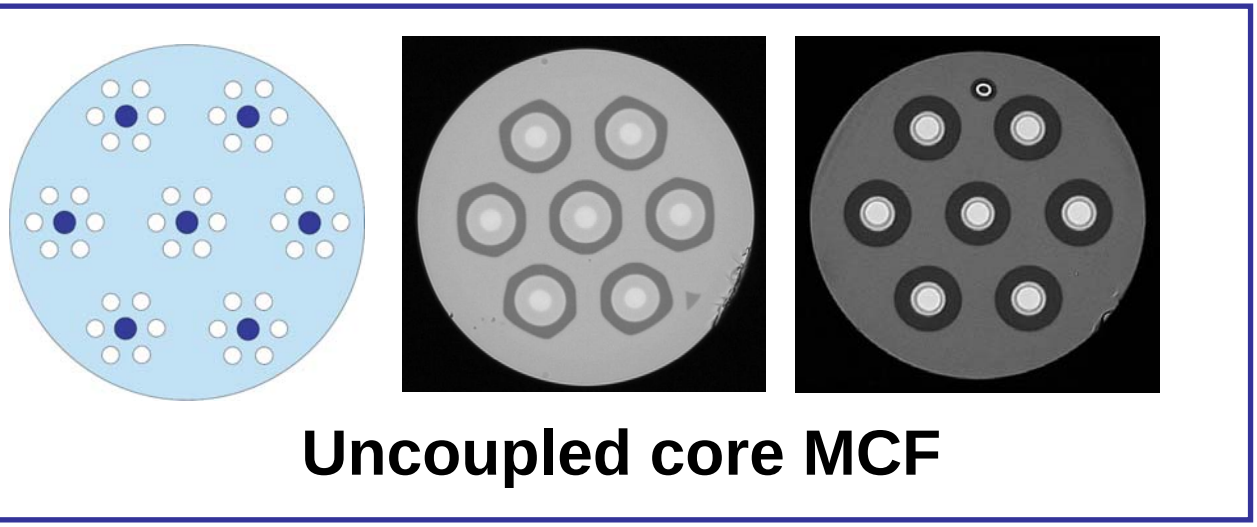
Multi-Core Fibers and Their Technical Feasibility



Uncoupled core MCF

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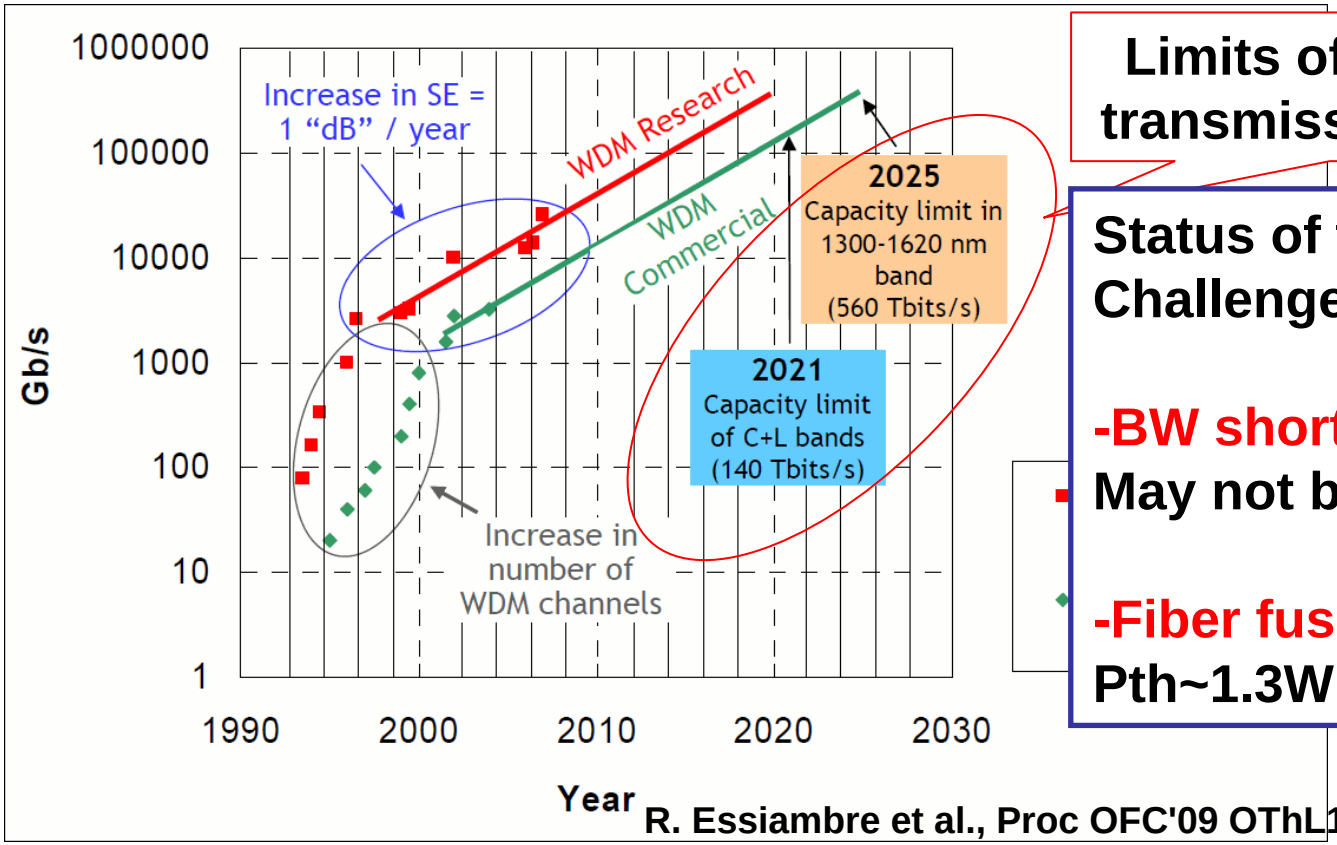
Outline

1. Background
2. Challenges of multi-core fiber(MCF)
3. Scalability for longer transmission
   ~ potential of MCF as for crosstalk ~
4. Summary

1. Background



Limits of the current transmission system?

Status of telecom Challenge?

-BW shortage: C+L+…
May not be scalable for single core?

-Fiber fuse
Pth~1.3W (λ=1.48μm)

R. Essiambre et al., Proc OFC'09 OThL1

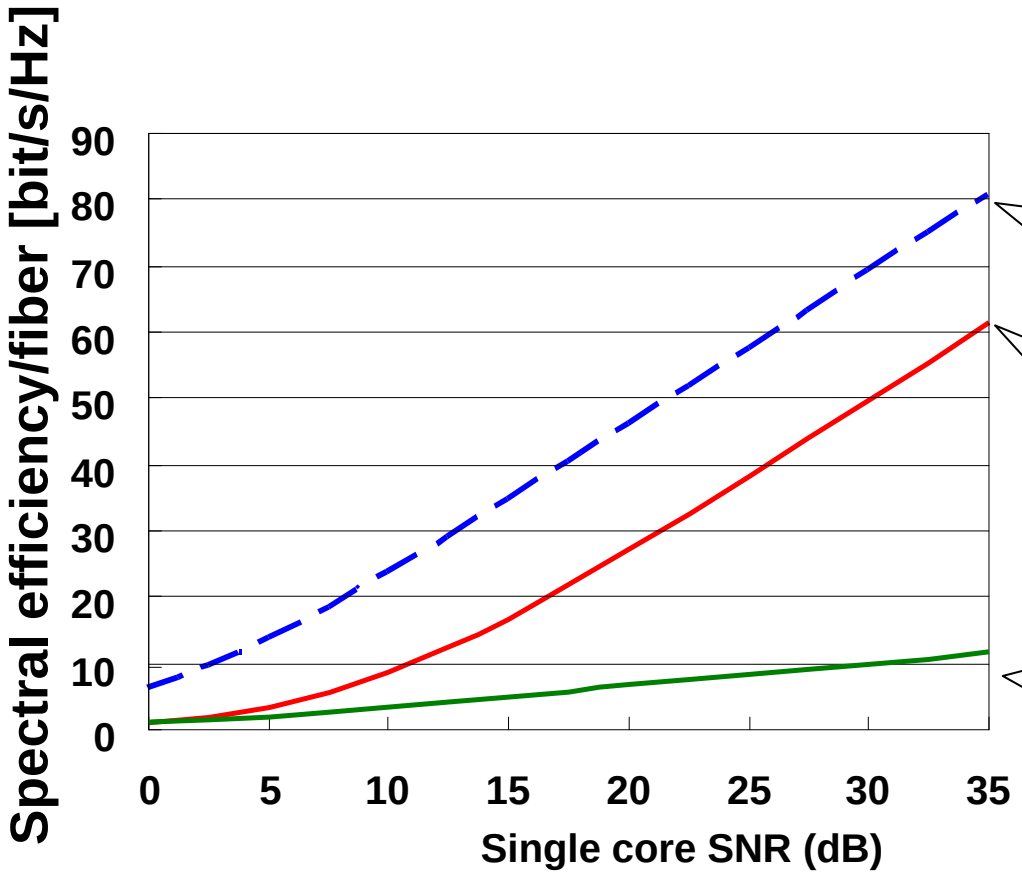
Candidates of breakthrough technologies for the limits

- Multi-level modulation
- Multi-mode control
- Multi-core fiber (MCF)

➡ **“3M”**

Why MCF is a promising measure?

- Merit of improving SE using SDM (Shannon limit)



7-core
Constant: power / core
$SE=7\log_2(1+SNR)$

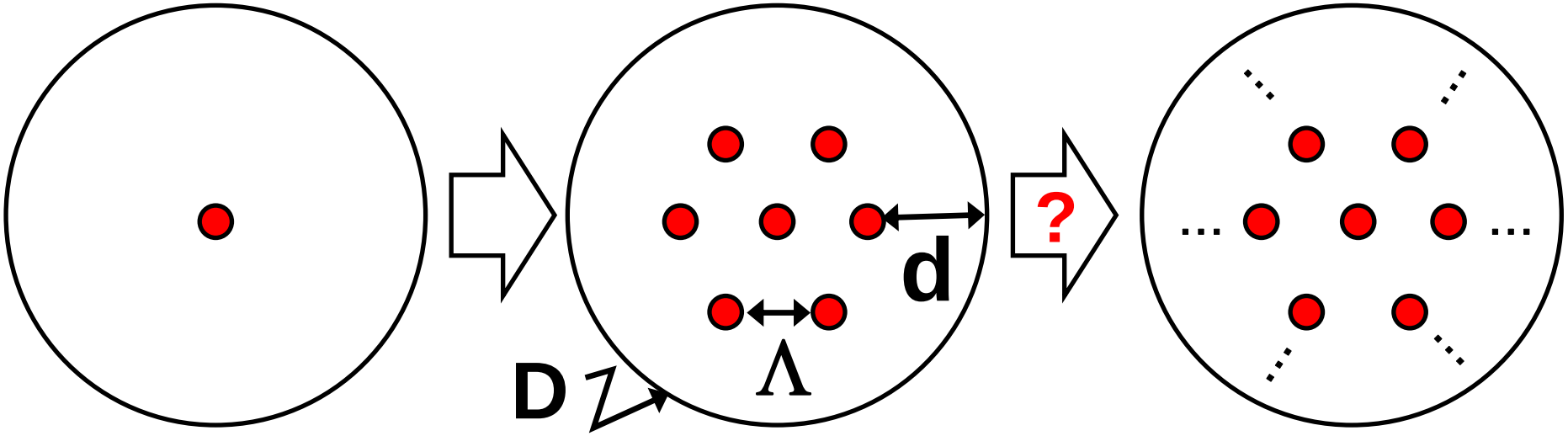
7-core
Constant: power/ fiber
$SE=7\log_2(1+SNR/7)$

Single-core
$SE=\log_2(1+SNR)$
SNR+3dB ➡ SE+1

MCF is a promising candidate to enhance OSNR and avoid Fiber fuse

2. Challenges of MCF

1. Densely arranged cores



Single core fiber　　7-core fiber　　More cores…

Items to be considered: Should design carefully considering crosstalk

Fiber structure

1) Core pitch : Λ
2) Cladding diameter : D
3) Core- outer cladding distance : d
4) Tight confinement into core

Condition of the evaluation

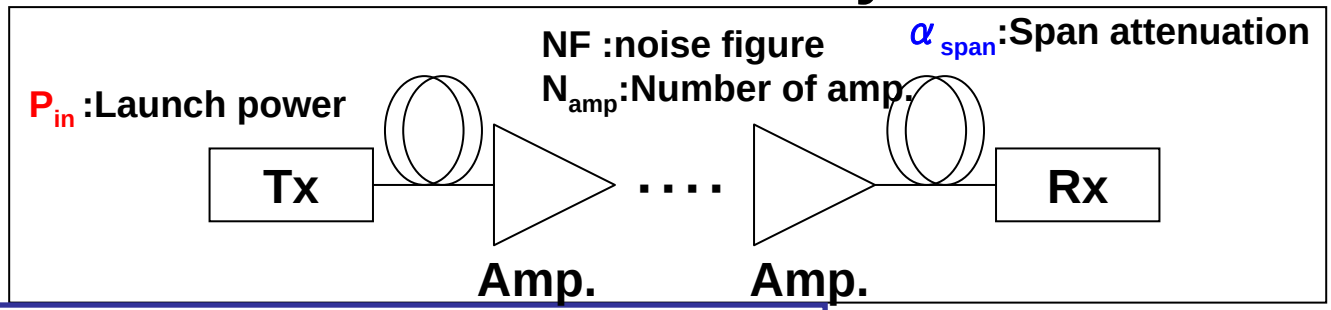
Fiber bend & twist

Other optical property?

2. Fiber loss

OSNR = 58 + P_{in} – NF – α_{span} (attenuation/Splice loss)– $10\log_{10}N_{amp}$

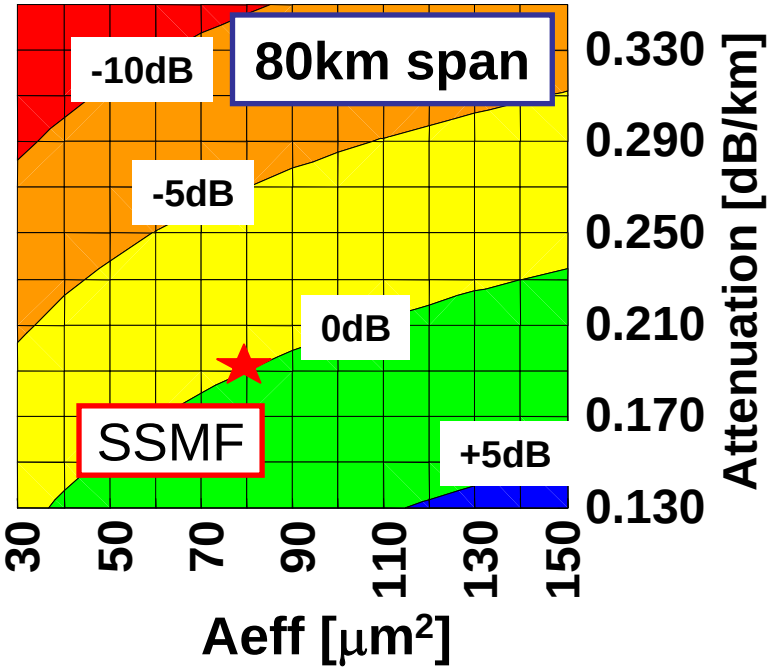
- **Enhancement of OSNR is always a MUST for any fiber**



Low Loss & Low Nonlinear Fiber
→Enhance Linear Transmission

-Low Nonlinearity
- **-Larger Aeff**

-Low Loss
- **- Fiber attenuation**
- **- connection loss**
- **- Bending loss**



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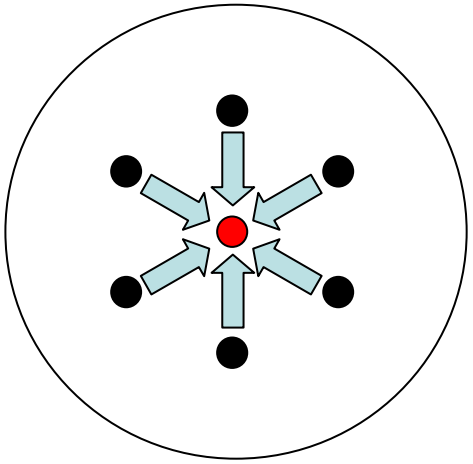
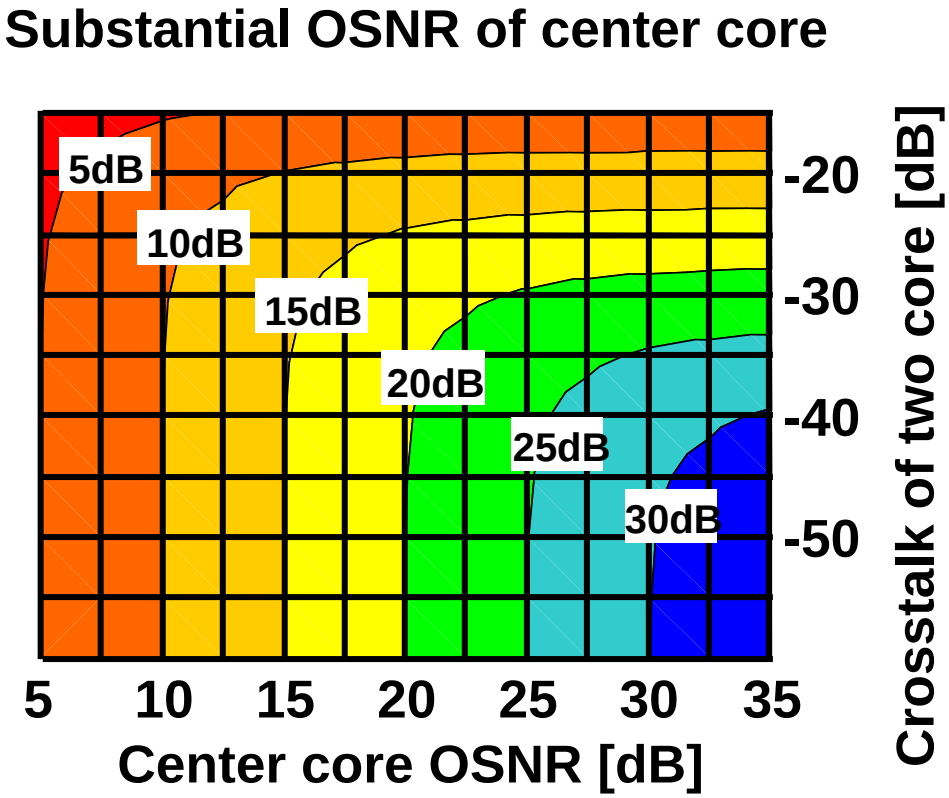
3. Inter-core crosstalk



Leakage of light

noise for center core



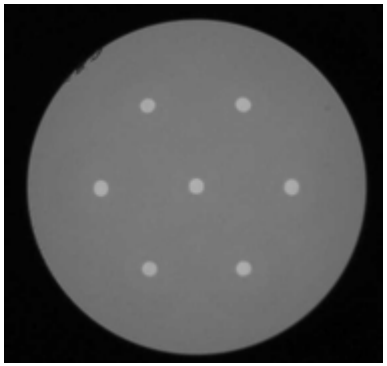
Crosstalk severely affects OSNR

Options for low-crosstalk design (1)

◆Decreasing mode coupling coefficient (κ)

1) Increase power confinement into core

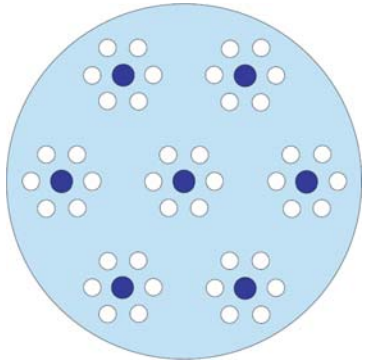
✓**High Δ/small core**

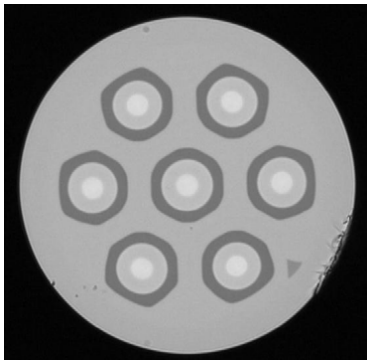


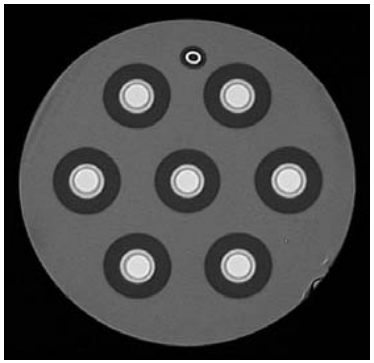
	Fiber A	Fiber B
Core Δ	0.7%	0.7%
Core dia.	6.1 μm	5.3 μm

K. Takenaga et al., IEICE Trans. Commun., **E94-B**(2), 409 (2011).

✓**Hole/trench-assisted core profile**







(Left) K. Saitoh, et al., OECC2010, 7C2-1.
(Center) K. Takenaga et al., OFC2011, OWJ4.
(Right) T. Hayashi et al., Opt. Express, **19**(17), 16576 (2011).

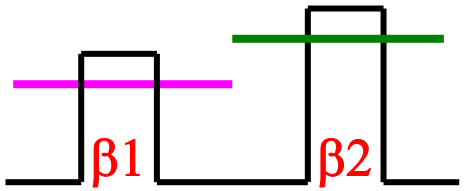
2) Enlarge core pitch

Most of the reported MCFs have core pitch larger than 35 μm.

Options for low-crosstalk design (2)

Apply phase-mismatch (Δβ) between cores

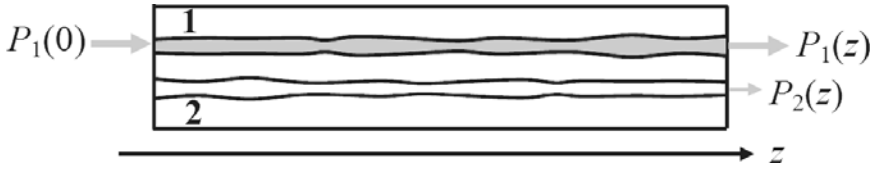
➢Heterogeneous MCF



Designed to induce $\Delta\beta = \beta 1 - \beta 2$

M. Koshiba et al., IEICE ELEX, **6**(2), 98-103 (2009).
K. Imamura et al., Opt. Express, **19**(11), 10595 (2011).

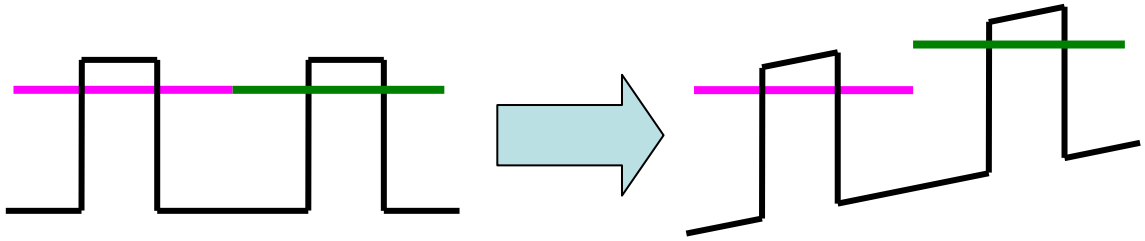
➢Quasi-homogeneous MCF



Structure fluctuation to induce Δβ.

K. Takenaga et al., IEICE Trans. Commun., **E94-B**(2), 409 (2011).

➢Homogeneous MCF utilizing fiber bend

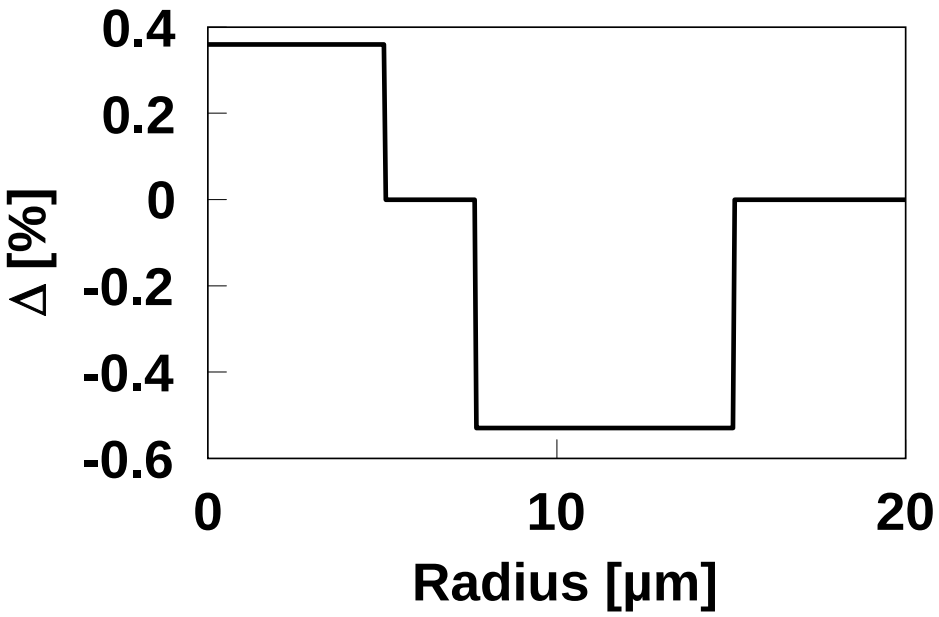


Fiber bend to induce Δβ.

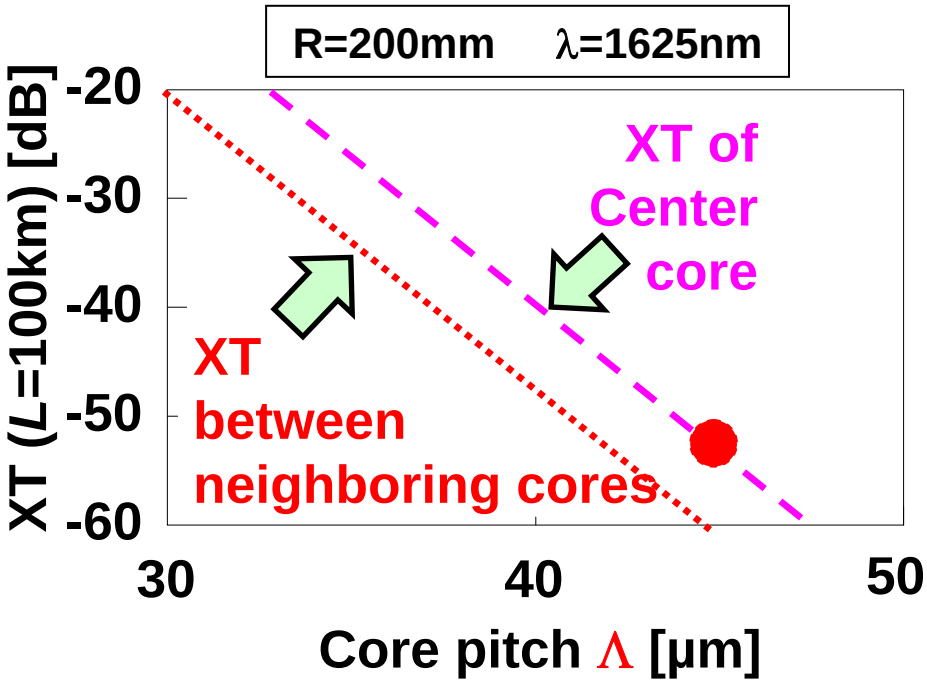
T. Hayashi et al., Opt. Express, **19**(17), 16576 (2011).

Homogeneous MCF using fiber bend for low-loss and crosstalk

- **Core design**
  Pure Silica was applied



- **Designed crosstalk**



Trench-assisted core

Core pitch D was 45 μm

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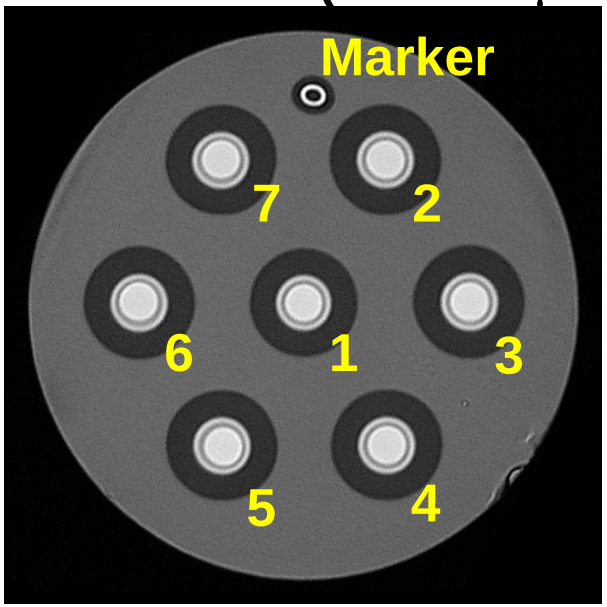
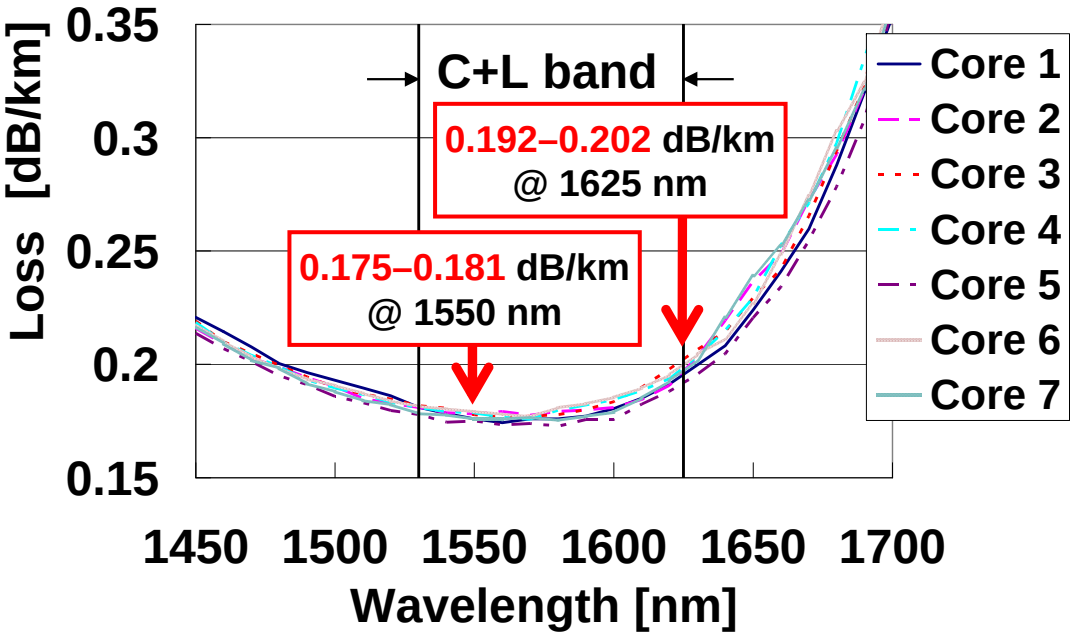
Optical characteristics of fabricated MCF

Crossection (OD=150μm)



Loss



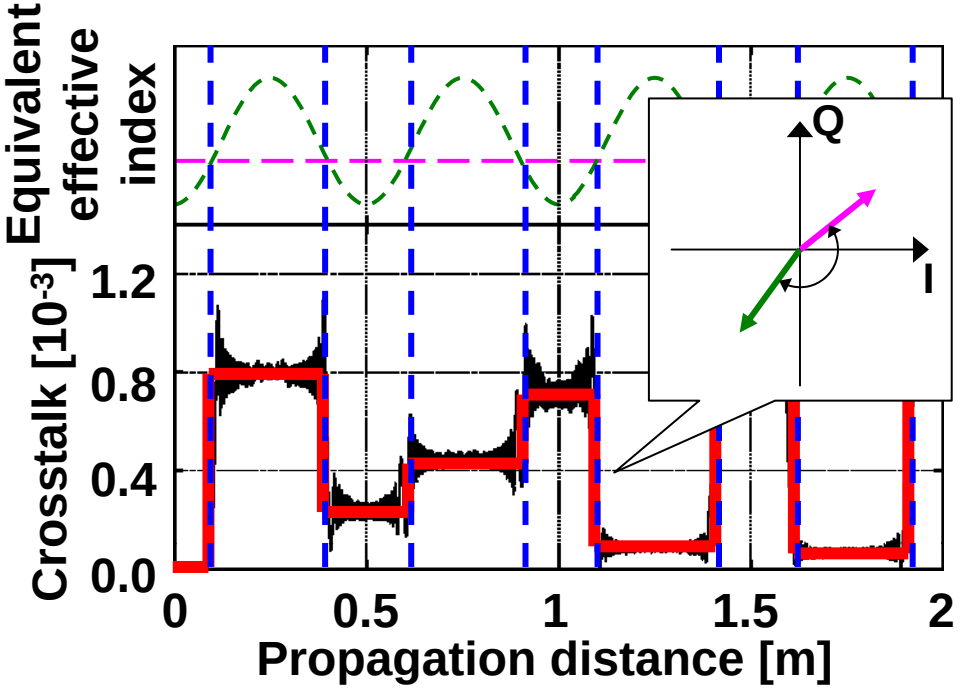
Optical properties

	λcc [nm]	MFD [μm]	Aeff [μm²]	CD [ps/nm/km]	D. slope [ps/nm²/km]	PMD [ps/√km]	Bending loss (R = 5 mm) [dB/turn]
λ [nm]		1550				C+L	1625
Min.	1483	9.72	78.2	22.1	0.062	0.044	0.019
Max.	1509	9.88	81.3	22.2		0.205	0.022

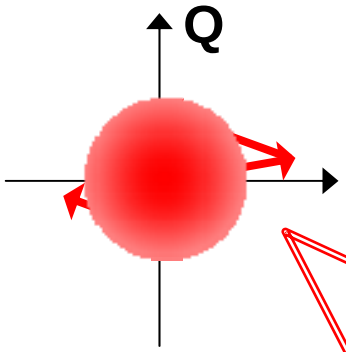
Achieved low loss and homogeneous characteristics

Crosstalk evolves longitudinally by perturbation and shows statistical distribution

➢ Evolution of XT in power



➢ Evolution of XT in I-Q plane

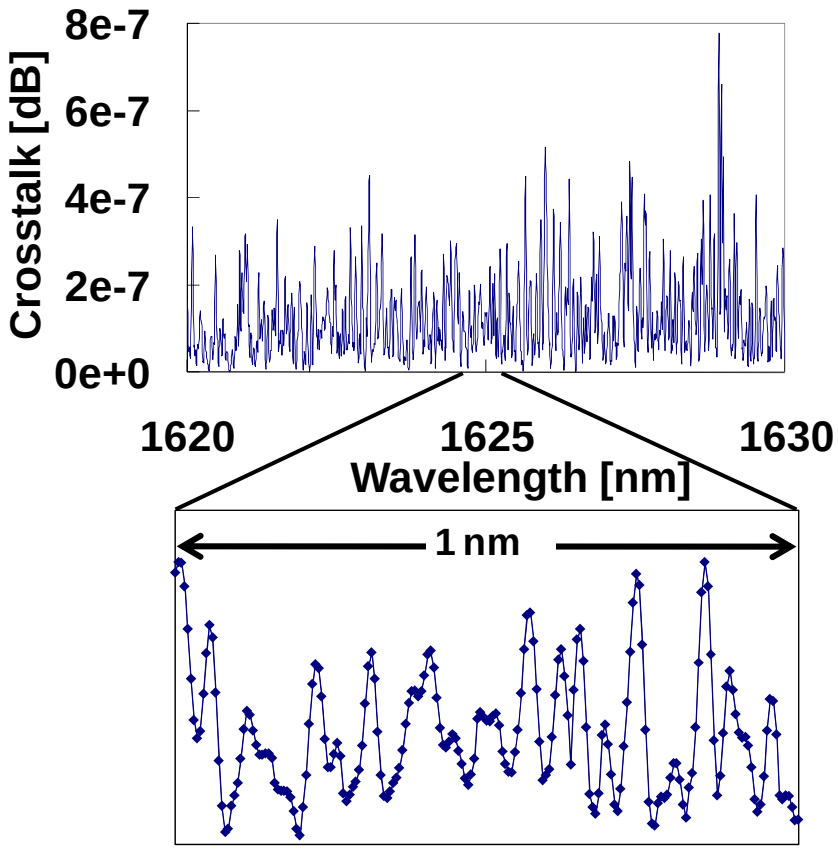


Direction of the changes can be varied significantly by slight perturbation of the propagation constants

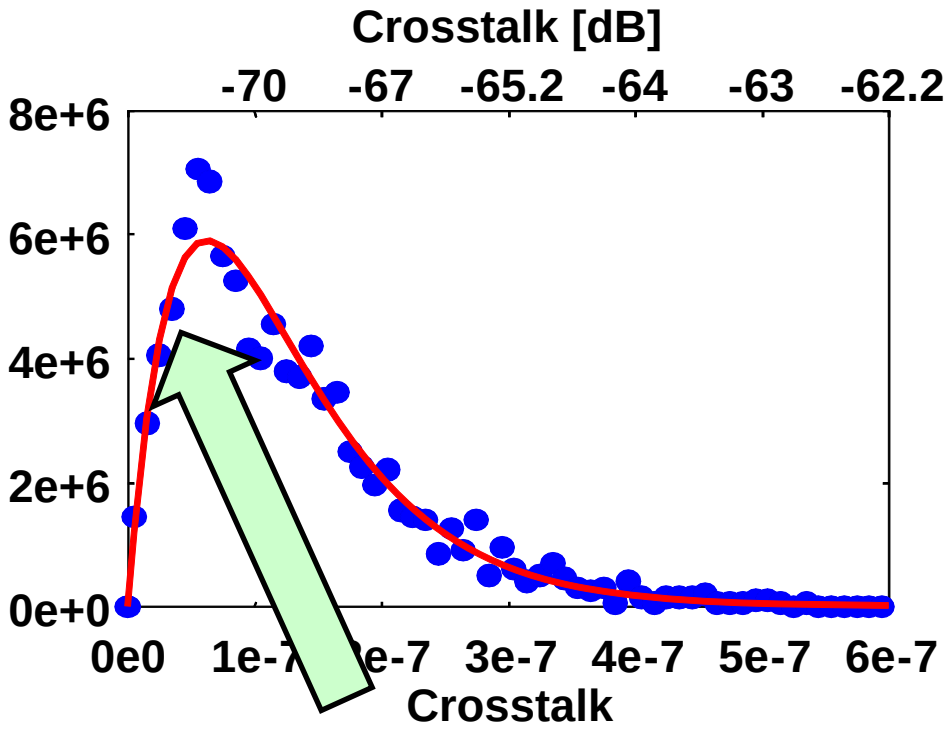
- The propagation constant: β can be varied by..
  - Changes of fiber bend & twist
  - Change of temperature
  - Change of wavelength

Statistical measurement of crosstalk

➢ **Measured XT spectrum (proposed "λ- scan" method)**



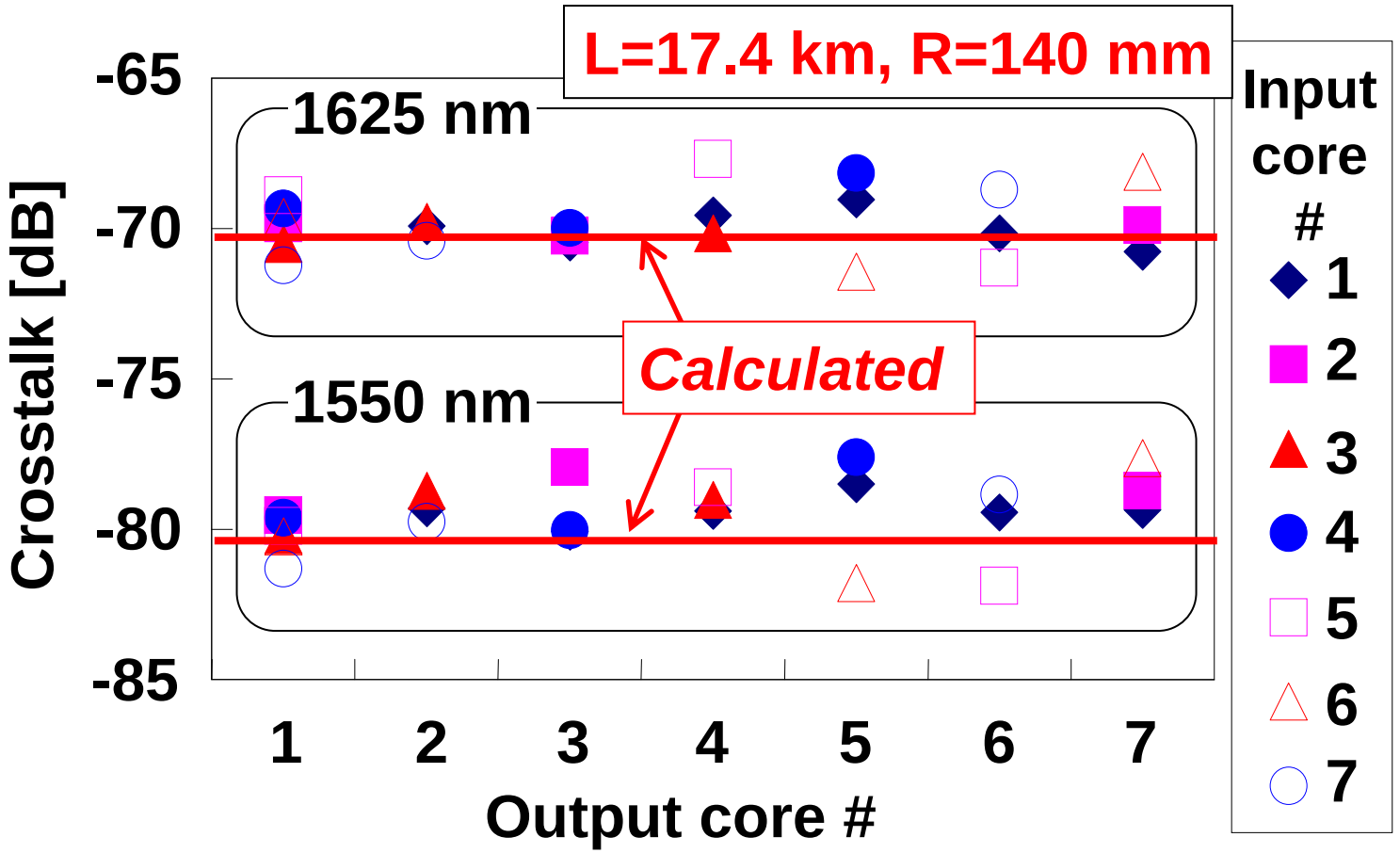
➢ **XT probability distribution**



$$\text{Mean: } XT_{\mu} = 2\,\frac{\kappa^2}{\beta}\,\frac{R}{\Lambda}\,L$$

*Detailed in
T. Hayashi et al., Opt. Express, **19**(17), 16576 (2011).

Measured crosstalk by λ-scan method

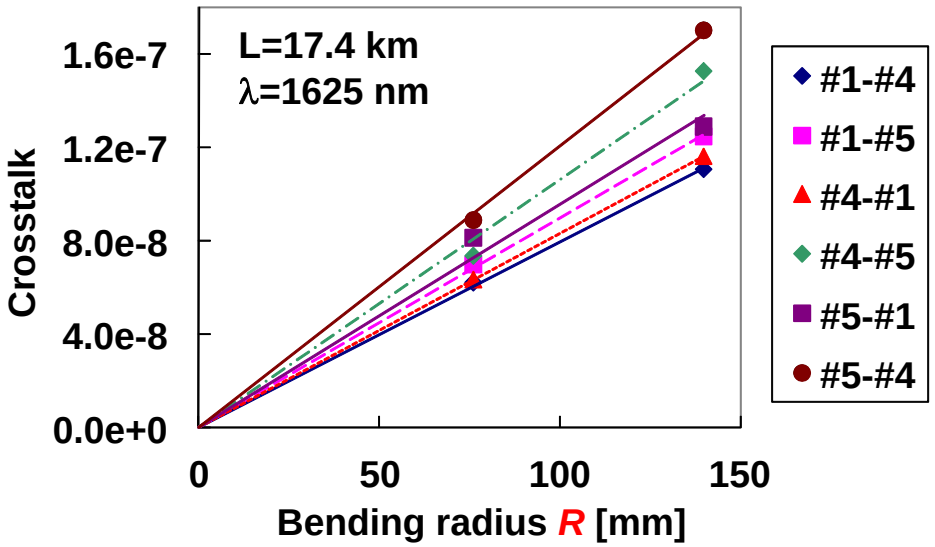


	1550 nm	1625 nm
Average value of two neighboring core	-79.5 dB	-69.8 dB
Crosstalk of center core	-72.3 dB	-62.1 dB

3. Feasibility for longer transmission ~ potential of MCF as for crosstalk ~

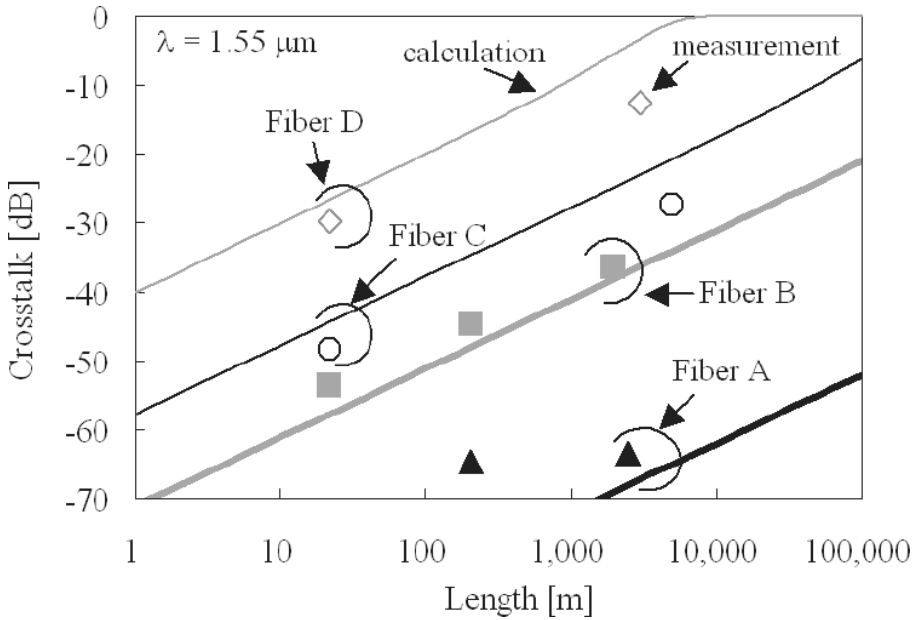
Crosstalk varies by bend and Length

➢Bending radius: R



XT ∝ *R*

➢Length: L



K. Takenaga et al., IEICE Trans. Commun., **E94-B**(2), 409 (2011).

L × 10 → XT +10 dB

XT ∝ *L*

Crosstalk is affected by the length and bend

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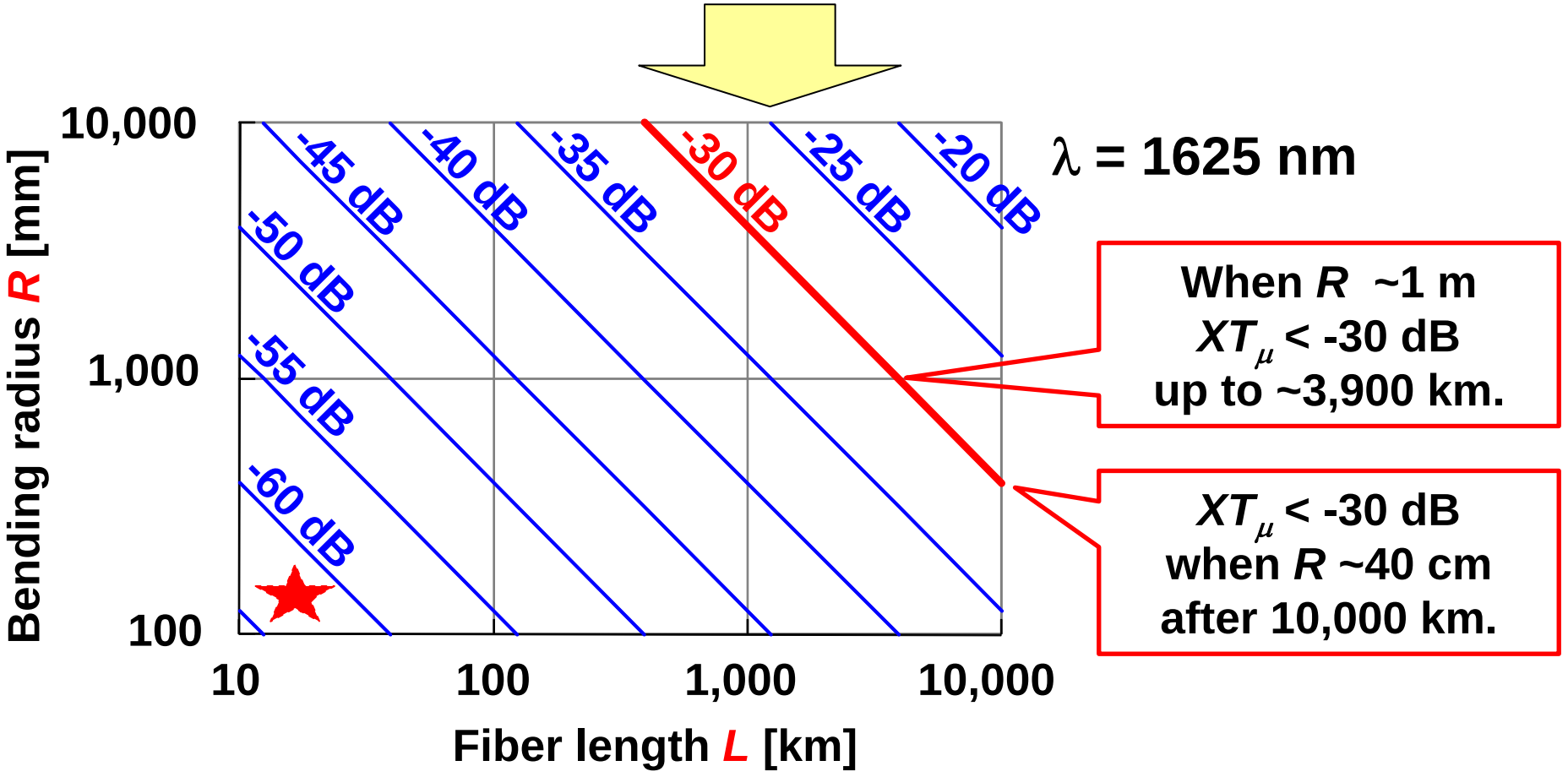
XT calculations for longer reach

XT_μ: -62.1 dB & $XT_\mu = 2\frac{\kappa^2}{\beta}\frac{R}{\Lambda}L$



4. Summary

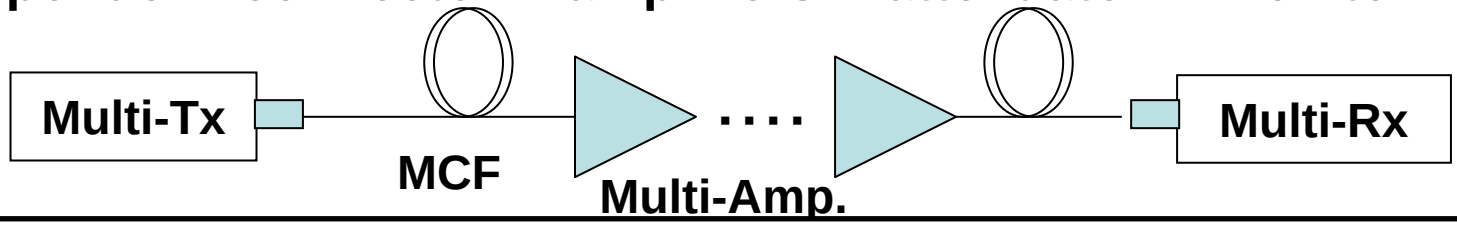
- ✓ Low-XT is necessary for present transmission technology
- ✓ Mechanism of crosstalk is investigated and proved lowest XT MCF, feasible of -30dB after 10,000km transmission

⇒Crosstalk change by microbending must be considered for the cable manufacturing (Mo.1.LeCervin.3 • 15:00)

⇒ In near future, more dense MCF expected to be proposed

⇒ Expansion of peripheral technologies may open the "real" SDM systems while keeping the merit of SDM

"transponder""connector" "amplifiers" "attenuator" "monitor?"



Establishing standard must be the future issue
[XT / λc / outer diameter] [XT meas. method] etc..

Acknowledgement

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