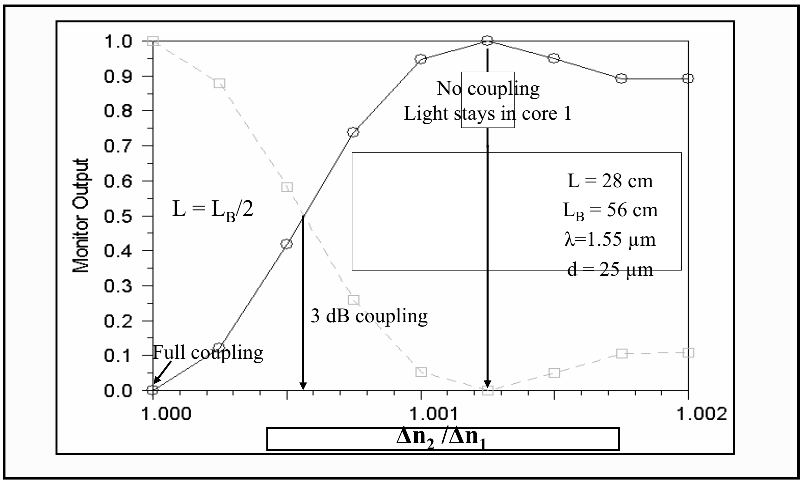
When to stop coupler fabrication



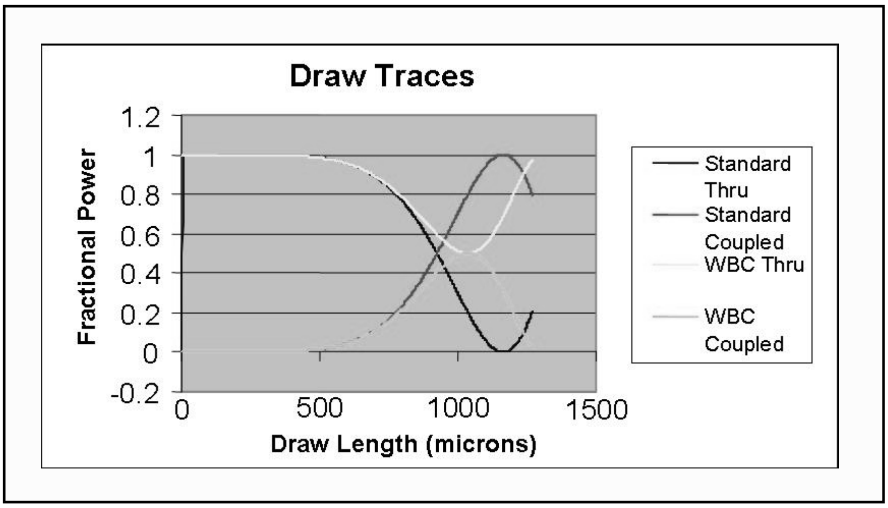
3 dB WDM 1480-1550

What is bad about these couplers?

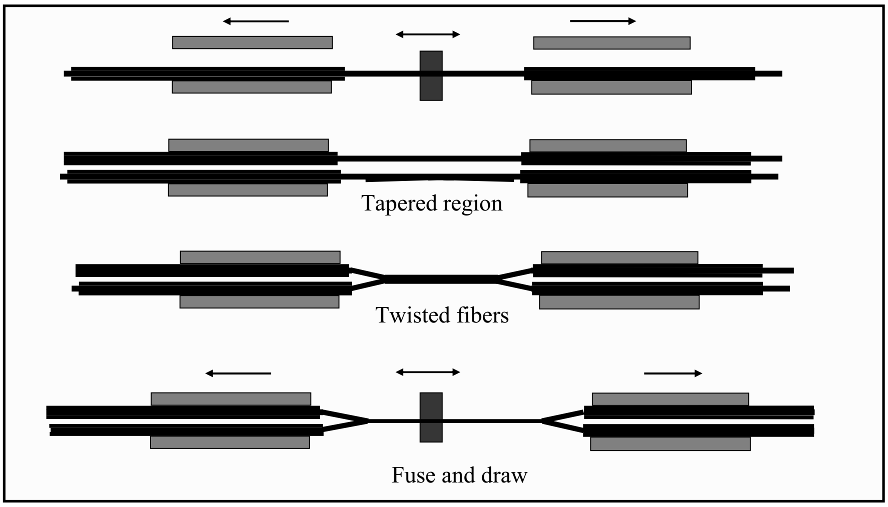
Effect of different Δn in cores



Fabrication of broadband couplers

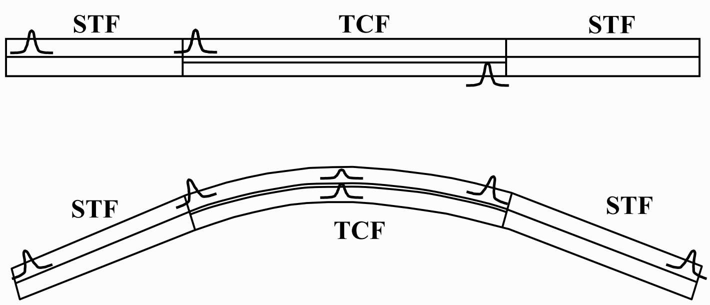


Fabrication of broadband couplers

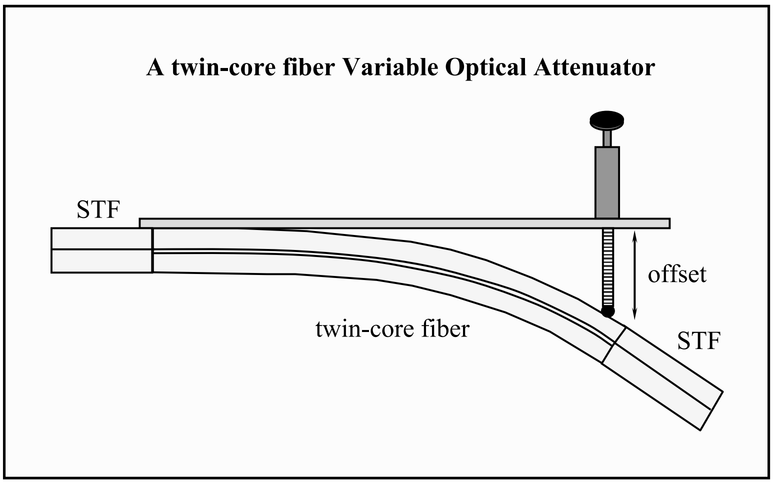


Side-issue

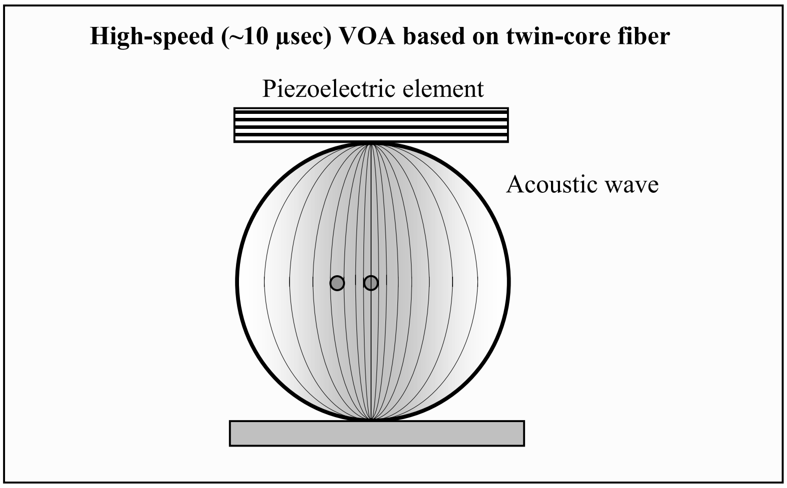
A twin-core fiber Variable Optical Attenuator



Side-issue

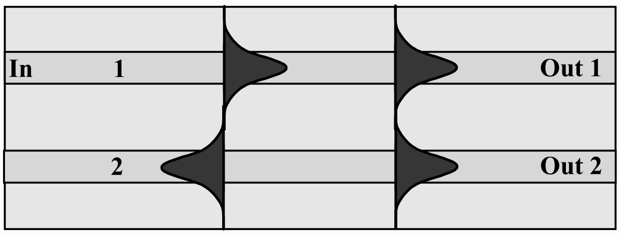


Side-issue



Simplified coupling theory

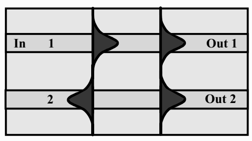
Supermodes:



Anti-symmetrical Symmetrical

Simplified coupling theory

Eigenmodes in a coupler



Input field: $E_{in}(y) = E_{01}\, e^{(x-d)^2/\omega^2} = E_{01}\, G1$

Assume G1 and G2 normalized, i.e., $|G1| = |G2| = 1$

Eigenmodes: symmetric $A_S = G1 + G2$; anti-symmetric $A_A = G1 - G2$

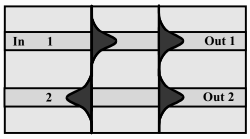
$G1 = 1/2\,(A_S + A_A)$
$G2 = 1/2\,(A_S - A_A)$

Propagation: phase difference between eigenmodes $e^{i \Delta\beta L}$

Input: $E_{in} = E_{01}\, G1 = E_{01}\, 1/2\,(A_S + A_A)$

Output: $E_{out} = E_{01}\, 1/2\,(A_S + A_A\, e^{i \Delta\beta L})$

Simplified coupling theory



Output: $E_{out} = E_{01}\ 1/2\ (A_S + A_A\ e^{\,i\,\Delta\beta\,L})$

Express output in terms of G1 and G2

$E_{out} = E_{01}/2\ (G1 + G2 + G1e^{\,i\,\Delta\beta\,L} - G2e^{\,i\,\Delta\beta\,L})$

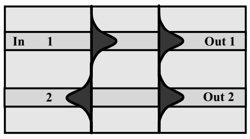
$E_{out} = \underbrace{E_{01}/2\ (G1 + G1e^{\,i\,\Delta\beta\,L})}_{E_{out1}} + \underbrace{E_{01}/2\ (G2 - G2e^{\,i\,\Delta\beta\,L})}_{E_{out2}}$

More general case Input $E_{in} = E_0\ (C1\ A_S + C2\ A_A)$

Output: $E_{out} = E_0\ (C1G1 + C1G2 + C2G1\ e^{\,i\,\Delta\beta\,L} - C2G2\ e^{\,i\,\Delta\beta\,L})$

Output: $E_{out} = E_0\ [\underbrace{G1\ (C1 + C2\ e^{\,i\,\Delta\beta\,L})}_{E_{out1}} + \underbrace{G2\ (C1 - C2e^{\,i\,\Delta\beta\,L})}_{E_{out2}}]$

Simplified coupling theory



$E_{out} = E_0\ [G1\ (C1 + C2\ e^{\,i\,\Delta\beta\,L}) + G2\ (C1 - C2e^{\,i\,\Delta\beta\,L})]$

Power output

$P_{out1} = |E_0|^2\ |G1|^2\ (C1^2 + C2^2 + 2\ C1\ C2\ \cos \Delta\beta\ L)$

$P_{out2} = |E_0|^2\ |G2|^2\ (C1^2 + C2^2 - 2\ C1\ C2\ \cos \Delta\beta\ L)$

For C1 = C2 = 1/2

$P_{out1} = |E_0|^2\ (1/4 + 1/4 + 1/2\ \cos \Delta\beta\ L)$

$$\mathbf{P_{out1} = 1/2\ |E_0|^2\ (1 + \cos \Delta\beta\ L)}$$

$$\mathbf{P_{out2} = 1/2\ |E_0|^2\ (1 - \cos \Delta\beta\ L)}$$

Power oscillates between waveguides

Maxwell's equations in a fibre coupler or TCF

$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t,$

$\nabla \times \mathbf{H} = \partial \mathbf{D} / \partial t,$

$\nabla . \mathbf{D} = 0$ (no free charges or currents)

$\nabla . \mathbf{B} = 0$

where

$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$

$\mathbf{B} = \mu_0 \mathbf{H} + \mathbf{M}$ (non-magnetic: $\mathbf{M} = 0$)

$\nabla \times \nabla \times \mathbf{E} = - 1/c^2\, \partial^2 \mathbf{E}/\partial t^2 - \mu_0\, \partial^2 \mathbf{P}/\partial t^2$

where **P** describes the material response to the **E** field.

No charges: $\nabla . \mathbf{E} = 0$, and since $\nabla \times \nabla \times \mathbf{E} = \nabla (\nabla . \mathbf{E}) - \nabla^2 \mathbf{E}$

In the frequency domain (ω), assuming harmonic expansion of the fields:

$\nabla^2 \check{\mathbf{E}} + n^2(\omega)\, k_0^2\, \check{\mathbf{E}} = 0$

where $k_0 = \omega/c = 2\pi/\lambda_0$

Maxwell's equations in a fibre coupler or TCF

In cylindrical coordinates:

$\partial^2 E_z / \partial \rho^2 + 1/\rho\ \partial E_z / \partial \rho + 1/\rho^2\ \partial^2 E_z / \partial \varphi^2 + \partial^2 E_z / \partial z^2 + n^2 k_0^2 E_z = 0$

and similar equations for E_φ, E_ρ, H_z, H_φ, H_ρ

Separation of variables: $E_z(\rho, \varphi, z) = F(\rho)\, \Phi(\varphi)\, Z(z)$

$d^2 Z / dz^2 + \beta^2 Z = 0$ (1)

$d^2 \Phi / d\varphi^2 + m^2 \Phi = 0$ (2)

$d^2 F / d\rho^2 + 1/\rho\ \partial F / \partial \rho + (n^2 k_0^2 - \beta^2 - m^2/\rho^2) F = 0$ (3)

Solutions:

(1): $Z = \exp(i\beta z)$, where β is the **propagation constant**

(2): $\Phi = \exp(im\varphi)$, where **m** is an integer so that Φ repeats at every $\varphi_m = \varphi_{m-1} + 2\pi$

(3): F = combination of Bessel functions

Modes in a fibre coupler or TCF

Implications:

- The product $\Phi(\varphi).F(\rho)$ gives the transversal field distribution across the waveguide, while $Z = \exp(i\beta z)$ tells us that light propagates along the waveguide as a sine/cosine.
- The various Bessel function combinations of $F(\rho)$ give rise to discrete solutions of the transverse field distribution. Like atomic levels in an atom or oscillating modes in a gitar string, these can be treated as eigenstates of the propagation equation.
- The stable solutions of the transverse field distribution are the *propagation modes*.
- The propagation constant depends on the field distribution in the core - different *modes* have different β. β depends on the overlap of the mode with core and cladding.

Modes in a fibre coupler or TCF

For coupled waveguides:
$\nabla^2 \check{\mathbf{E}} + n^2(\omega)\, k_0^2\, \check{\mathbf{E}} = 0$
has approximate solution:

$\mathbf{E}(r, \omega) \sim \hat{\mathbf{e}}\, \{\tilde{A}_1(z, \omega)\, F_1(x,y) + \tilde{A}_2(z, \omega)\, F_2(x,y)\} e^{i\beta z}$

The transversal part in (x,y) or in (r,φ) is solved separately to give the individual waveguide propagation modes.
Generally, each arm supports only the fundamental mode (nealy Gaussian)

Replacing in the wave equation and after a few hours work (slowly varying envelope approximation):

$d\tilde{A}_1/dz = i(\beta_1 - \beta)\, \tilde{A}_1 + i\, \kappa_{12}\, \tilde{A}_2$

$d\tilde{A}_2/dz = i(\beta_2 - \beta)\, \tilde{A}_2 + i\, \kappa_{21}\, \tilde{A}_1$

Modes in a fibre coupler or TCF

In the time domain

$\partial A_1/\partial z + (1/v_{g1})\, \partial A_1/\partial t + (i\beta_{21}/2)\, \partial A_1^2/\partial t^2 = i\, \kappa_{12} A_2 + i\delta_a A_1$

$\partial A_2/\partial z + (1/v_{g2})\, \partial A_2/\partial t + (i\beta_{22}/2)\, \partial A_2^2/\partial t^2 = i\, \kappa_{21} A_1 - i\delta_a A_2$

where

$v_{g1} = 1/\beta_{11}$ is the group velocity in guide 1

β_{21} is the group velocity dispersion parameter of waveguide 1

$\delta_a = 1/2\, (\beta_{01} - \beta_{02})$

$\beta = 1/2\, (\beta_{01} + \beta_{02})$

Coupling in a fibre coupler or TCF

CW beams

$\partial A_1/\partial z = i\, \kappa_{12} A_2 + i\delta A_1$

$\partial A_2/\partial z = i\, \kappa_{21} A_1 + i\delta A_2$

Time derivatives are zero

$\partial^2 A_1/\partial z^2 + \kappa^2 A_1 = 0$

where $\kappa = [(\kappa_{12}\, \kappa_{21})^{1/2} + \delta]^{1/2}$

Solution: harmonic oscillator

Assume power coupled into one port:

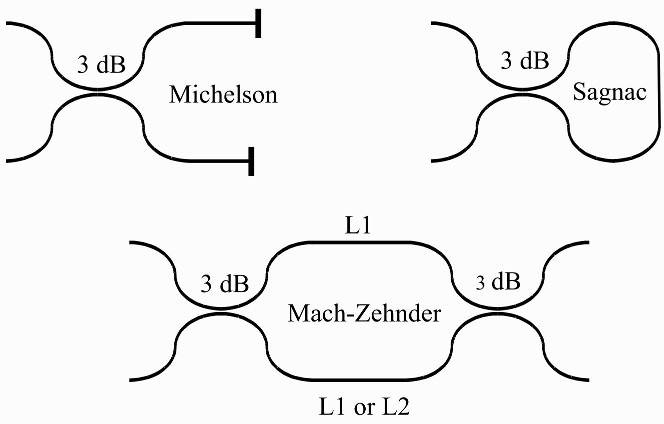
$A_2\,(z=0) = 0,\ A_1\,(z=0) = A_0$

$A_1(z) = A_0\, [\cos(\kappa z) + i\, (\delta/\kappa)\sin(\kappa z)]$

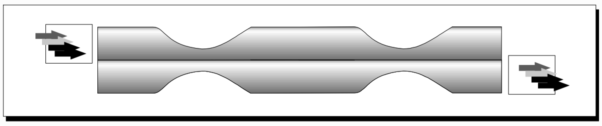
$A_2(z) = A_0\, [i\, (\kappa_{21}/\kappa)\sin(\kappa z)]$

Power couples from waveguide 1 to waveguide 2

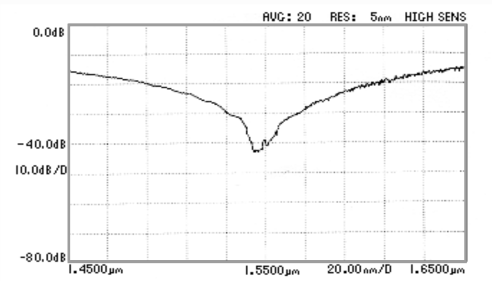
Standard Interferometers



Standard Mach-Zehnder Interferometer



Applications: Add / Drop Multiplexers and Sensors



Features

- Standard couplers
- Insertion loss < 0.2 dB
- PDL < 0.1 dB
- Reflectivity < -50 dB
- Interferometer balanced to 0.04 wavelengths
- Single sided devices available
- Standard & custom fibers
- Dimensions 125 mm x 5 mm

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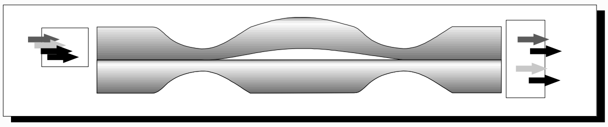
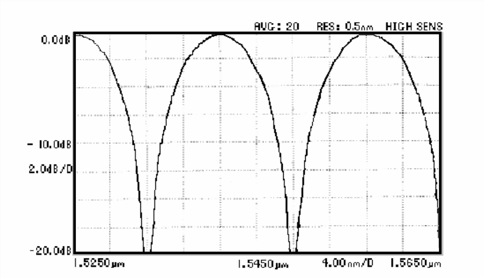
Unbalanced Mach-Zehnder



Applications: Wavelength Division Multiplexers and Sensors



Features

- Narrow channel spacing 3.2 - 240 nm
- Insertion loss < 0.2 dB
- PDL < 0.1 dB
- Reflectivity < -50 dB
- Interferometer balanced to 0.04 wavelengths
- Dimensions 125 mm x 5 mm

Thomas & Betts

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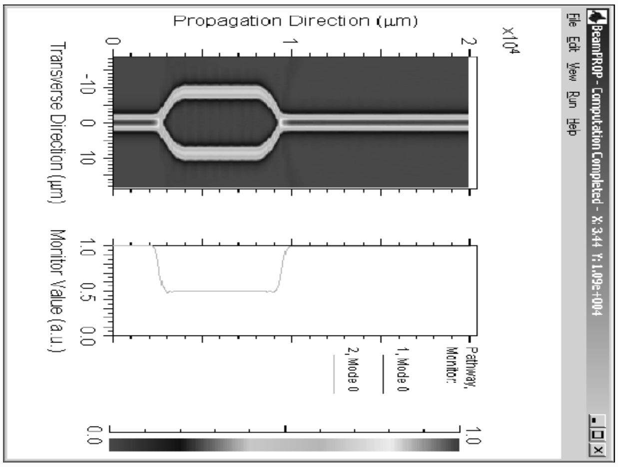

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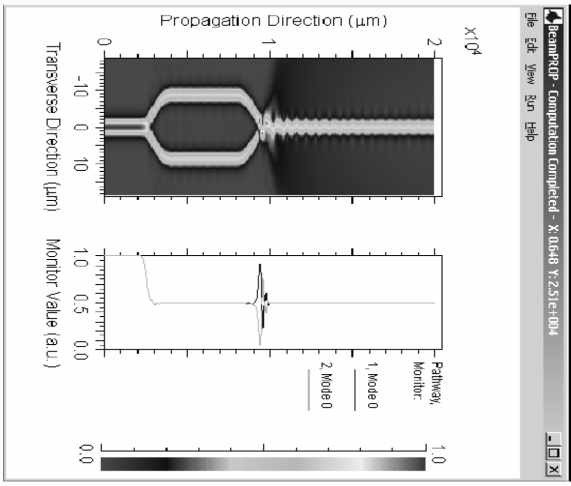

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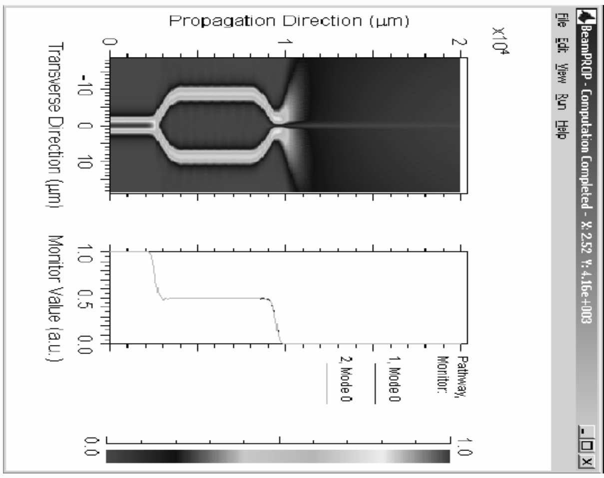

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FiberLogix
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Rikensen
Oz Optics
Emit
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General Photonics
Newport
Melles Griot

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Summary

Fused couplers: most important passive component
Stable technology
2x2 common (Fabrication, reliability issues)
1xN expanding
MM devices useful for Fiber Lasers
Principles of coupling
Twin-core fiber
Simulations and simplified theory
MZI