Graded-Index Core Polymer Optical Waveguide for High-bandwidth-density On-Board Interconnect

Takaaki Ishigure

Faculty of Science and Technology
Keio University

Performance Development in Super Computer

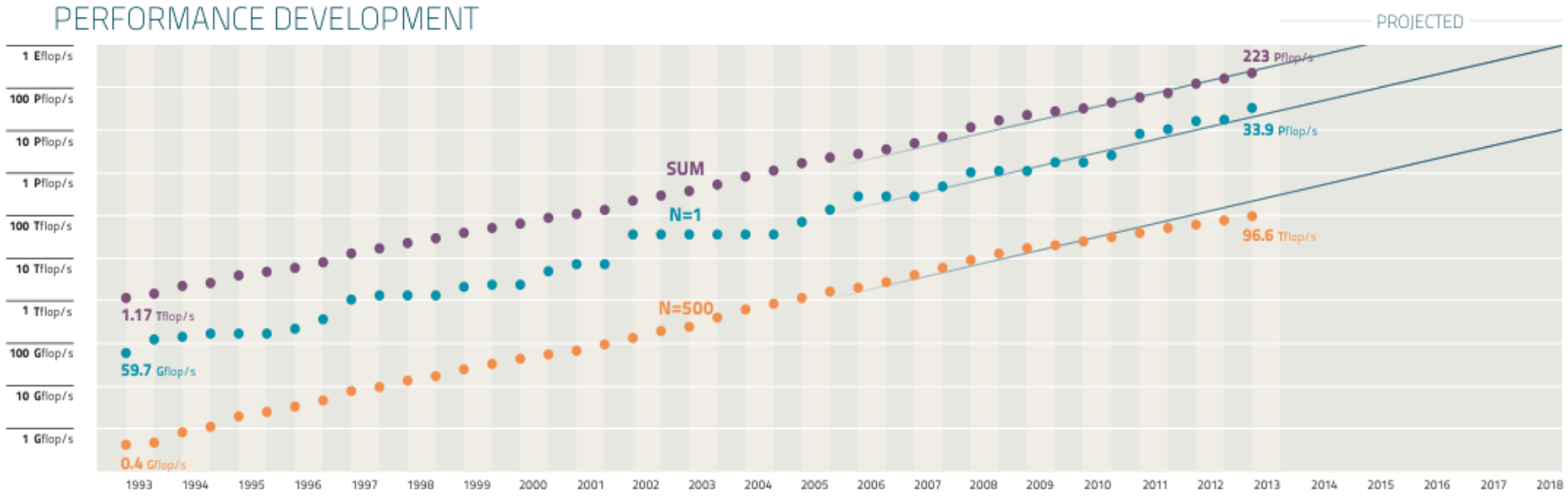
Ref. http://s.top500.org/static/lists/2013/06/TOP500_201306_Poster.png

TOP500® JUNE 2013

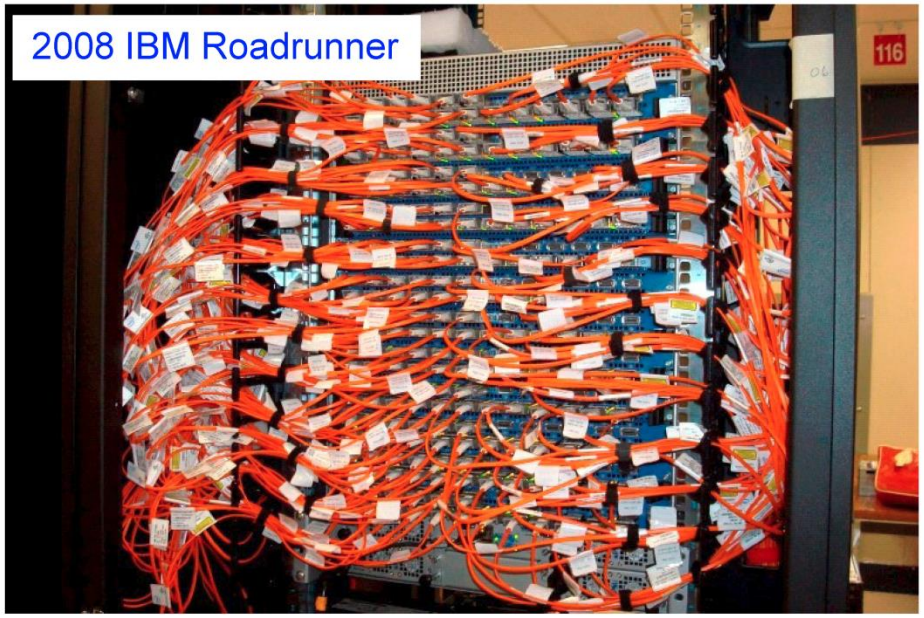
PRESENTED BY UNIVERSITY OF MANNHEIM · ICL UT INNOVATIVE COMPUTING LABORATORY THE UNIVERSITY of TENNESSEE · BERKELEY LAB Lawrence Berkeley National Laboratory

FIND OUT MORE AT www.top500.org

	NAME	SPECS	SITE	COUNTRY	CORES	R_{MAX} PFLOP/S	POWER MW
1	**Tianhe-2 (Milkyway-2)**	NUDT, Intel Ivy Bridge (12C, 2.2 GHz) & Xeon Phi (57C, 1.1 GHz), Custom interconnect	NUDT	China	3,120,000	**33.9**	17.8
2	**Titan**	Cray XK7, Opteron 6274 (16C, 2.2 GHz) + Nvidia Kepler (14C, .732 GHz), Custom interconnect	DOE/SC/ORNL	USA	560,640	**17.6**	8.3
3	**Sequoia**	IBM BlueGene/Q, Power BQC (16C, 1.60 GHz), Custom interconnect	DOE/NNSA/LLNL	USA	1,572,864	**17.2**	7.9
4	**K computer**	Fujitsu SPARC64 VIIIfx (8C, 2.0GHz), Custom interconnect	RIKEN AICS	Japan	705,024	**10.5**	12.7
5	**Mira**	IBM BlueGene/Q, Power BQC (16C, 1.60 GHz), Custom interconnect	DOE/SC/ANL	USA	786,432	**8.16**	3.95

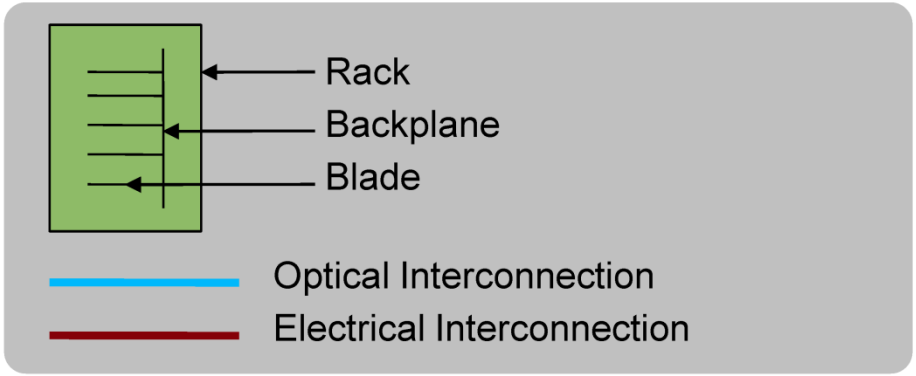


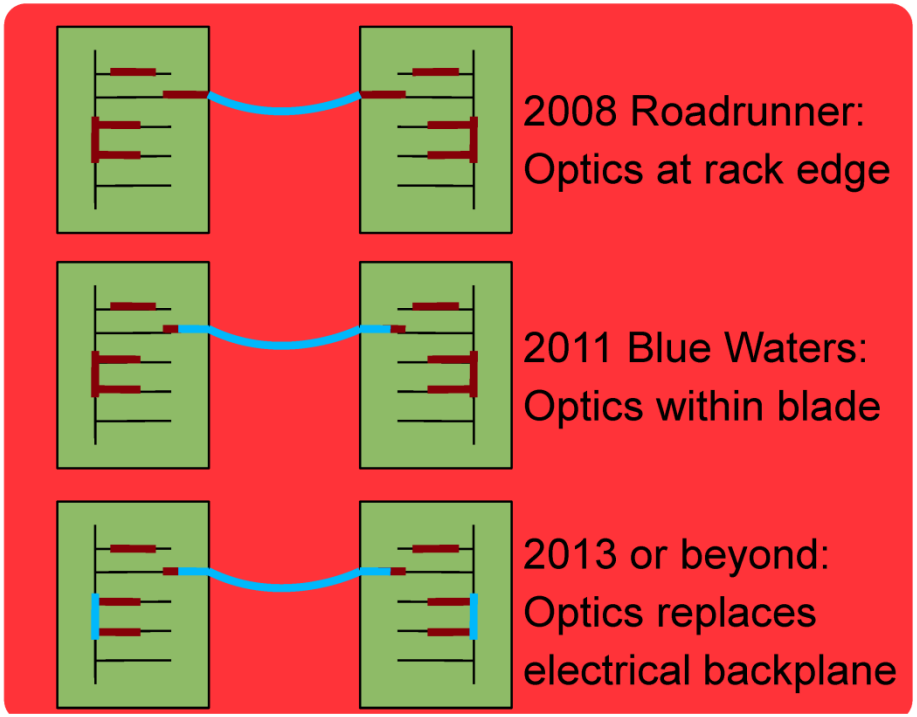
Super Computers from IBM



2

2012? IBM Power 775



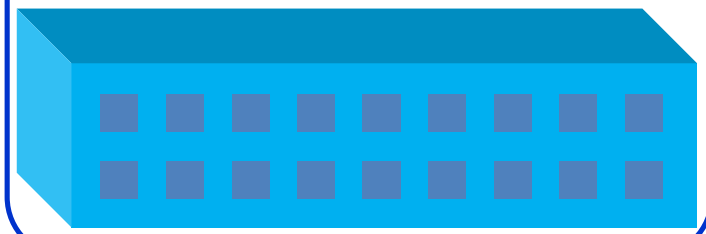


Polymer waveguides for on-board application

Optical Wiring Board (PCB)

Chip to chip link: < 0.3 m

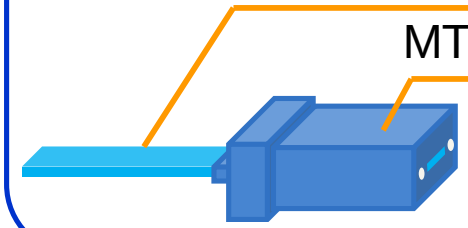
Board to board link: 0.3 m ~ 1 m



Connect to other devices

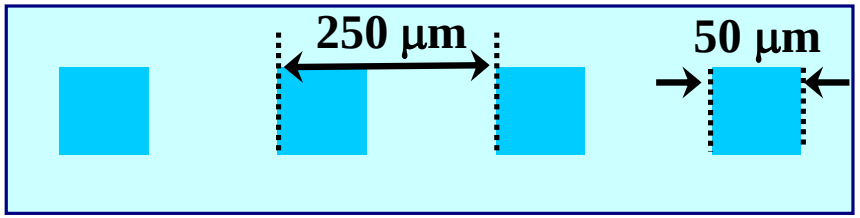
GI multimode fiber ribbon

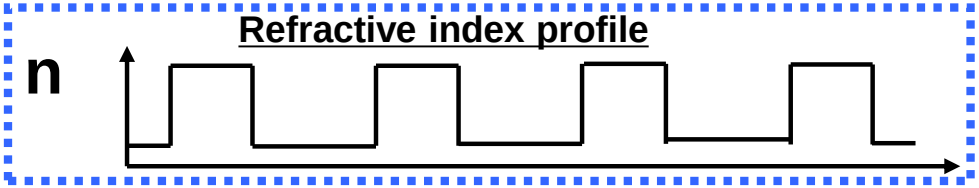
MT connector



Existing Waveguide

Step-Index (SI) Rectangular cores

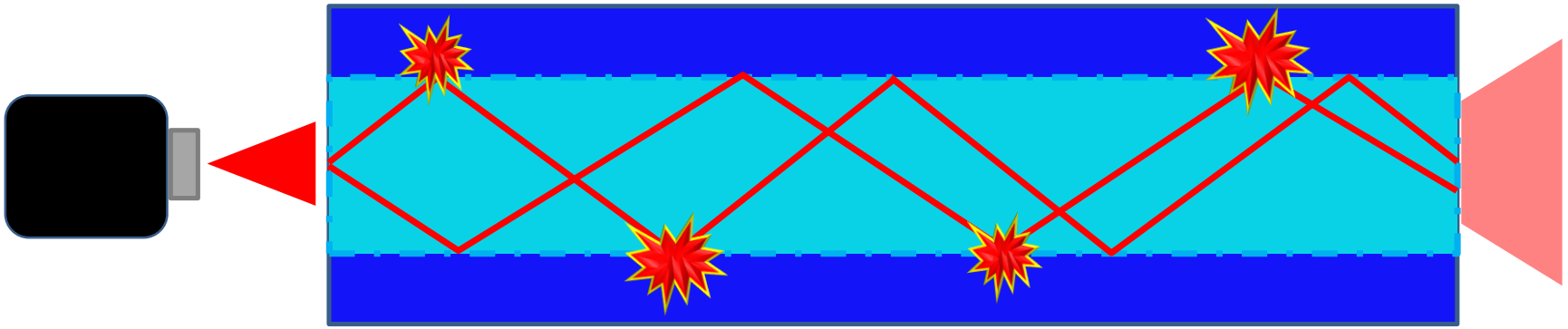




➢ **Concerned issues**

- Large propagation loss
- Crosstalk at highly-integration

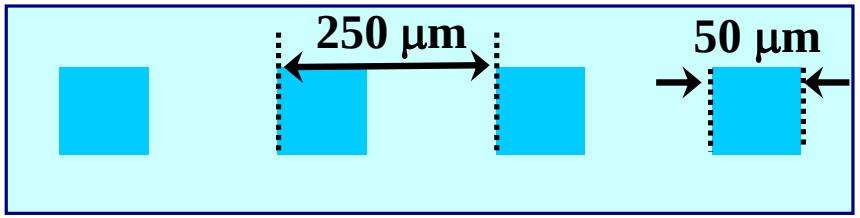
Scattering loss at the core-cladding boundary

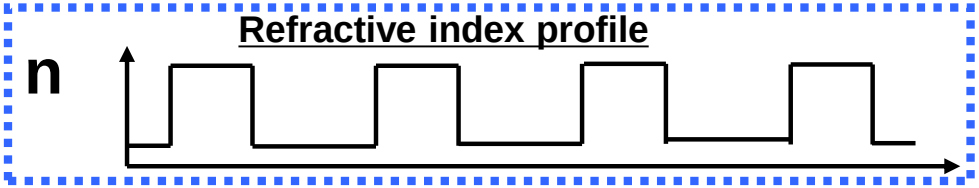


The scattering loss caused by the structural irregularity at the core-cladding boundary would easily increase, because all the modes propagate by total internal reflection at the boundary.

Existing Waveguide

Step-Index (SI) Rectangular cores

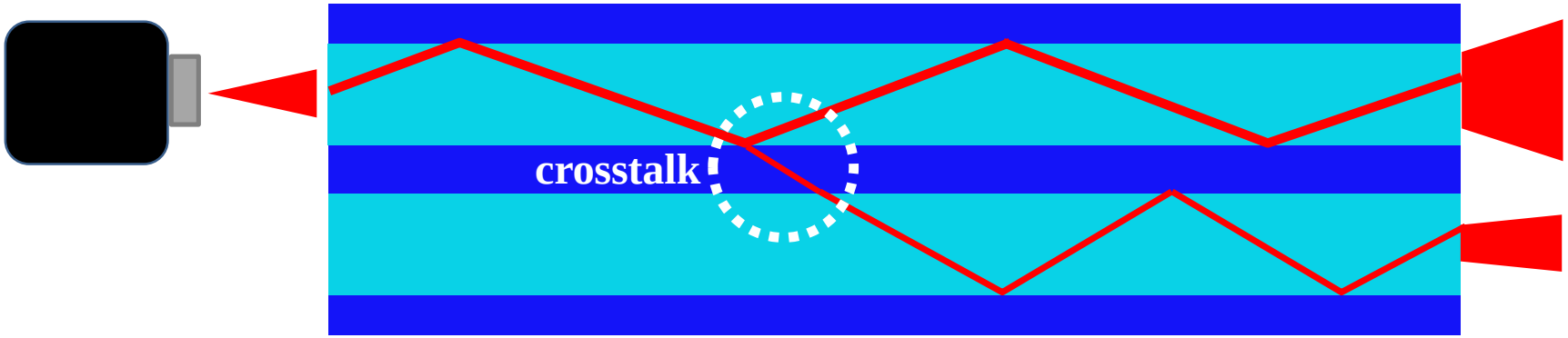




➢ Concerned issues

- Large propagation loss
- Crosstalk at highly-integration

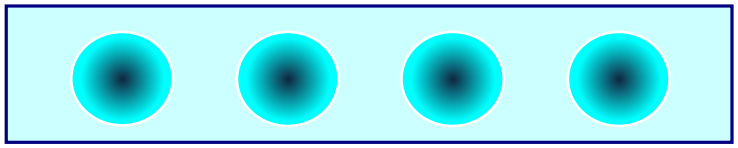
Inter-channel crosstalk

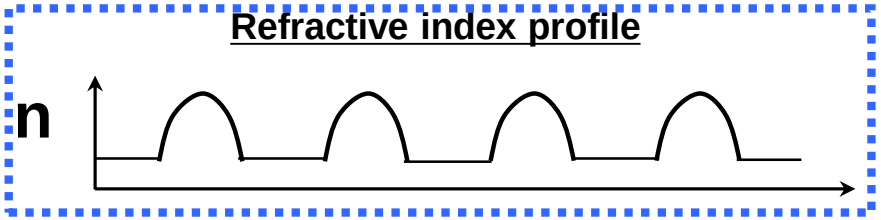


Since all the modes are reflected at the core-cladding boundary, inter-channel crosstalk is concerned in the case of densely-aligned waveguide.

Graded-Index Core Waveguide

Graded-Index (GI) Circular cores

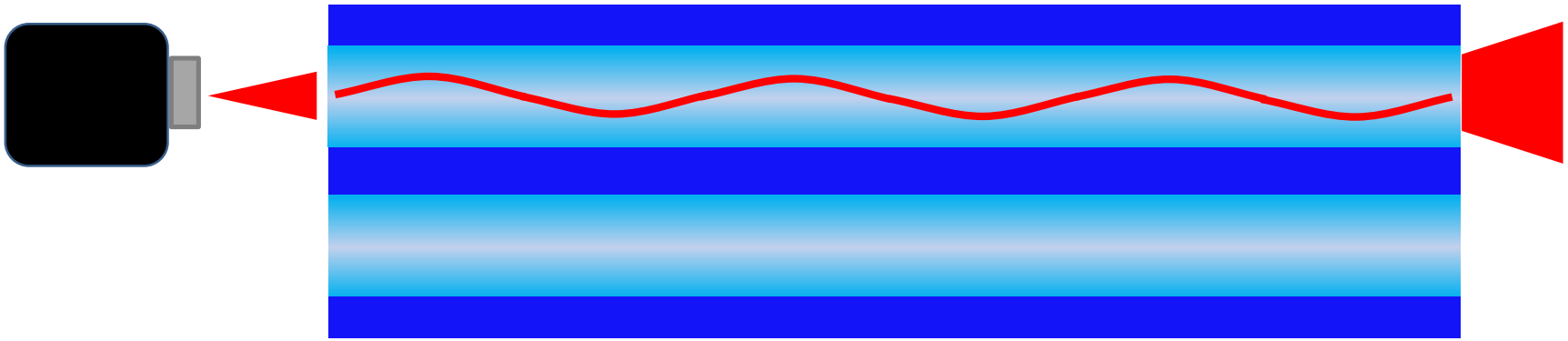




➢ **Advantages of GI circular core**

- Low propagation loss
- Low inter-channel crosstalk
- High coupling efficiency with a fiber

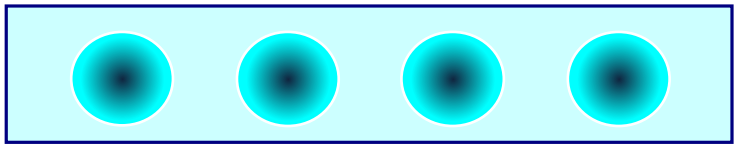
Reduction of inter-channel crosstalk

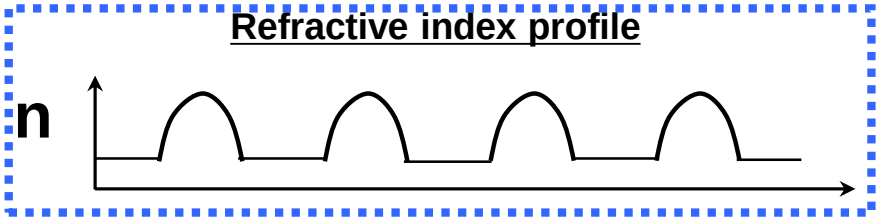


Modes in GI profile propagate around the core center, which can reduce inter-channel crosstalk even at highly-integration.

Graded-Index Core Waveguide

Graded-Index (GI) Circular cores

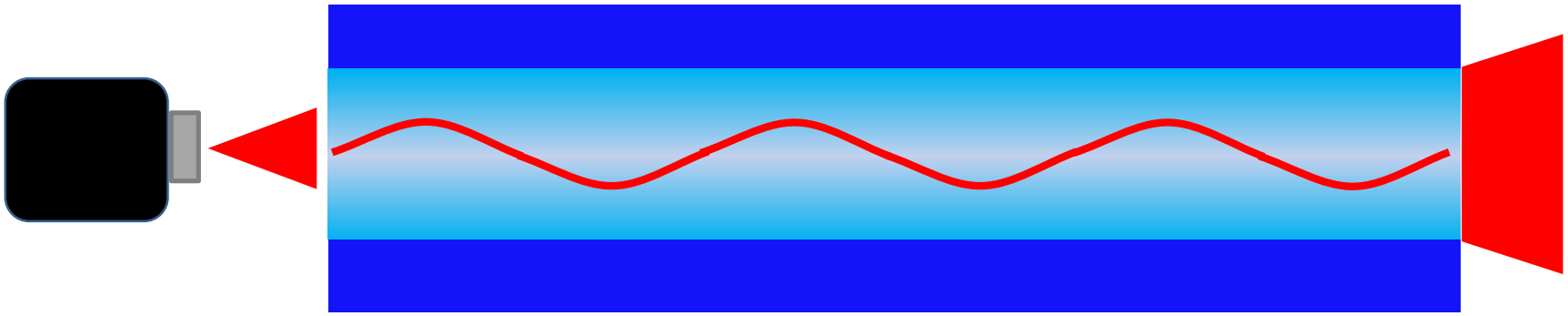




➢ **Advantages of GI circular core**

- Low propagation loss
- Low inter-channel crosstalk
- High coupling efficiency with a fiber

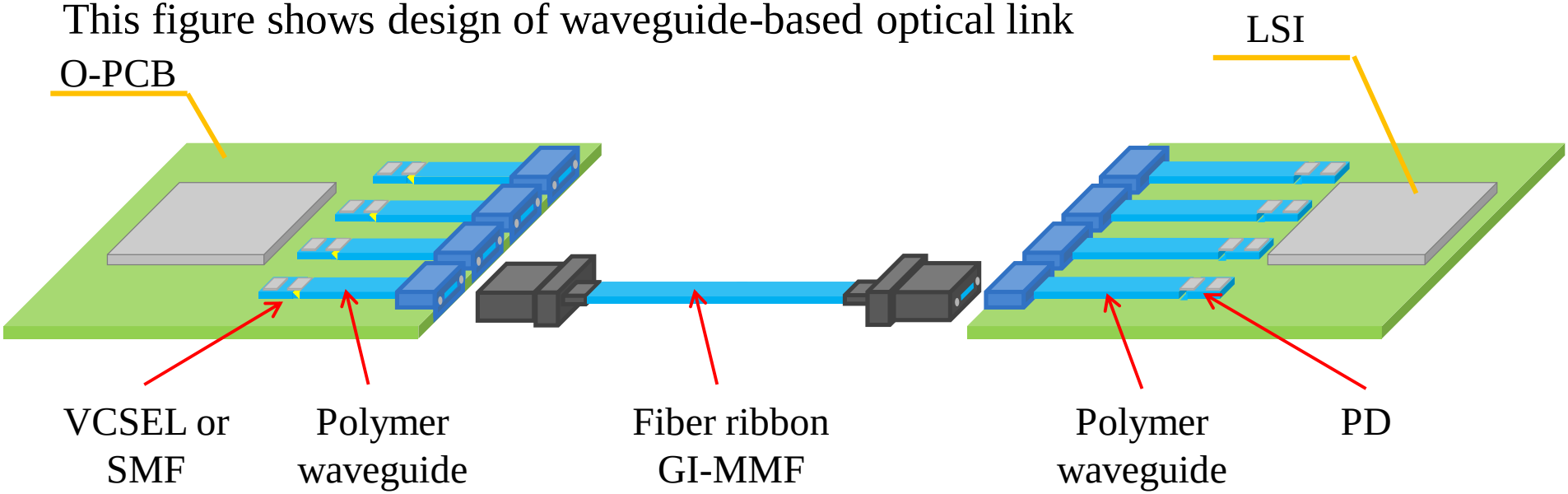
Minimum loss of GI profile



It is expected that the propagation loss could be as low as possible, because GI profile confines mode fields around the core center.

Polymer Waveguide Based Link

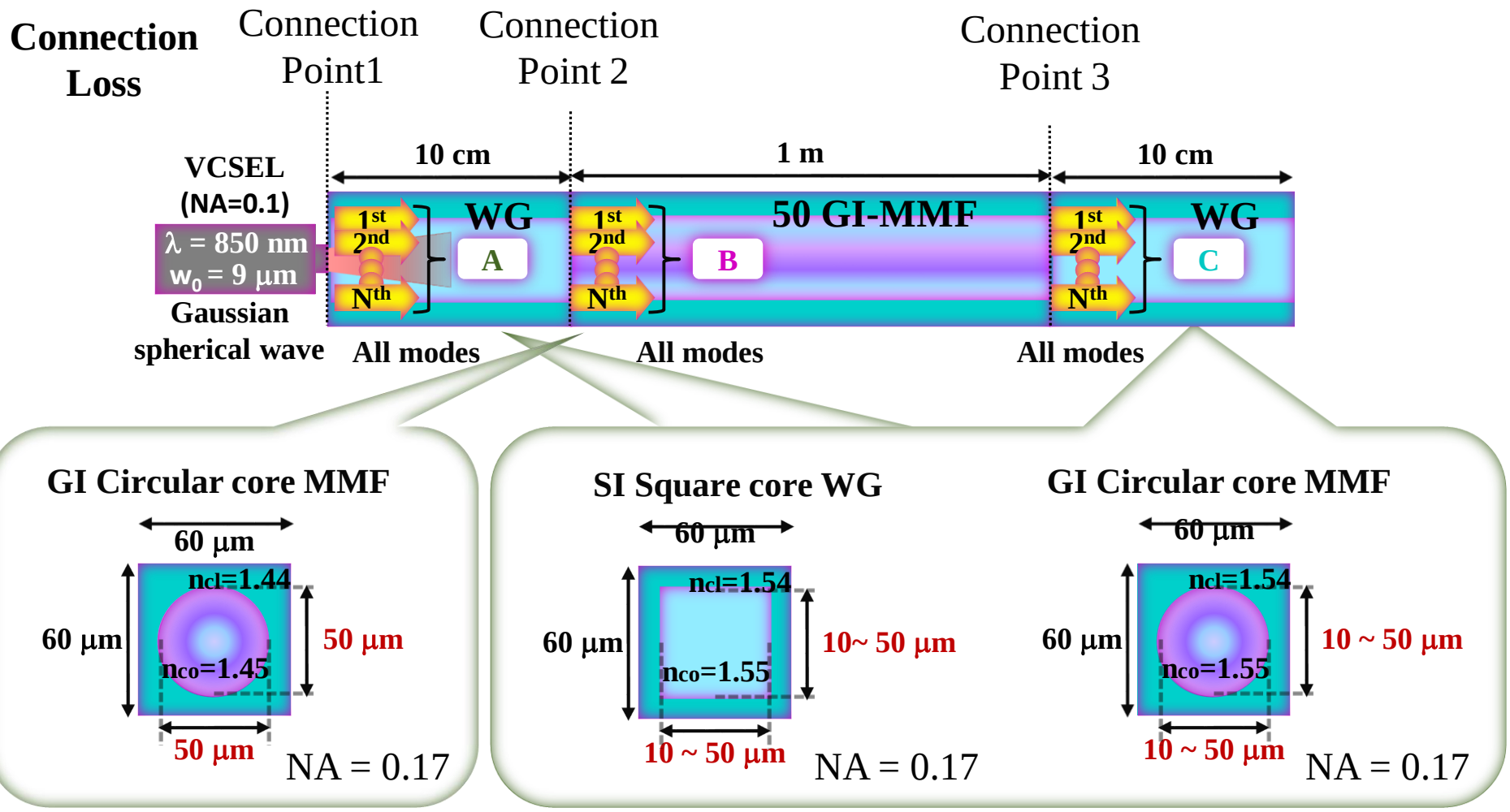
This figure shows design of waveguide-based optical link



Connection Loss Simulation

Link Model

(Solver : FIMM-WAVE, FIMM-PROP)

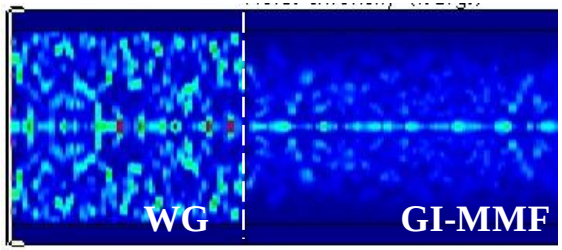


Core size dependency of the connection loss is simulated.

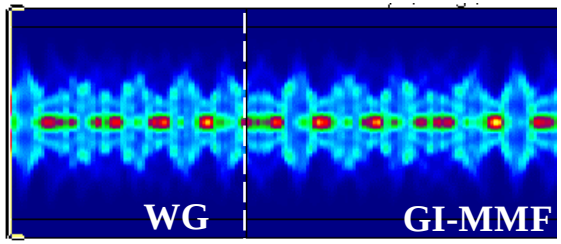
Connection Loss Simulation

Mode Profiles

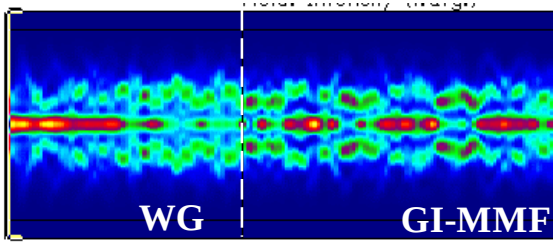
50x50 μm SI waveguide



50 μm-ϕ GI waveguide

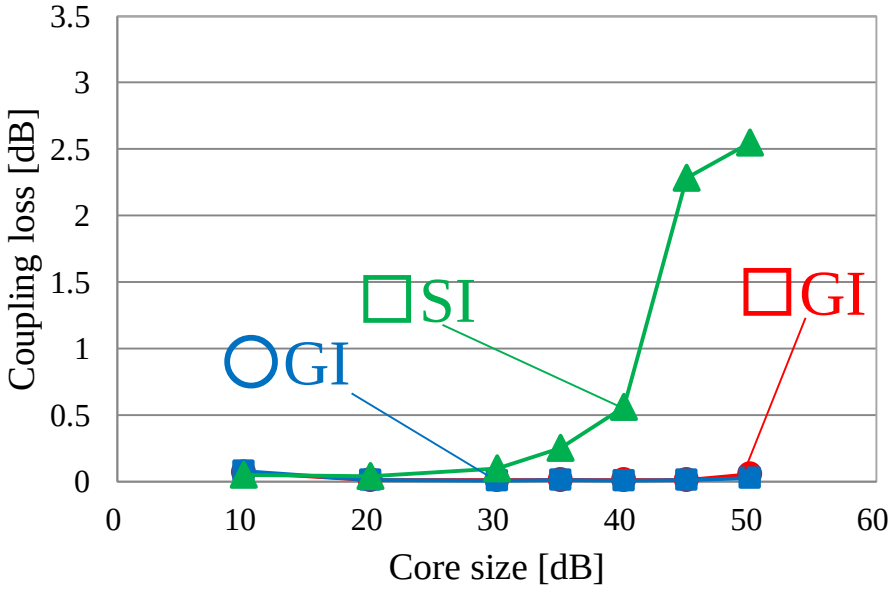


50x50 μm GI waveguide

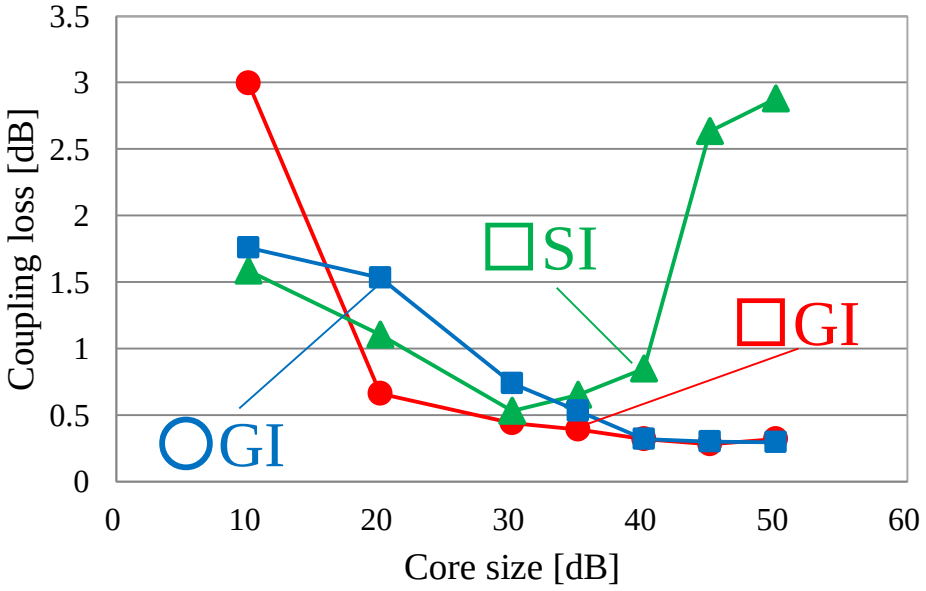


Calculated Results

Connection 2



Connection 1+2+3

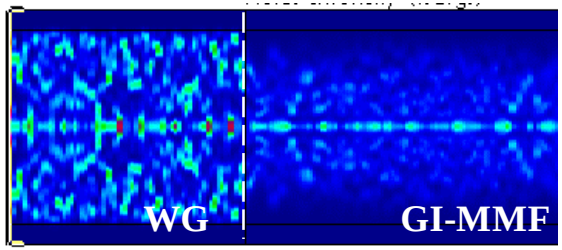


GI core shows low loss in wide rage of core size at connection 2

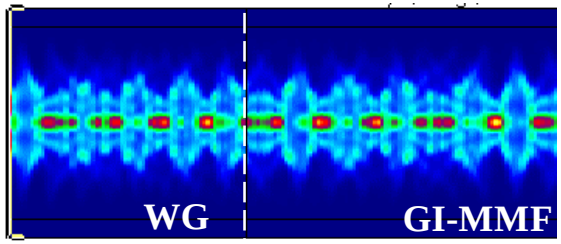
Connection Loss Simulation

Mode Profiles

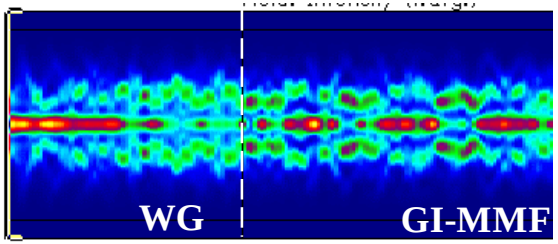
50x50 μm SI waveguide



50 μm-ϕ GI waveguide

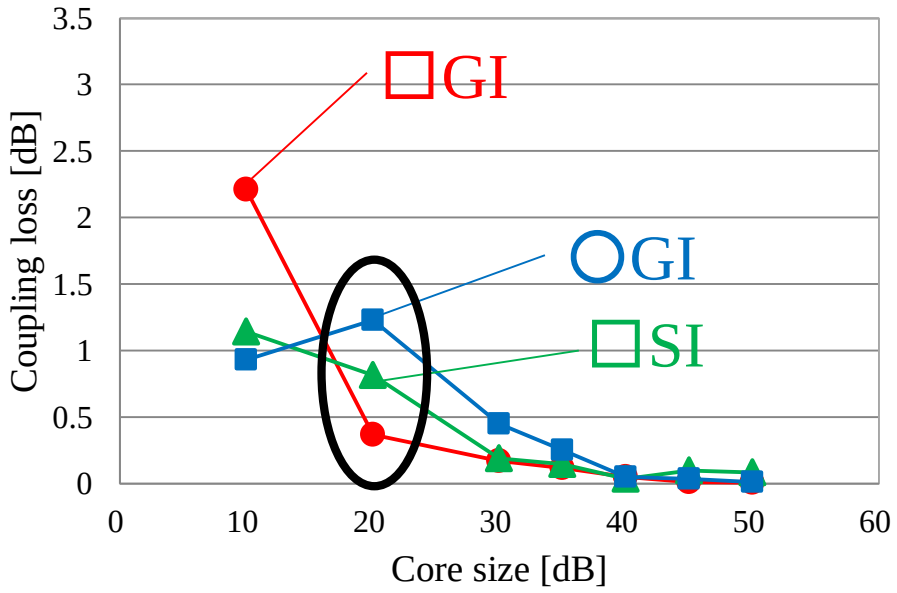


50x50 μm GI waveguide

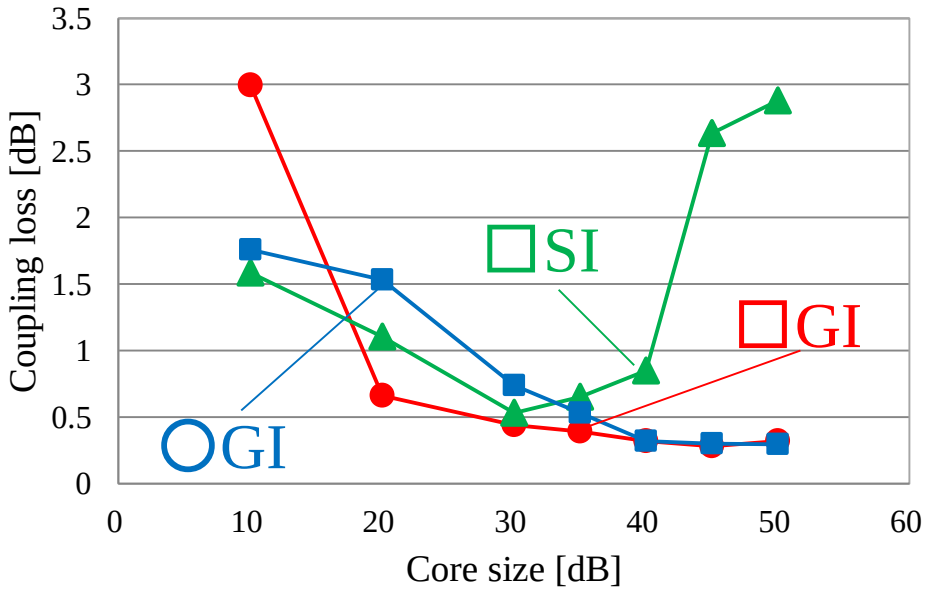


Calculated Results

Connection 3



Connection 1+2+3



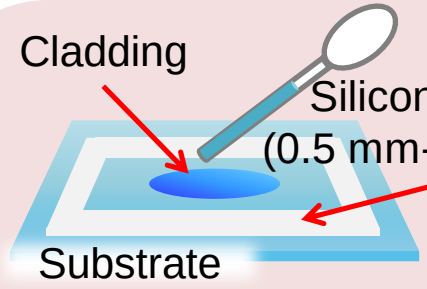
矩形GI型コアは接続点3において低損失を示した

The Mosquito Method

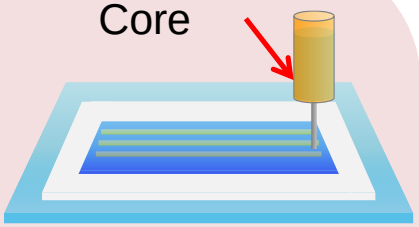
Utilizing A Micro Dispenser For Fabricating "Circular GI Core"

New Fabrication Method: Mosquito Method

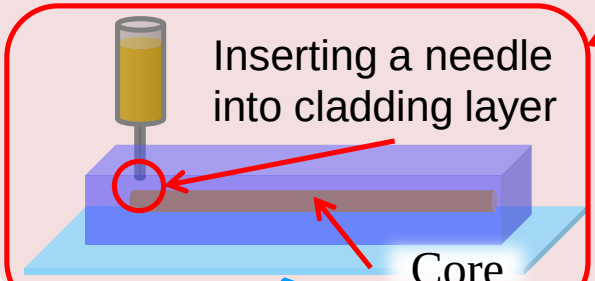
Dispenser

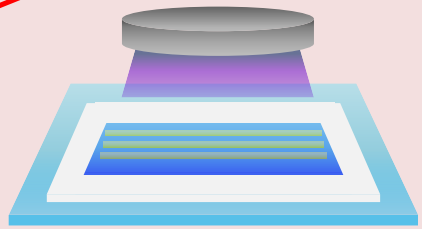


1. Coating cladding layer *Before UV cure(viscous)



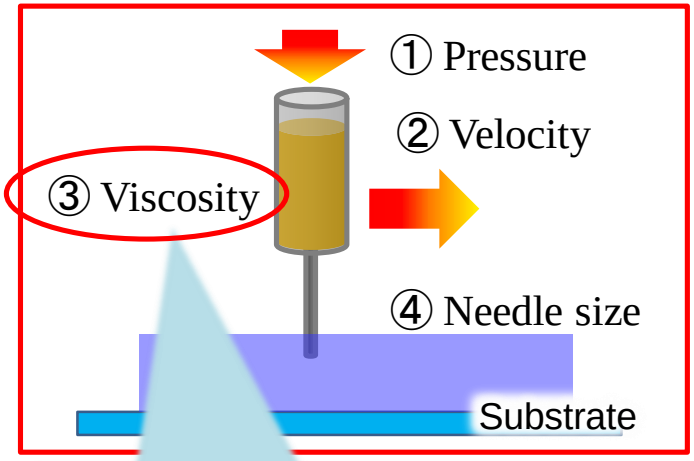
2. Forming core by "**Mosquito method**"



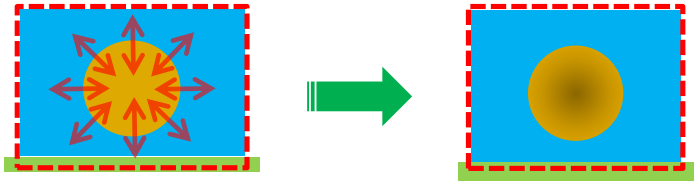


3. UV exposure

Parameter of Dispenser



High viscosity material is used for maintaining circular core



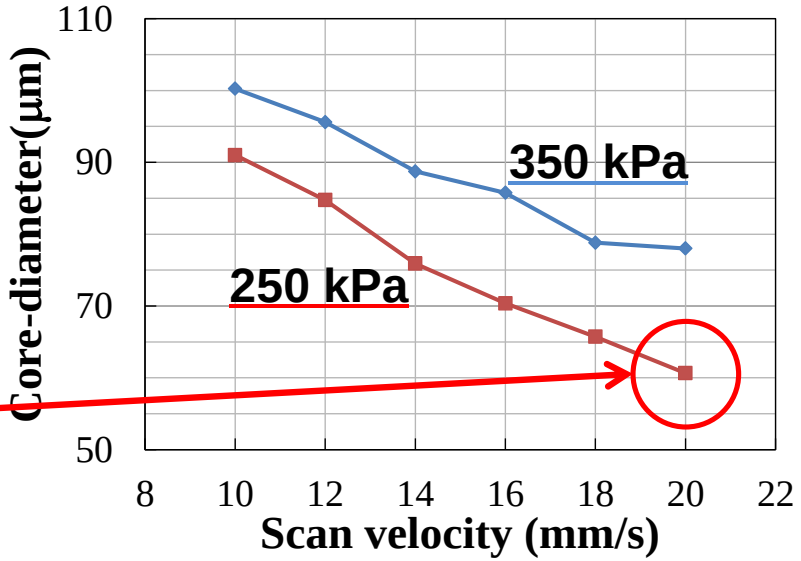
Formation of GI distribution using monomer diffusion

Fabrication of circular core less than 50 μm diameter is investigated for high density wiring.

Dispensing Conditions and Obtained Waveguides

Dispensing condition

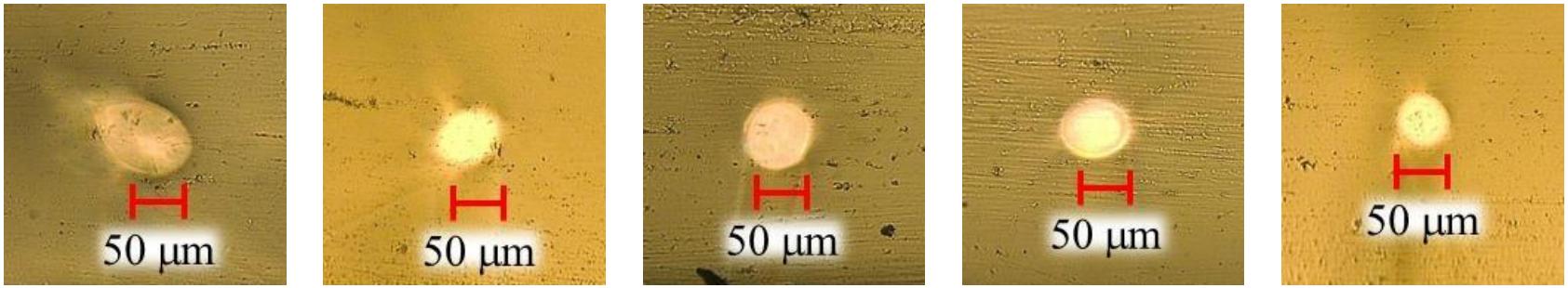
Pressure	250, 350 kPa
Scan velocity	10, 12, 14, 16, 18, 20 mm/s
Core	FX-W712(ADEKA Corp.)
Cladding	FX-W713(ADEKA Corp.)
Needle	190 μm



The repeatability of core-diameter of fabricated waveguides is confirmed.

Core-diameter dependence on dispensing pressure and scan velocity Variance : ± 5 %

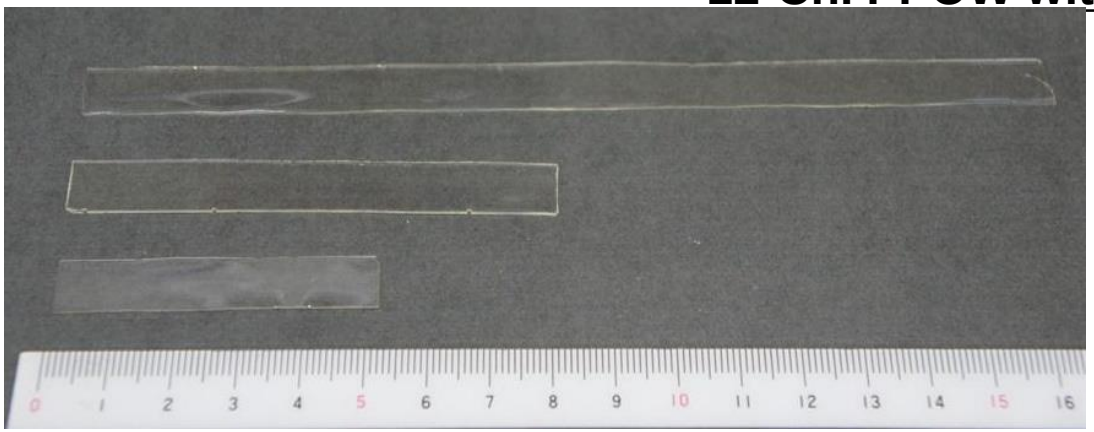
LOW — Scan velocity — HIGH



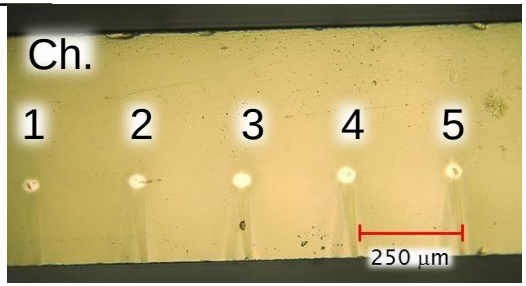
Forming a smaller circular core needs to dispense with lower pressure and to scan more quickly.

Fabricated Waveguides and Their Index Profiles

12-Ch. PPOW with GI-core



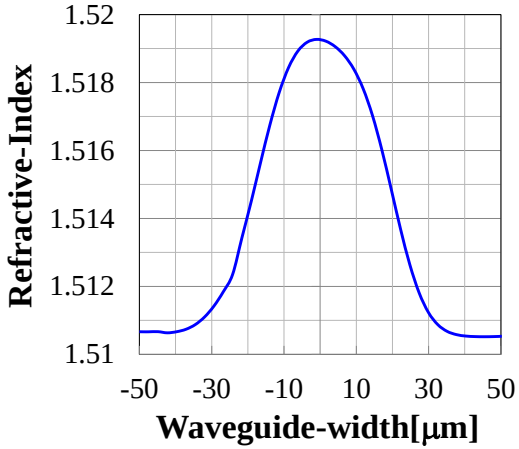
15-, 8- and 5-cm straight waveguide

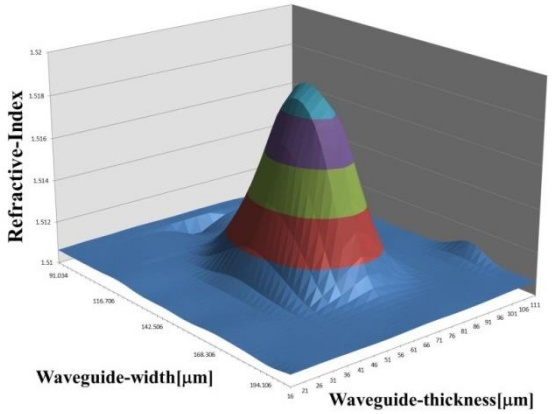


Cross-section

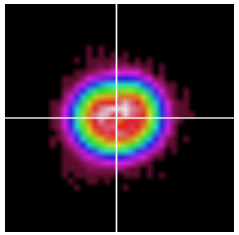
Core-diameter 40 μm; Pitch 250 μm

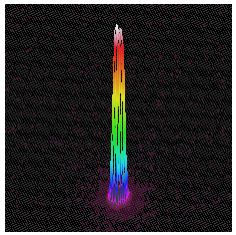
Index profile measured using an interference microscope



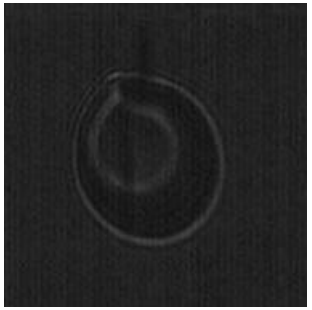


Refractive-index profile





2D & 3D NFP Image

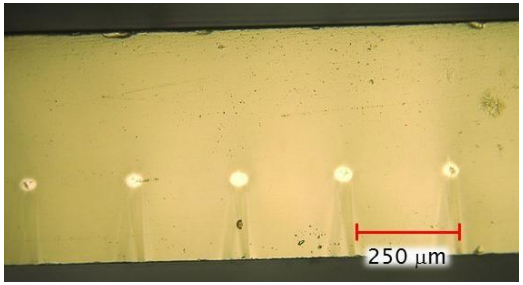
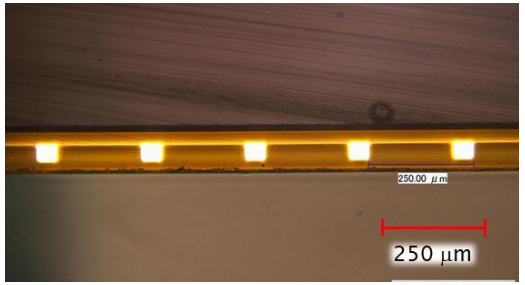
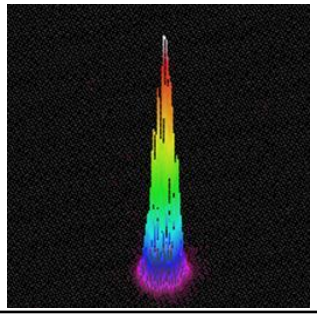
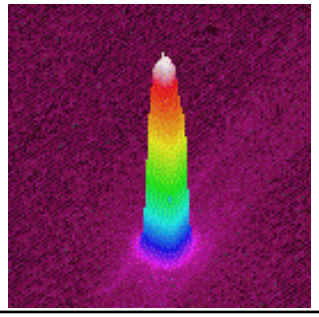


Interference pattern

PPOWs with GI-circular-core are fabricated successfully.

Comparison between SI and GI Waveguides

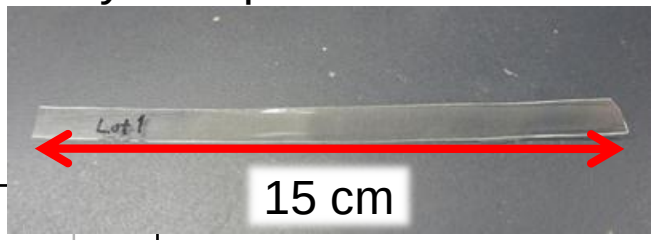
SI and GI Core waveguides using the same polymer materials

	Mosquito(GI)	Photolithography(SI)
Core/Cladding	FX-W712/FX-W713	FX-W712/FX-W713
Core-diameter	40 μm	40x40 μm
Pitch	250 μm x 12 ch.	250 μm x 12 ch.
Waveguide-length	5 cm	5 cm
Cross-section		
NFP Image		

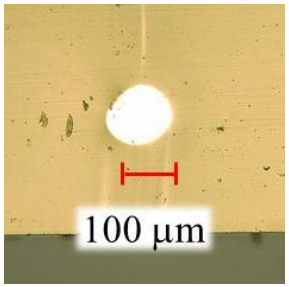
Insertion loss and crosstalk of each waveguide are measured.

Propagation loss

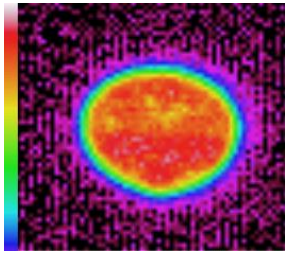
Propagation loss of the waveguide (ADEKA Corp.) fabricated by Mosquito method is measured by cut-back method (15.5 → 5 cm).



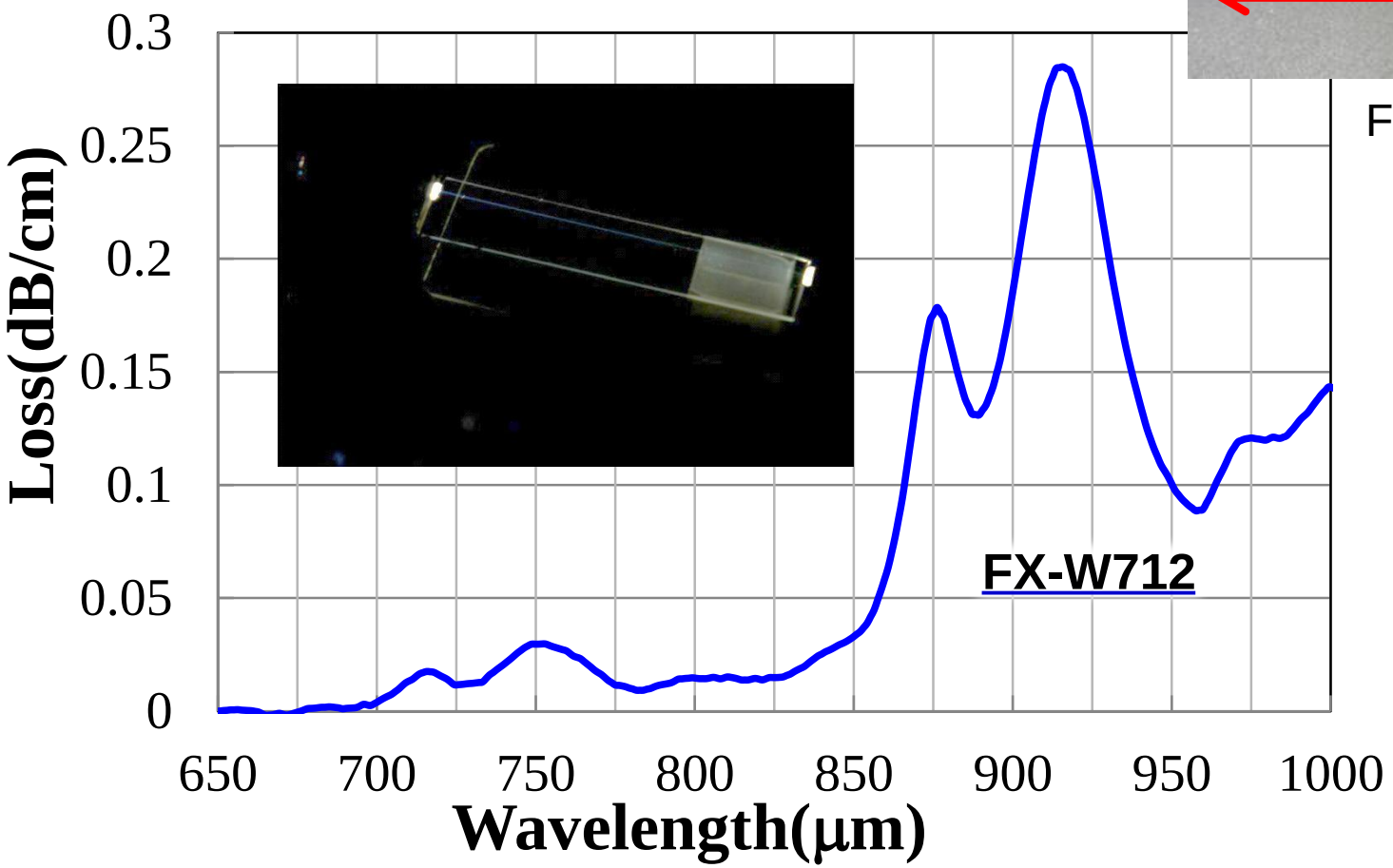
Fabricated waveguide



Cross-section



2D NFP image



FX-W712 (ADEKA Corp.) is expected as one of the low loss waveguide materials.

Insertion Loss

Experimental setup

- GI(Mosquito method)
- SI(Photolithography)

Result

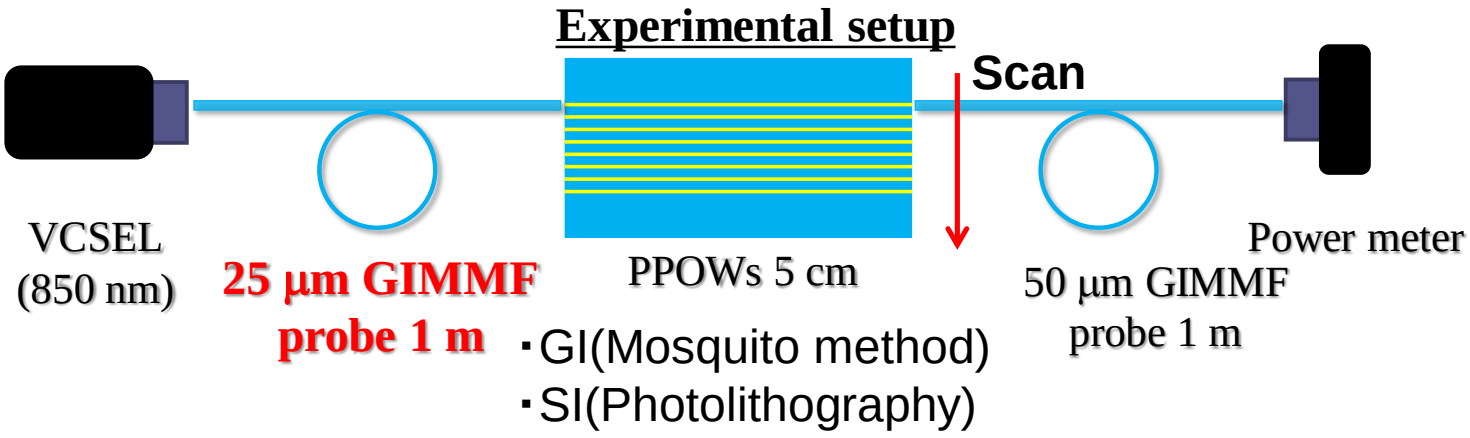
GI	Launching probe		
	SMF	25GI	50GI
Loss[dB]	1.58	1.83	2.52

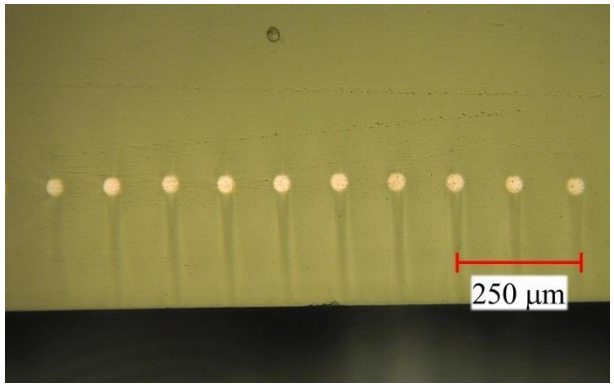
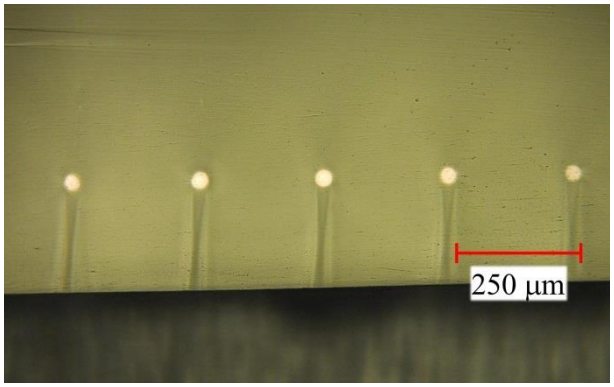
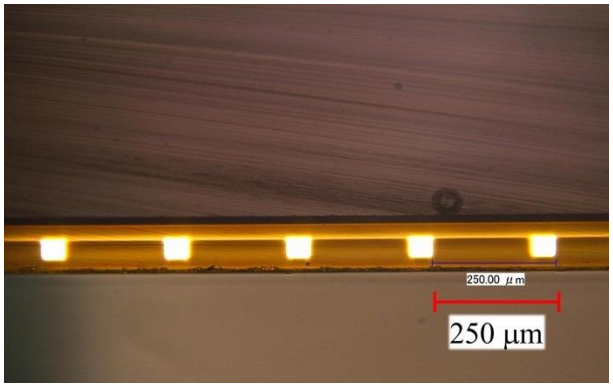
SI	Launching probe		
	SMF	25GI	50GI
Loss[dB]	1.72	2.30	2.68

* Insertion loss average of 12-channels

GI-core waveguides exhibit lower insertion loss than SI-type.

Inter-Channel Crosstalk

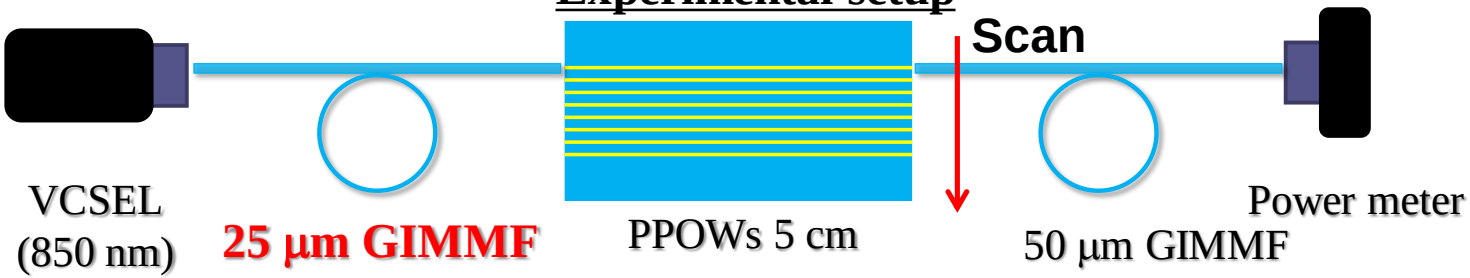


GI core 125-μm pitch	GI core 250-μm pitch	SI core 250-μm pitch
		

For high-density wiring, the waveguide with a 125-μm pitch is fabricated and compared crosstalk value to waveguides with a 250-μm pitch.

Inter-Channel Crosstalk

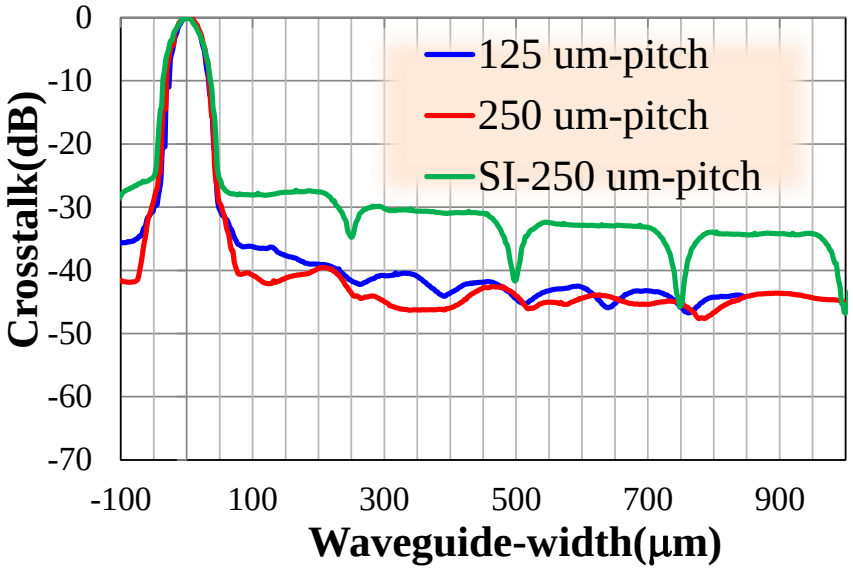
Experimental setup



- GI(Mosquito method)
- SI(Photolithography)

Result

25 μm GIMMF→WG→ 50 μm GIMMF



Ch.	GIWG 125 μm[dB]	GIWG 250 μm[dB]	SIWG 250 μm[dB]
2	-36.4	-43.6	-34.8
3	-41.6	-44.0	-41.7
4	-42.9	-45.2	-45.8
5	-44.6	-45.1	-46.8

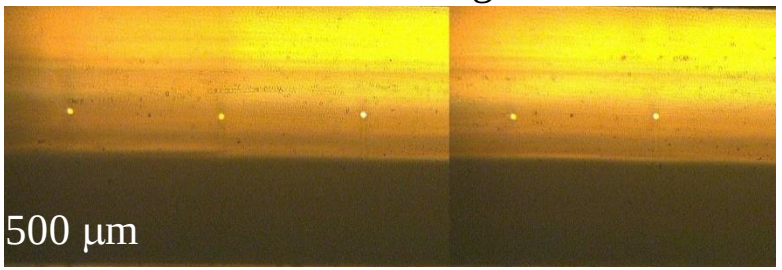
Crosstalk of waveguide with narrower pitch than 250 μm is lower than SI-WG.

For Satisfying the Single-Mode Condition

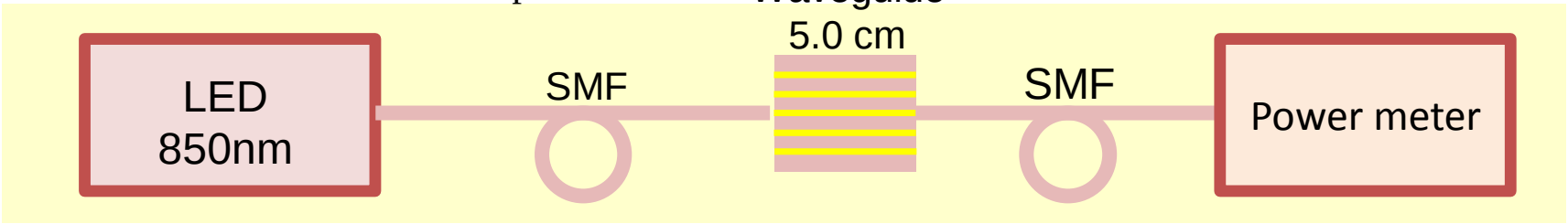
Fabrication Conditions

Core	Silicone Resin PO-46(n=1.47) (From TOK)
Clad	Silicone Resin TPIR-224(n=1.43) (From TOK)

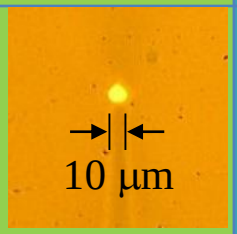
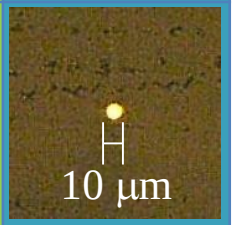
Fabricated Waveguide



Loss Evaluation Setup



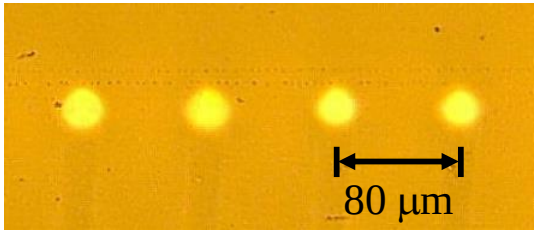
Insertion Losses

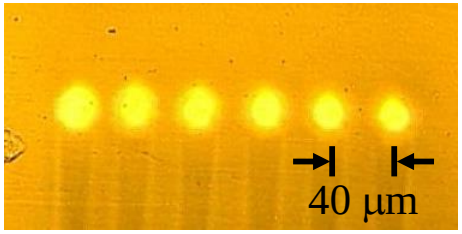
	1	2
Cross-section		
Average [dB]	5.31	3.27
Minimum [dB]	4.84	2.17

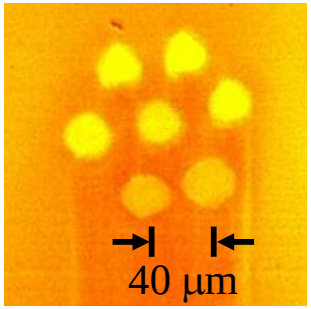
Low insertion loss achieved

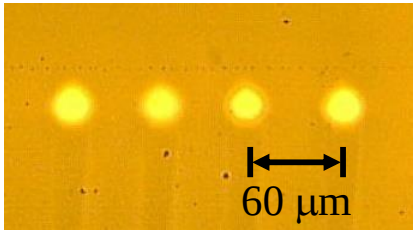
3-Dimensional･Narrow-Pitch･Fan-Out Structure

Cross-sections of narrower pitch waveguides







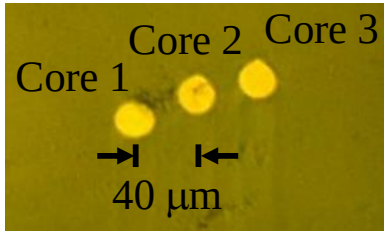


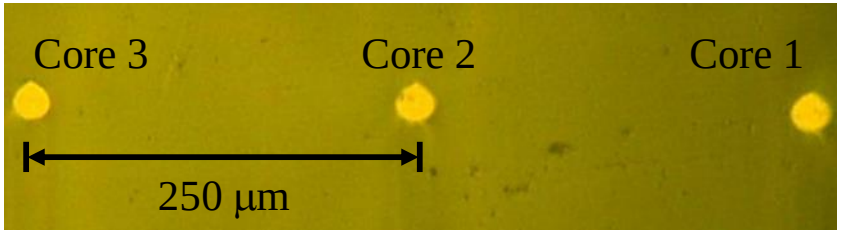
Slight deformation and pitch deviation

Horizontal position of the neighbor core(s) varied

60～80-μm pitch could be the minimum (from a 230-μm O. D. needle)

For further narrower pitch, height variation is a promising way.





Fan-out structure is realized.

KEIO UNIVERSITY
CALAMVS GLADIO FORTIOR
1858

The Photo-Addressing Method

For Fabricating "Square GI Core"

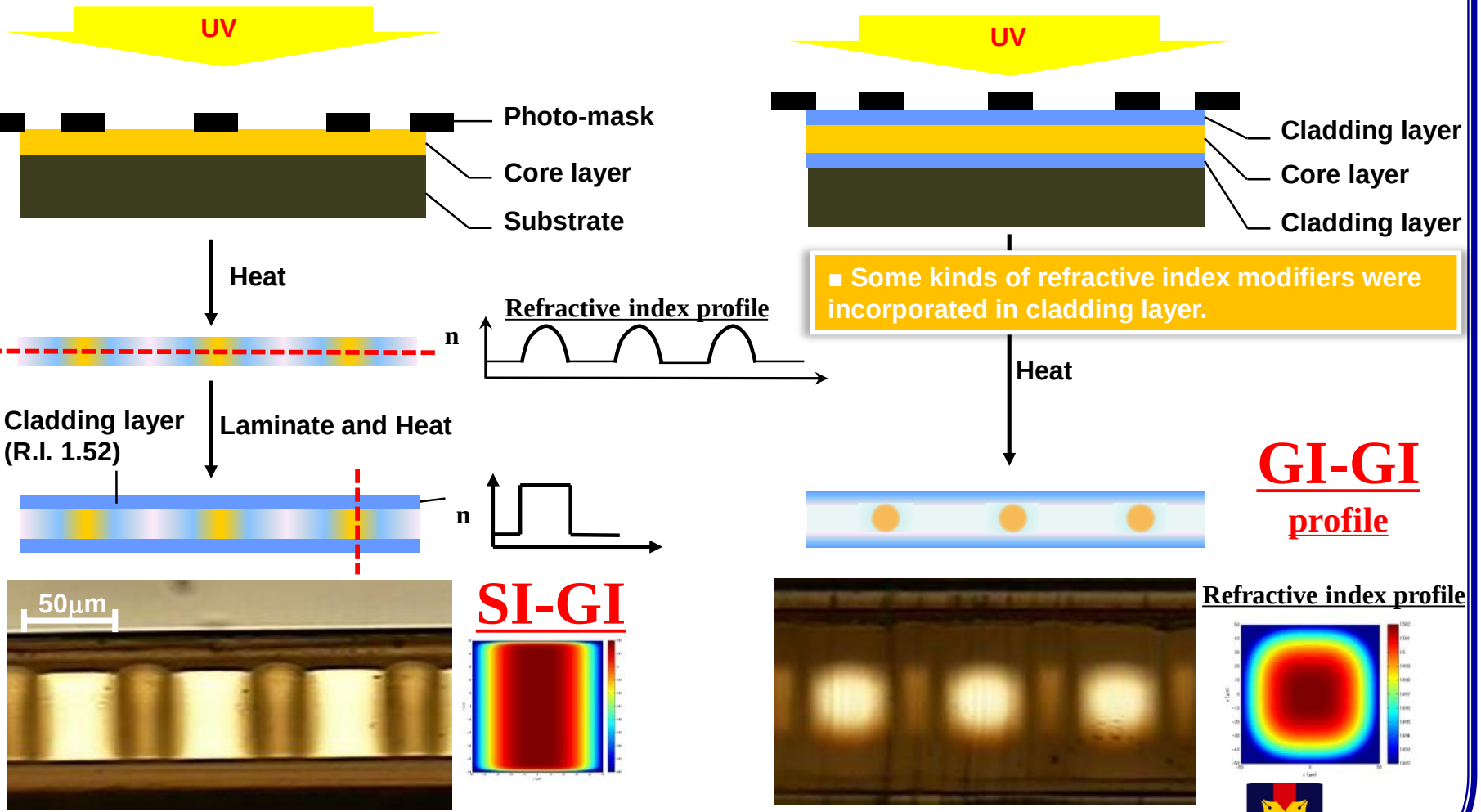
Low-Loss Design and Fabrication of Multimode Polymer Optical Waveguide Circuit with Crossings for High-Density Optical PCB

T. Ishigure, K. Shitanda, T. Kudo
Keio Univ. / Yokohama, JP

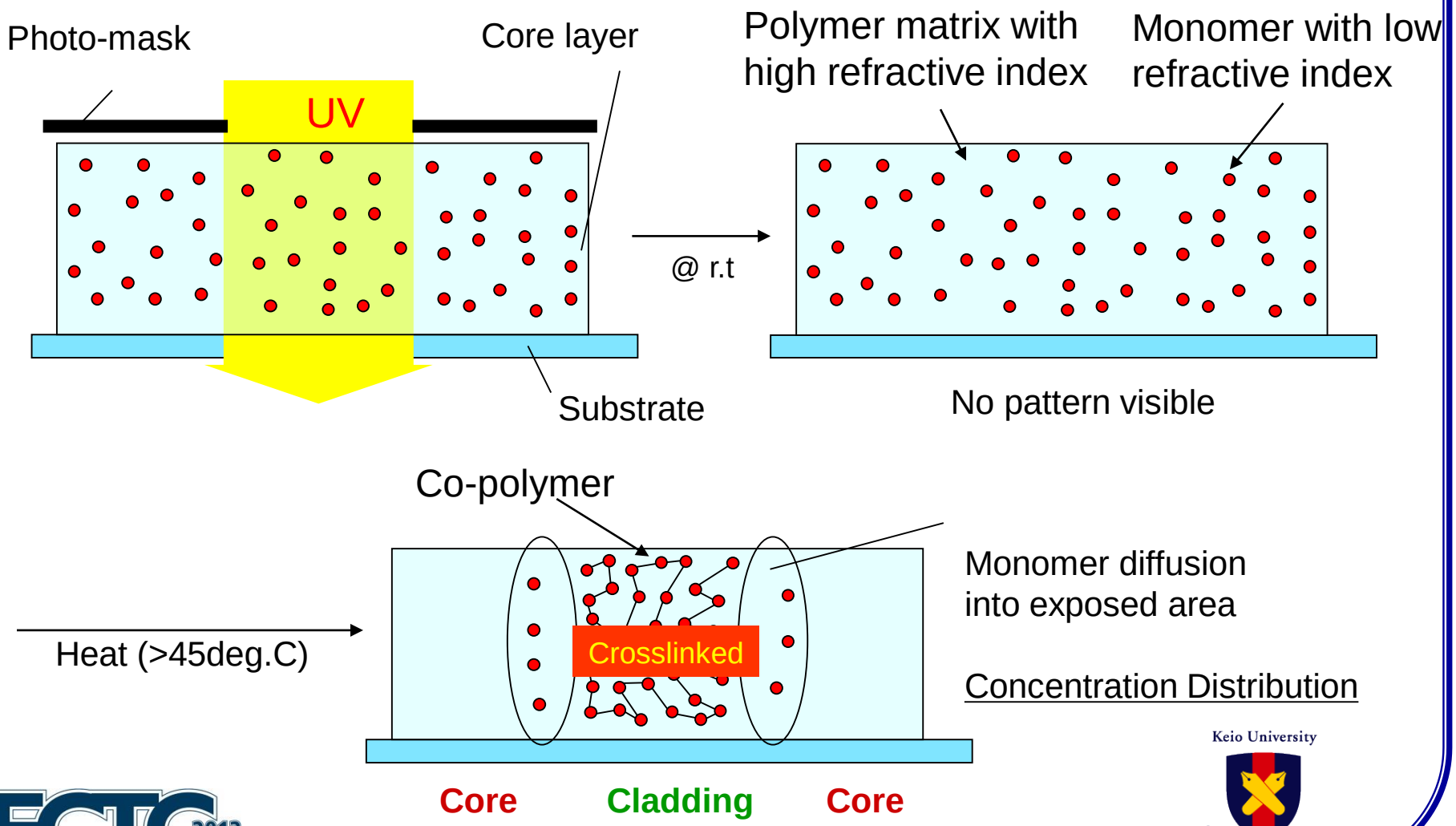
S. Takayama, K. Moriya, T. Mori, K. Choki
Sumitomo Bakelite / Utsunomiya, JP

How GI-core Waveguide Fabricated?

Photo-Addressing Technique

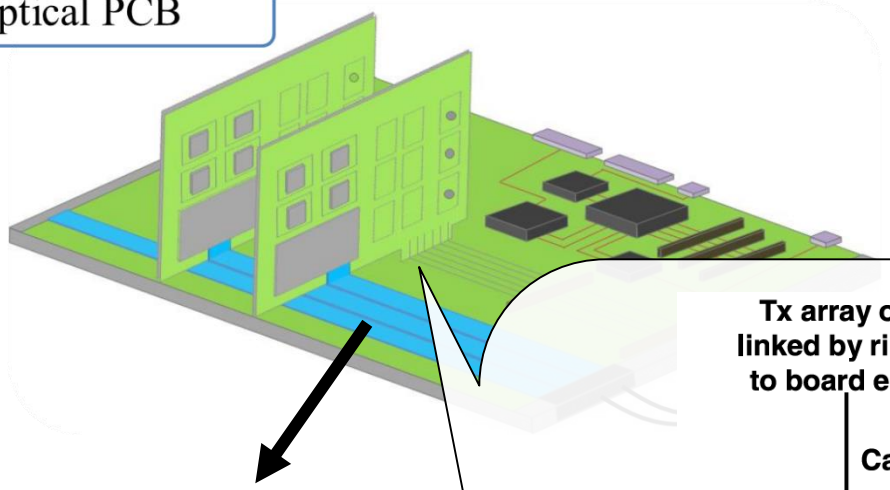


Concentration Distribution leads to Index Profile



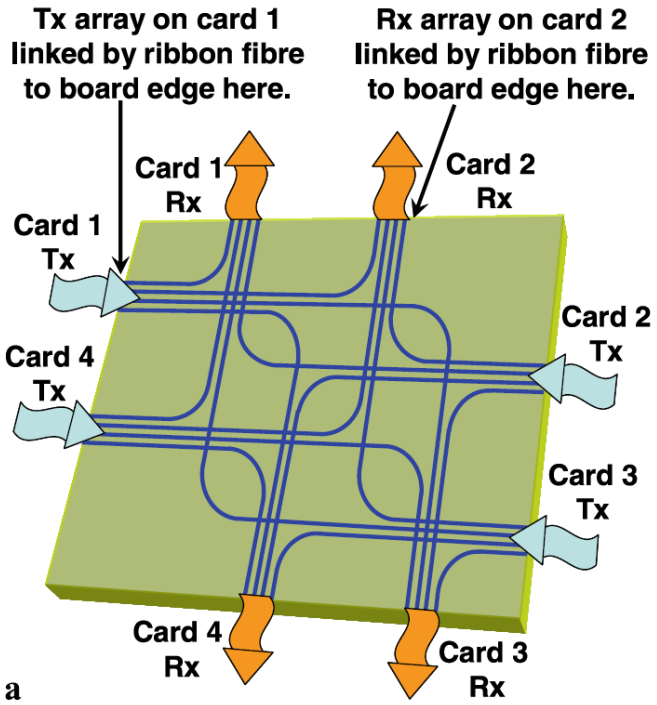
Optical PCB with Crossed Waveguides

Optical PCB



Polymer Waveguides

J. Beals IV, et al., Appl. Phys. A, 95, 983 (2009)



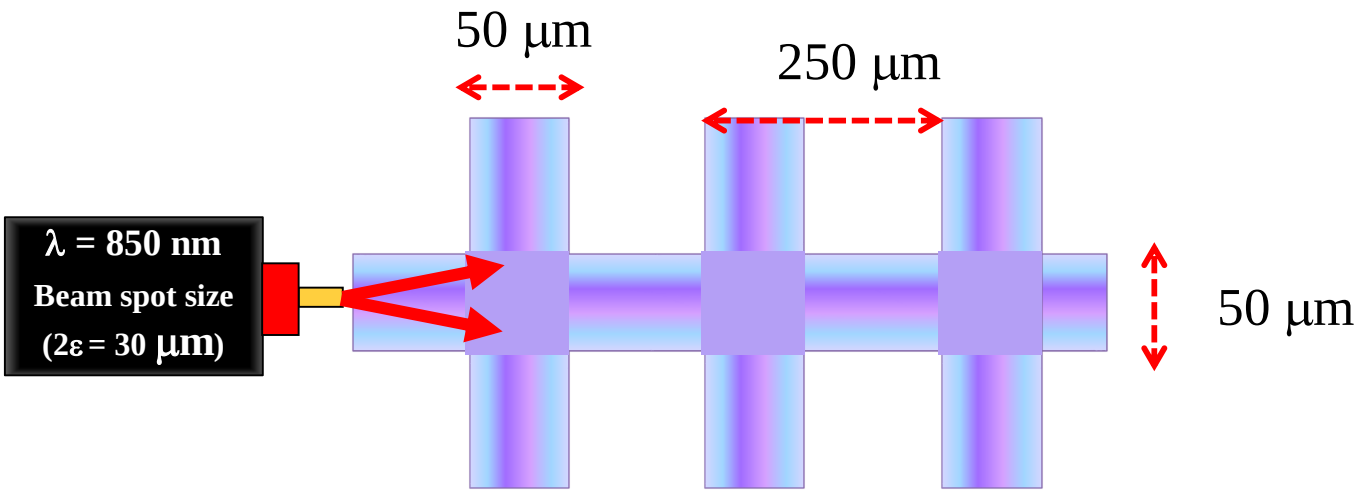
Loss Estimation using Ray-Trace Method

Power-Law Form

$n_{co} = 1.553$ $n_{cl} = 1.536$

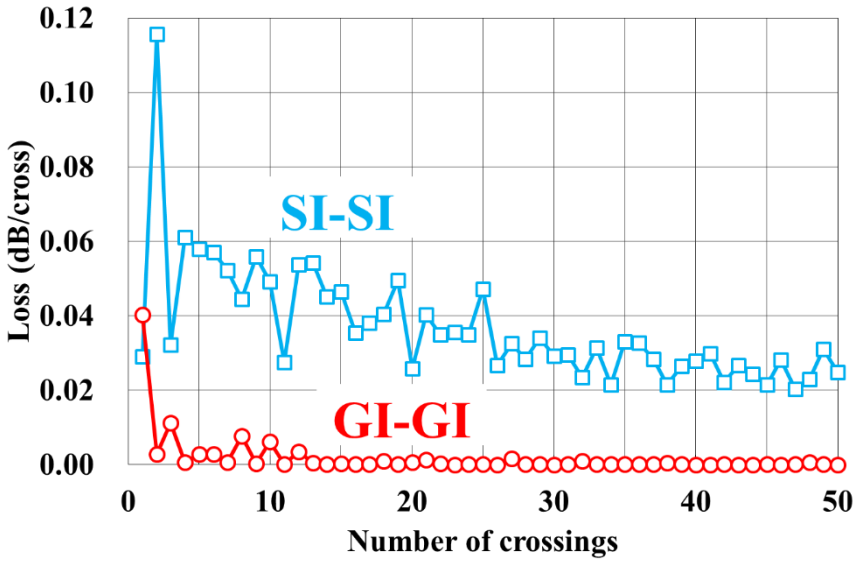
$$n(x,y) = n_{co}\{1 - 2\Delta[f(x) + g(y)]\}^{1/2} \qquad f(x) = \left|\frac{x}{a_x}\right|^p, \quad g(y) = \left|\frac{y}{a_y}\right|^q$$

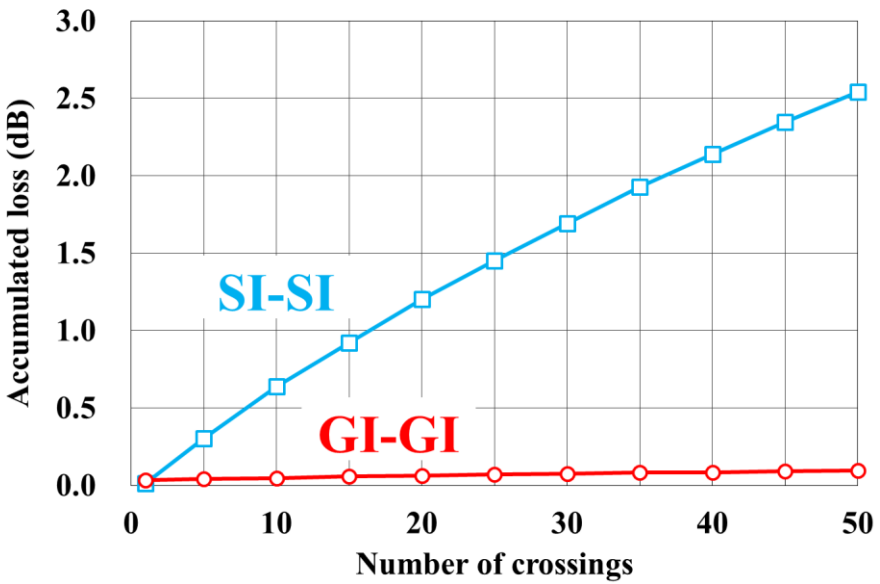
Launch Condition for Ray-Trace Simulation



Input NA is set to be 0.2.
Intensity distribution is "Gaussian."

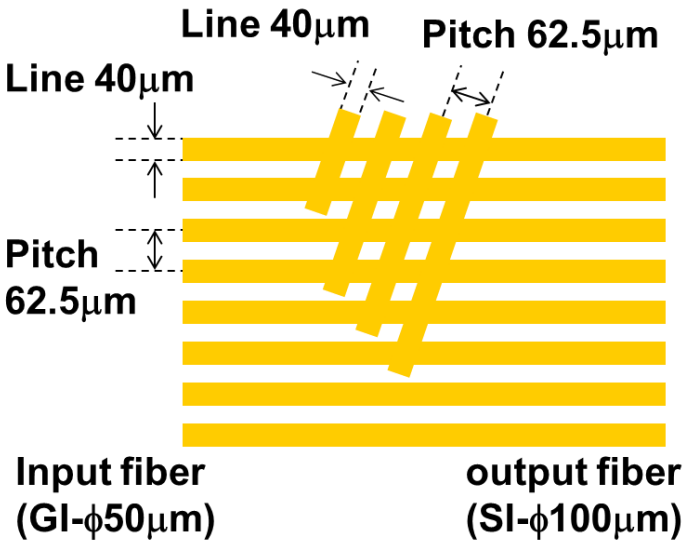
Results of Simulation

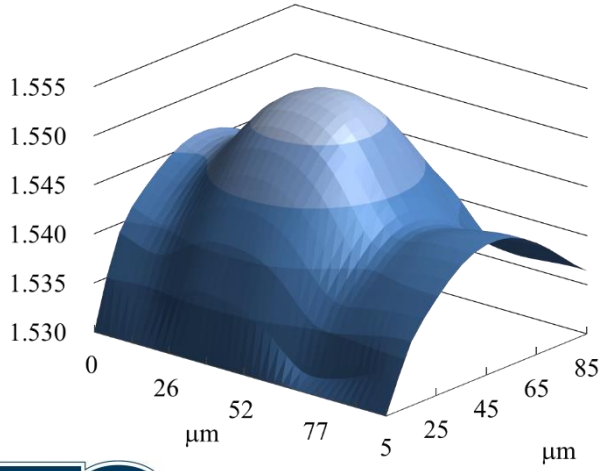


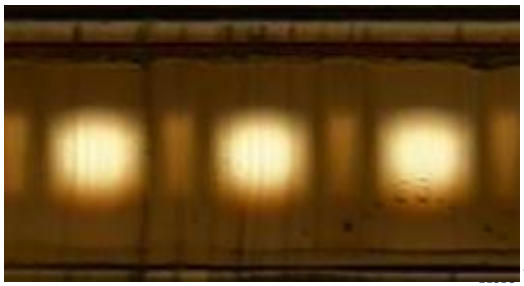


Very low loss in GI-GI despite SI-SI intersection

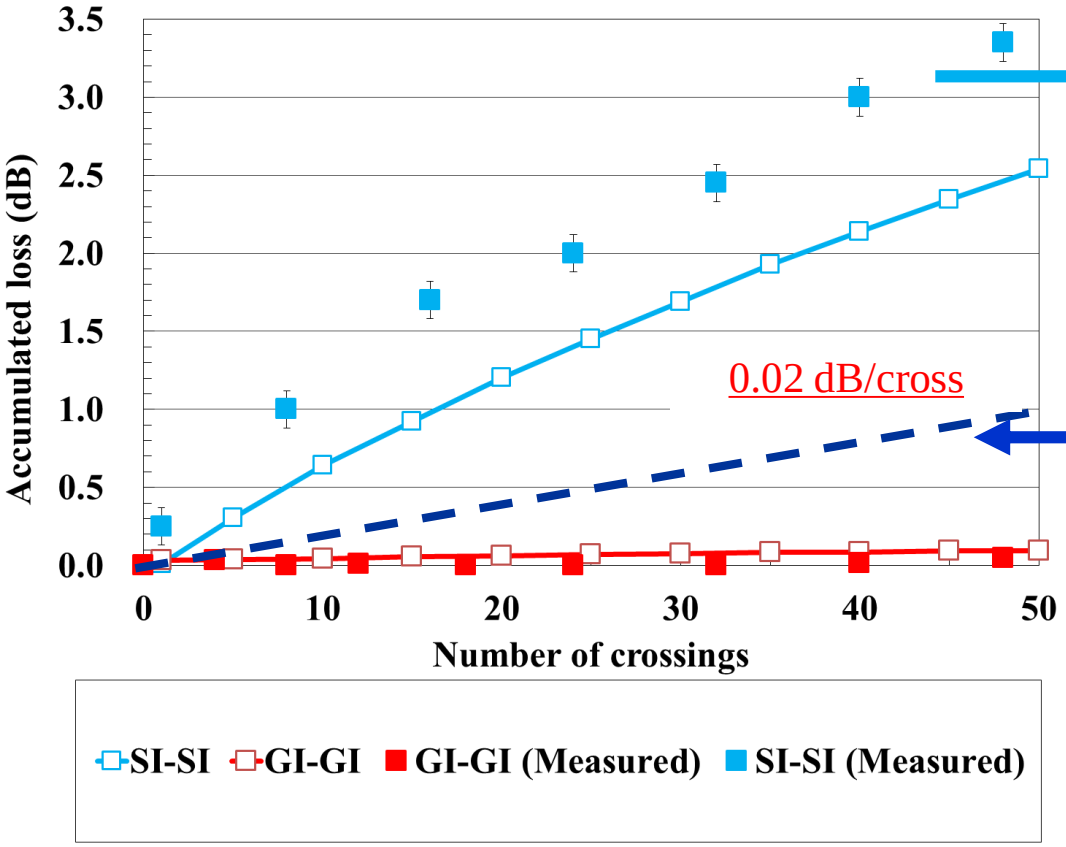
GI-Core Crossed Waveguide by Photo Addressing

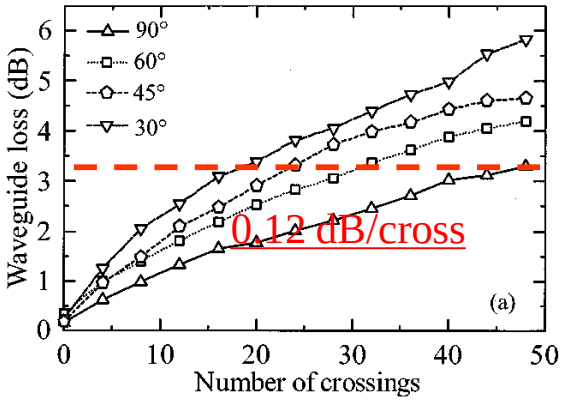


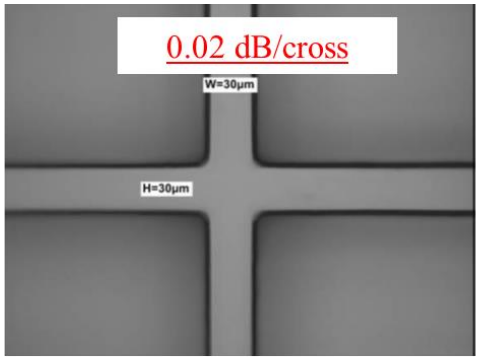




Comparison: Simulated & Measured

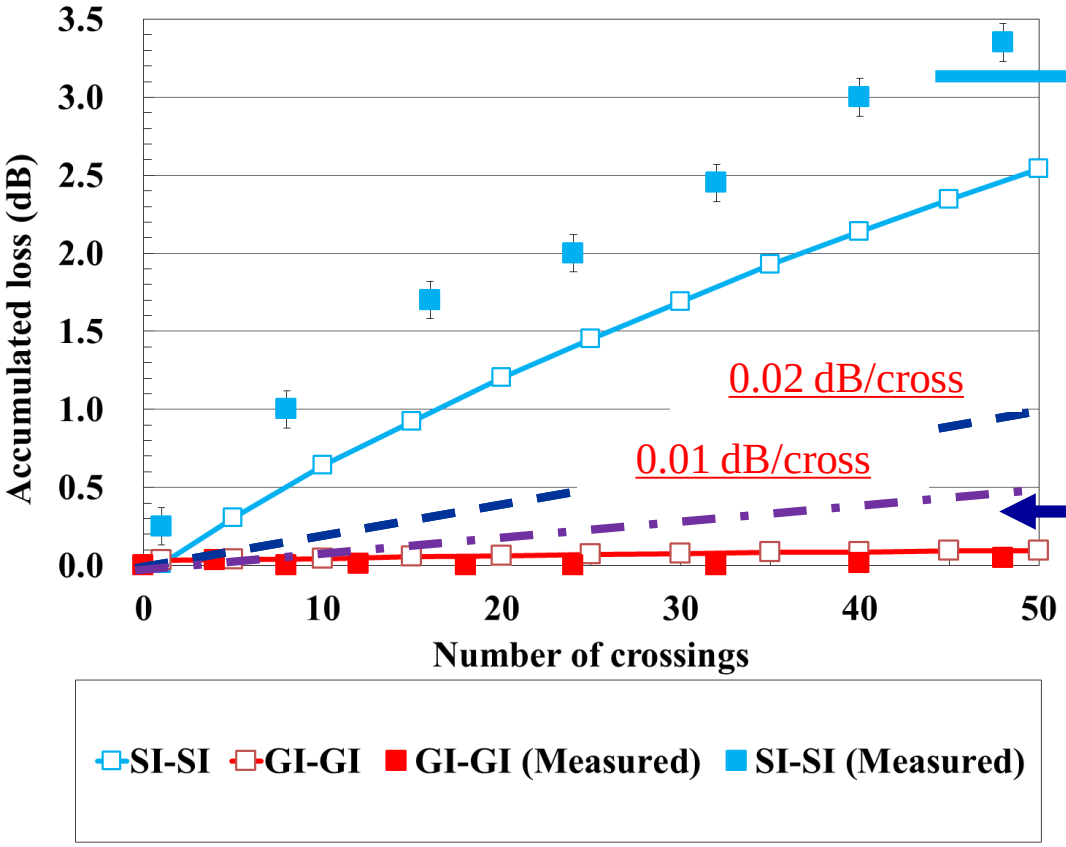


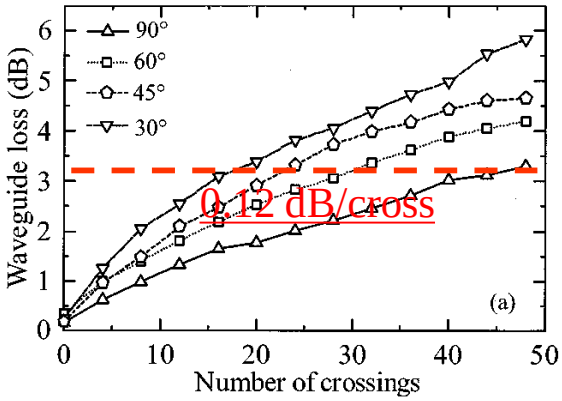


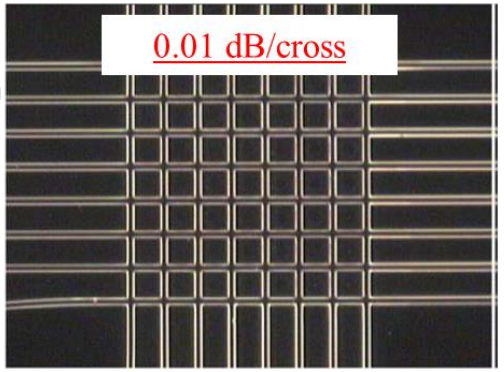


G.L. Bona, et al., Proc. SPIE. 5453, 134 (2004)

Comparison: Simulated & Measured



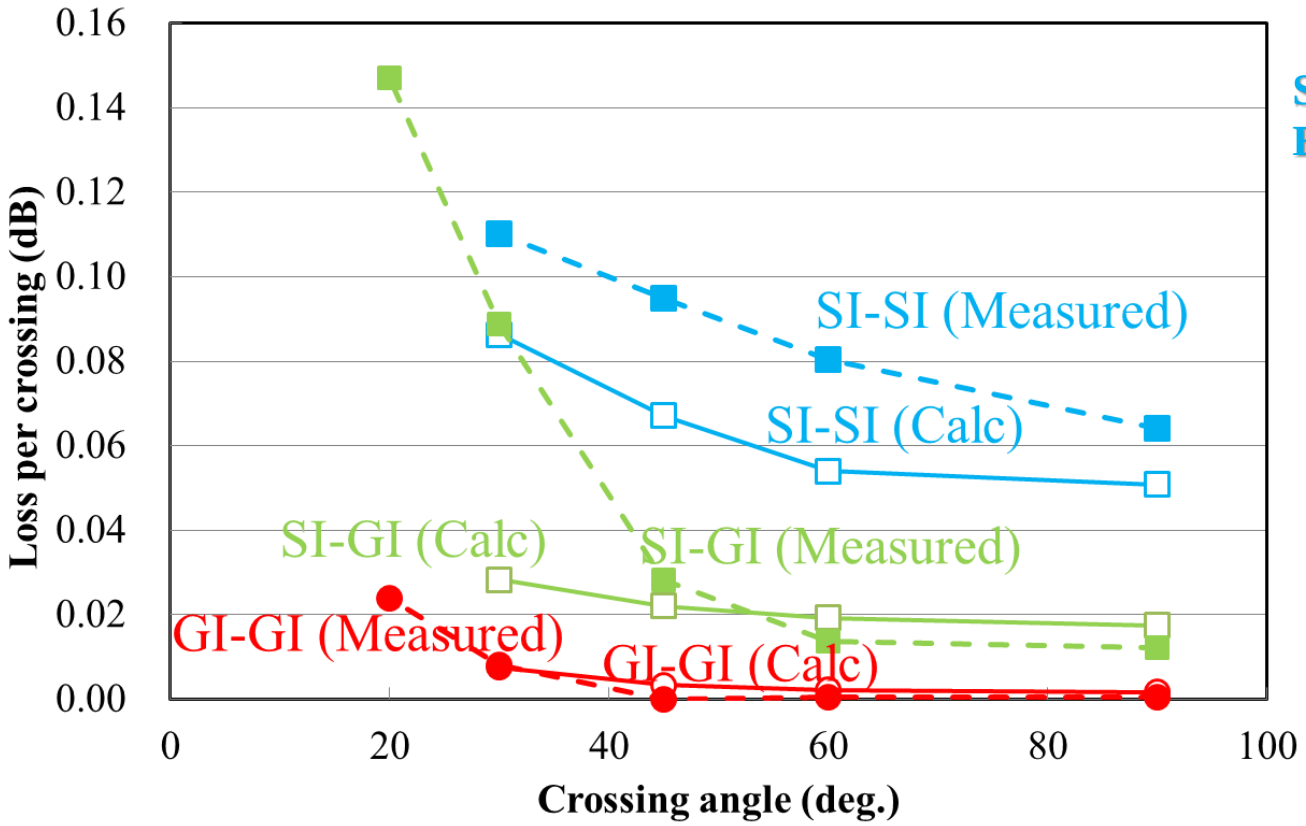




J. Beals IV, et al., Appl. Phys. A, 95, 983 (2009)

The loss of GI-GI is one-order lower than the lowest results of SI-SI. 0.0019 dB/cross

Crossing Angle Dependence



SI-SI:
Excess loss is observed

SI-GI:
Loss abruptly increases with decreasing the angle.

GI-GI:
Good agreement with simulated results.
Remarkably low loss even at 20-deg. angle.

Conclusions

We introduce the advantages of GI-Core waveguide as follows:

- Low propagation loss because of the smaller effect of the core-cladding boundary roughness.
- Low inter-channel crosstalk even under smaller pitch due to the optical confinement
- High modal bandwidth

GI-core polymer waveguides will play an important role for high-speed and high-density on-board optical interconnects.

Thank you very much for your attention