Raman Amplification and Dispersion Compensation

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Denmark

Scope

Discuss development done with

OFS Fitel Denmark

on Raman amplification and other non-linearities in optical fibers.

Aknowlegdements:

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Stig Nissen Knudsen
Lars Grüner Nielsen
Yujun Qian

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Outline

Introduction

- Basic Dispersion compensation

Transmission fiber

- Raman pumped NZDF, TW-Reach
- Dispersion managed spans, Ultrawave

Lumped Raman amplification

- Principle, motivation
- Dispersion Compensating Raman Amplifier, DCRA

Non-linear measurements

- Raman amplification, Rayleigh scattering, MPI and non-linear response

Highly non-linear fiber, HNLF

- Properties and applications

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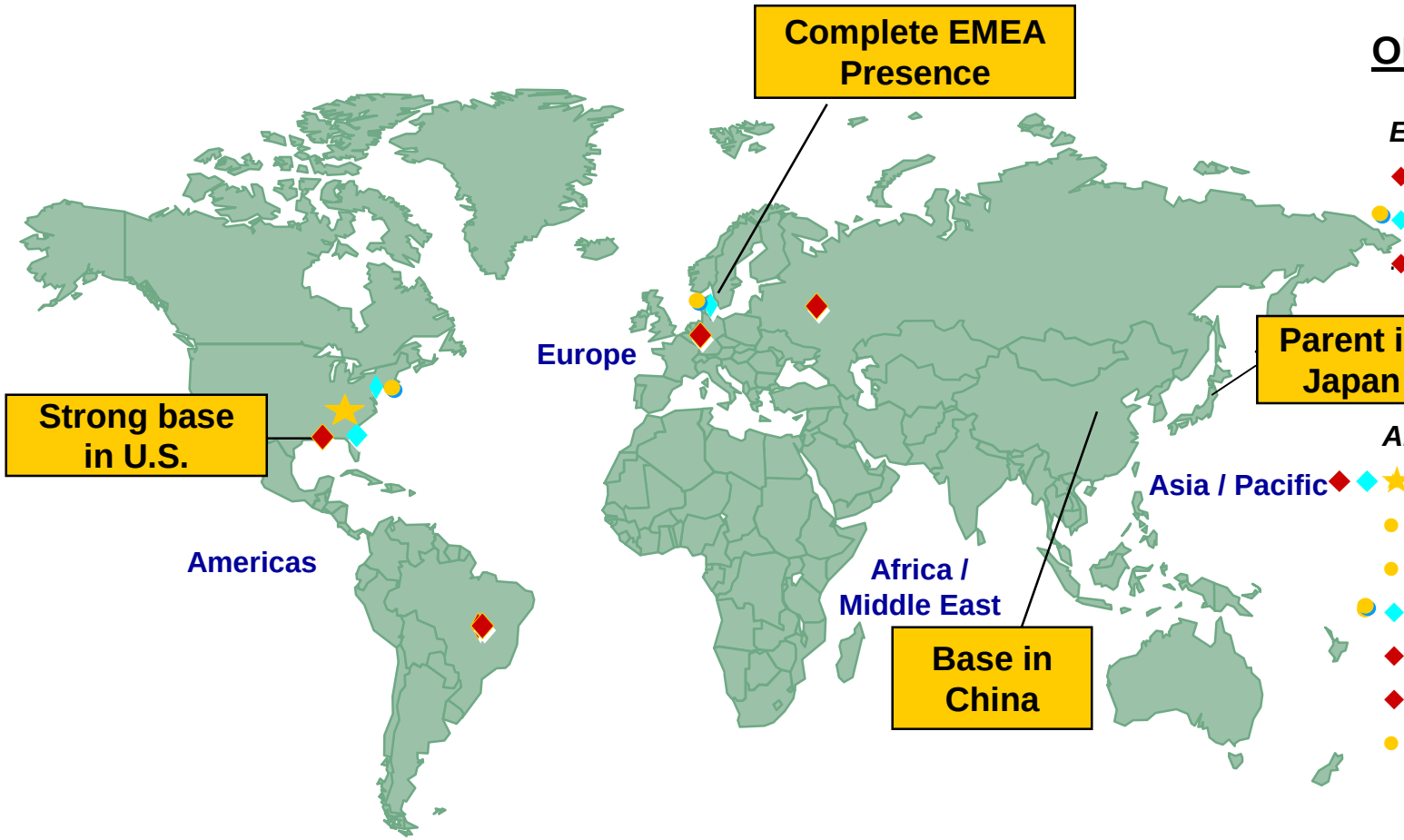
Introduction

OFS Global Reach

◆ Fibre ◆ Cable ● Specialty Photonics and Optical Connectivity



OFS Locations

Europe

- ◆ Augsburg, GERMANY
- ● ◆ Brøndby, DENMARK
- ◆ Voronezh, RUSSIA

America

- ◆ ◆ ★ Norcross, GA – HQ
- ● Somerset, NJ
- ● Avon, CT
- ● ◆ Sturbridge, MA
- ◆ Carrollton, GA
- ◆ Brazil
- ● Omaha, NE

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OFS in Denmark

Production in Denmark

Transmission Fibers

- Matched Cladding Single-mode Fiber
- TrueWave™ Single-mode Fiber
- Ocean Fiber
- UltraWave™ IDF / SLA Fiber

Specialty Photonics

- Dispersion Compensating Modules
- Erbium Doped Fibers
- Polarization Maintaining EDF
- Raman Fiber and HNLF
- DCRA: Dispersion Compensating Raman Amplifier (collaboration with Furukawa)

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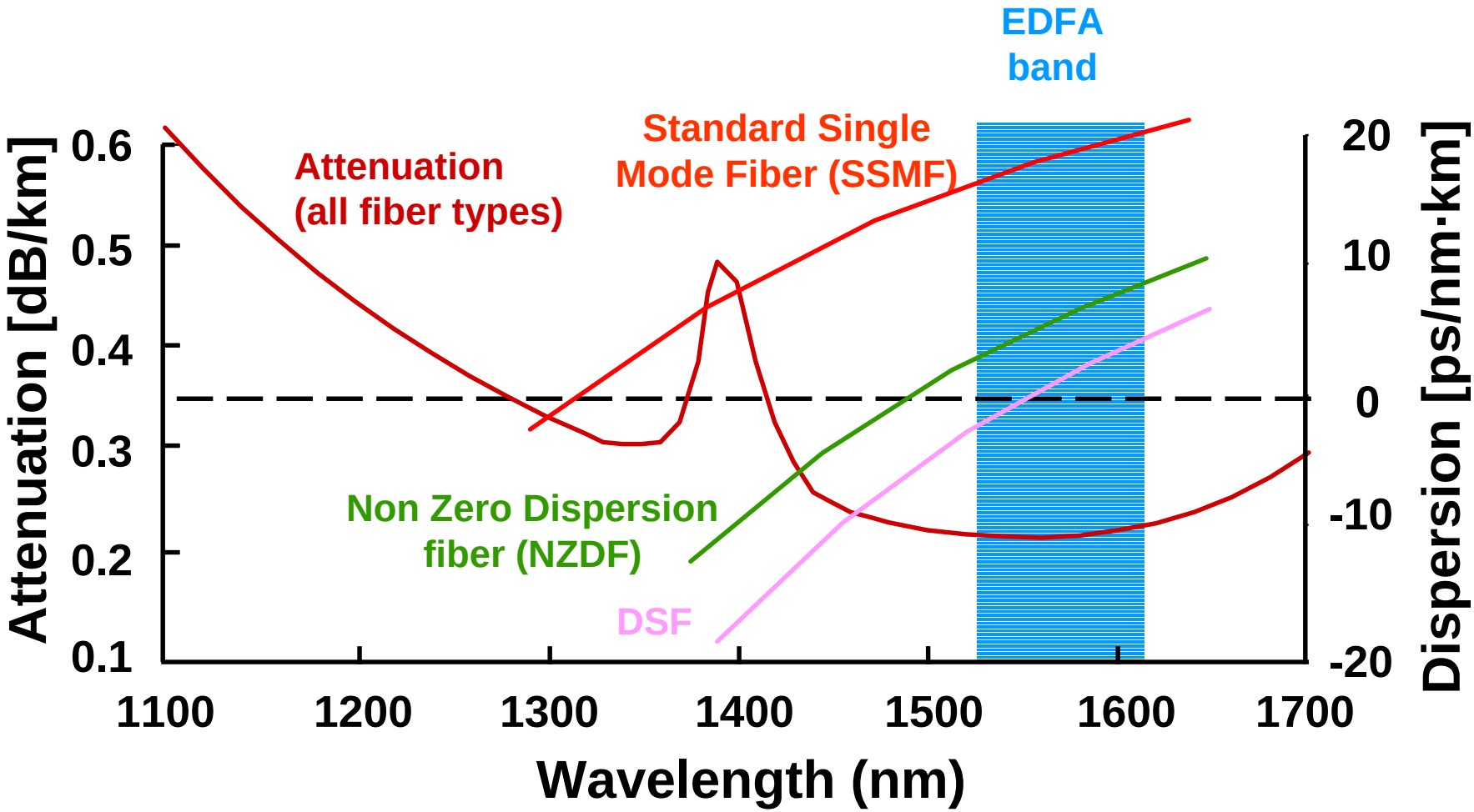
Fiber Dispersion and Attenuation



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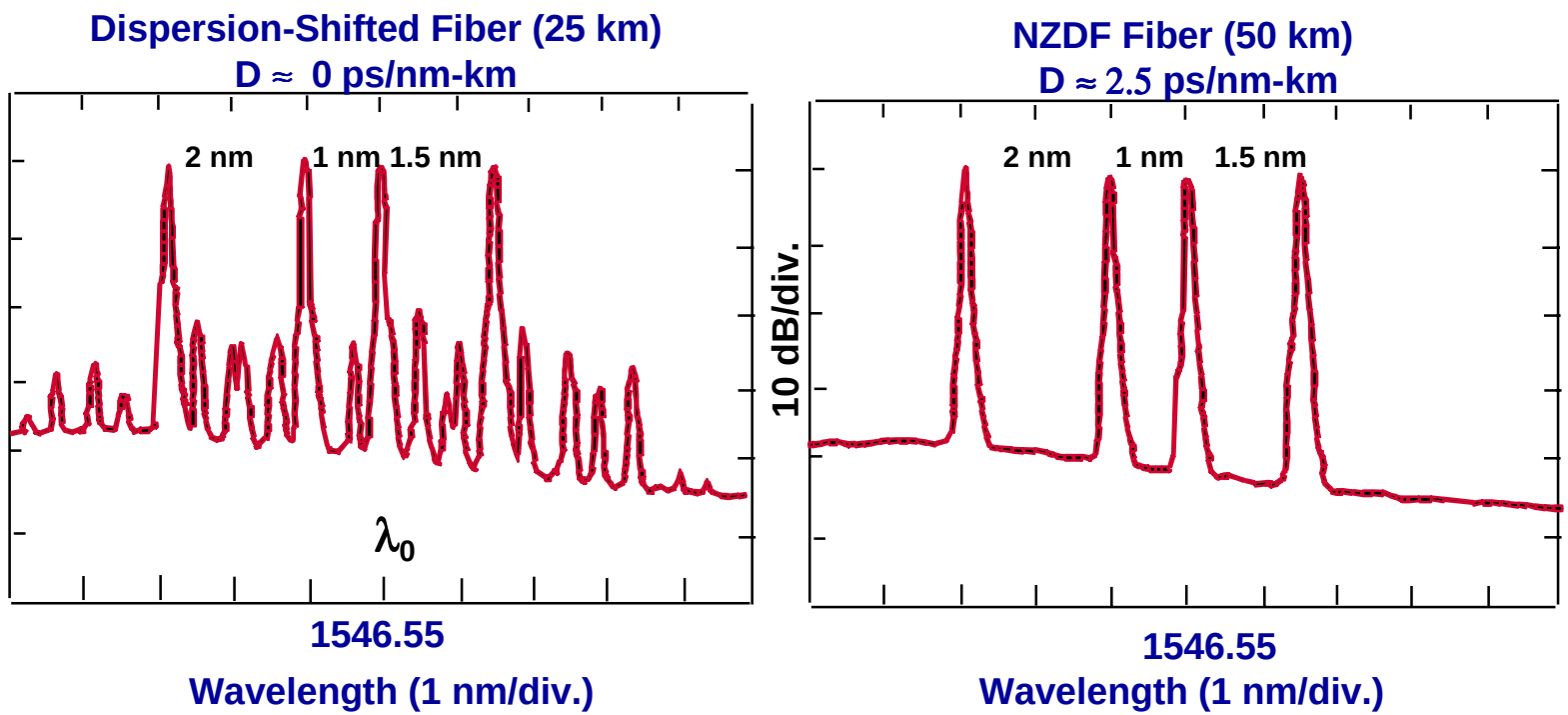
DSF and NZDF

Why not have zero dispersion? → Four Wave Mixing, FWM



Optical Launch Power = 3 dBm/channel

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Transmission Distances Without Dispersion Compensation

Bit rate (Gbit/s)	Non-shifted fiber (km)	NZDF (km)
2.5	1000	3400
10	60	200 – 400*
40	4	13

*Low dispersion NZDF, TW-RS

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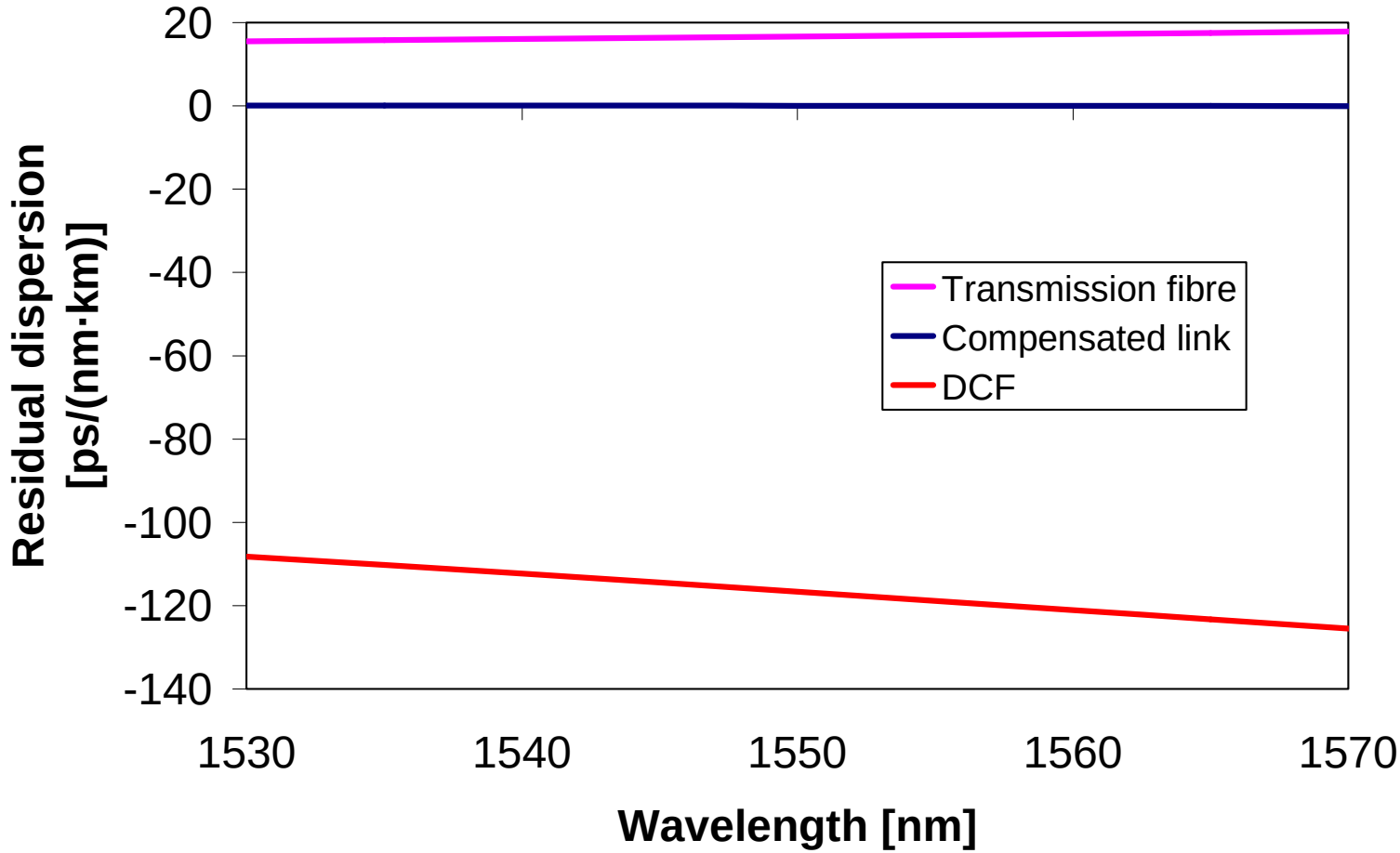
Basic Dispersion Compensation



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Simultaneous Dispersion and Slope Compensation

Relative Dispersion Slope: RDS = Slope / Dispersion

Total link dispersion: $D_T = D_{SSMF}L_{SSMF} + D_{DCF}L_{DCF}$

Dispersion compensation: $L_{DCF} = D_{SSMF}L_{SSMF} / -D_{DCF}$

Total link dispersion slope: $S_T = S_{SSMF}L_{SSMF} + S_{DCF}L_{DCF}$

Dispersion and slope compensation: $RDS_{DCF} = RDS_{SSMF}$

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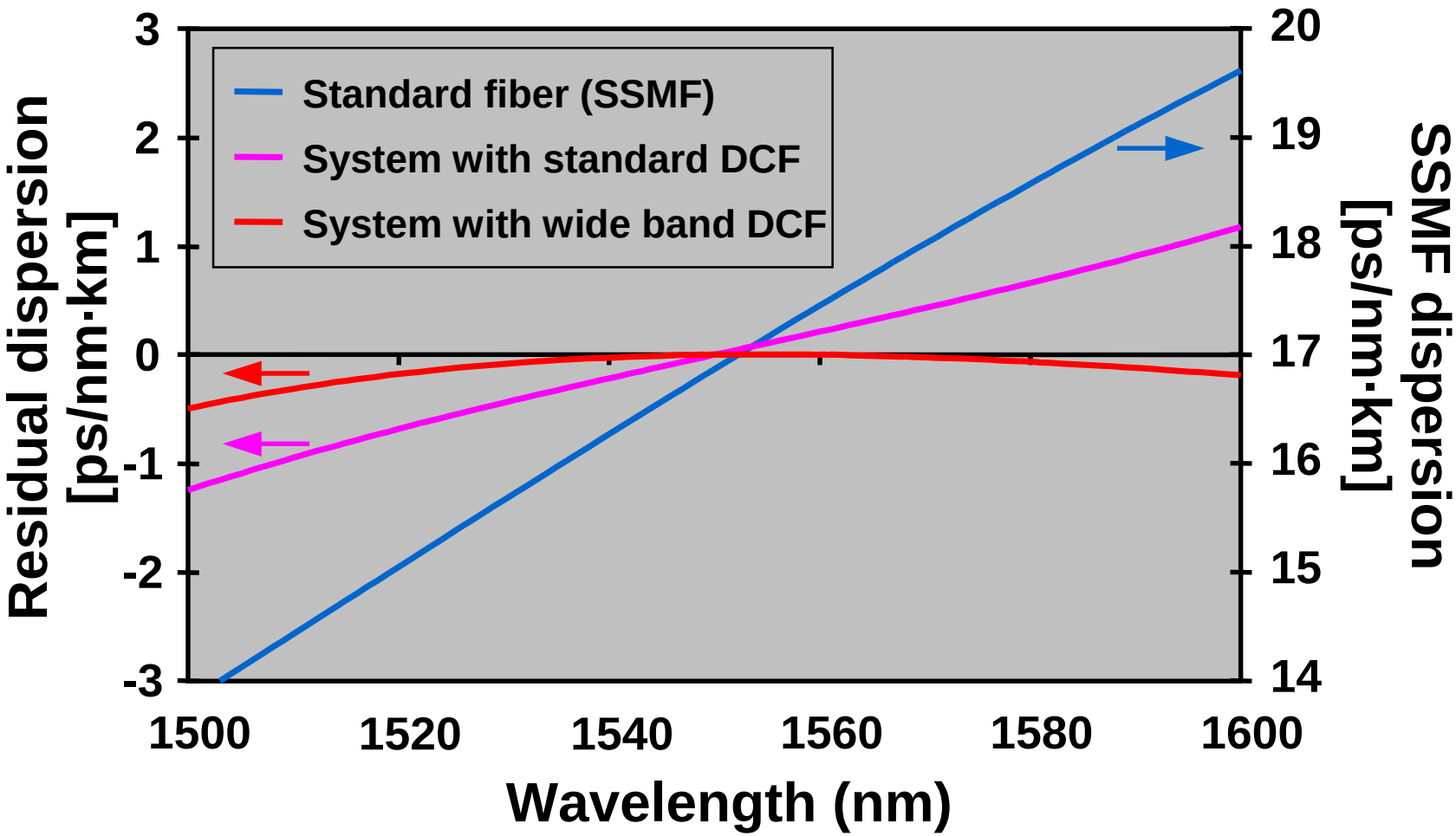
Dispersion Slope Compensation



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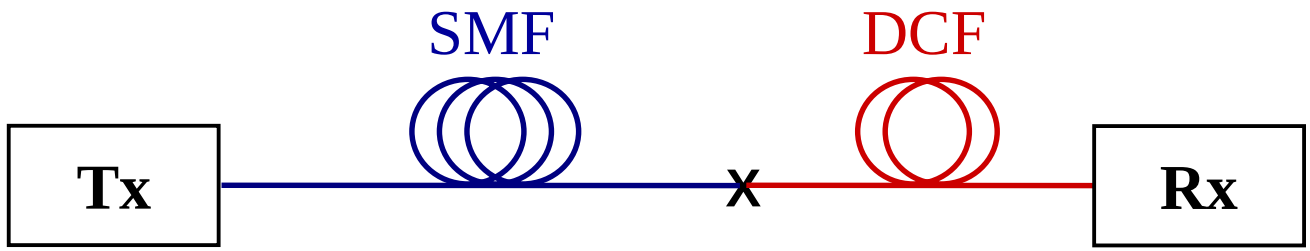
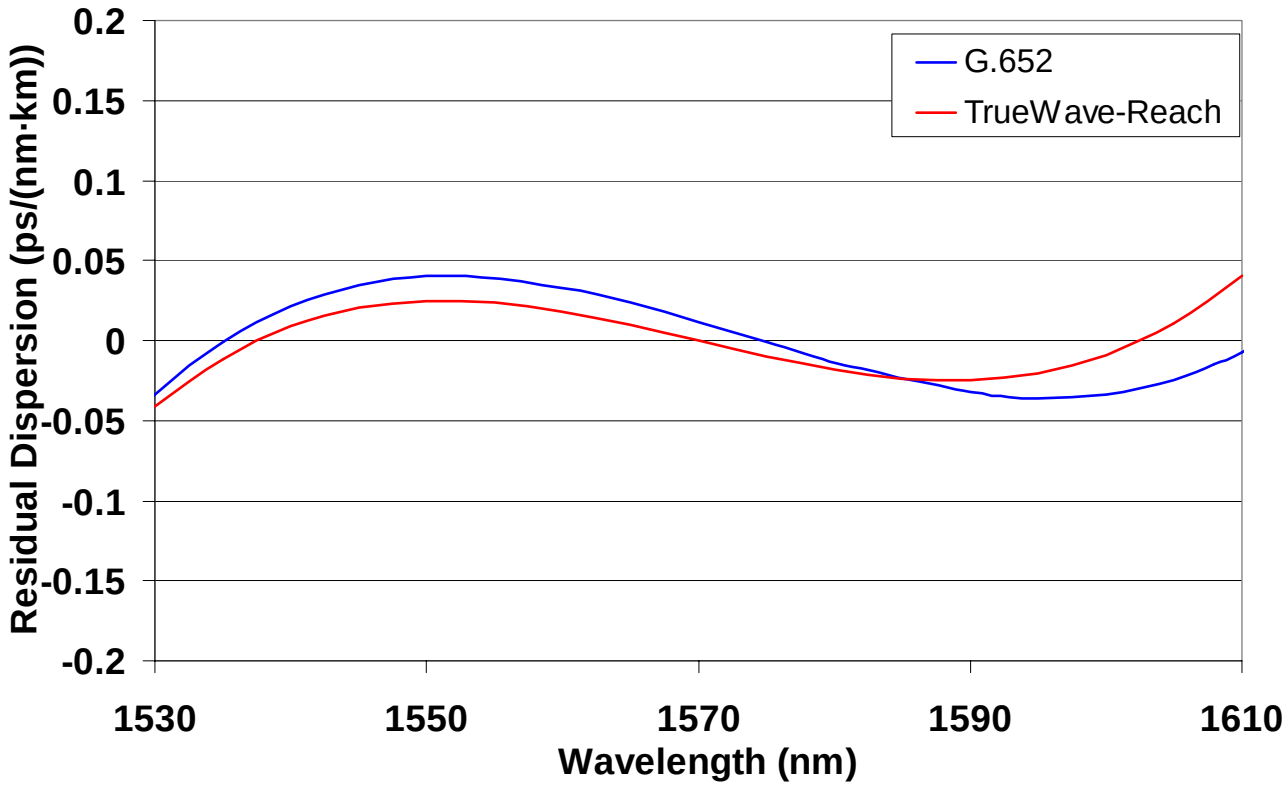
Basic Compensated System, Residual Dispersion





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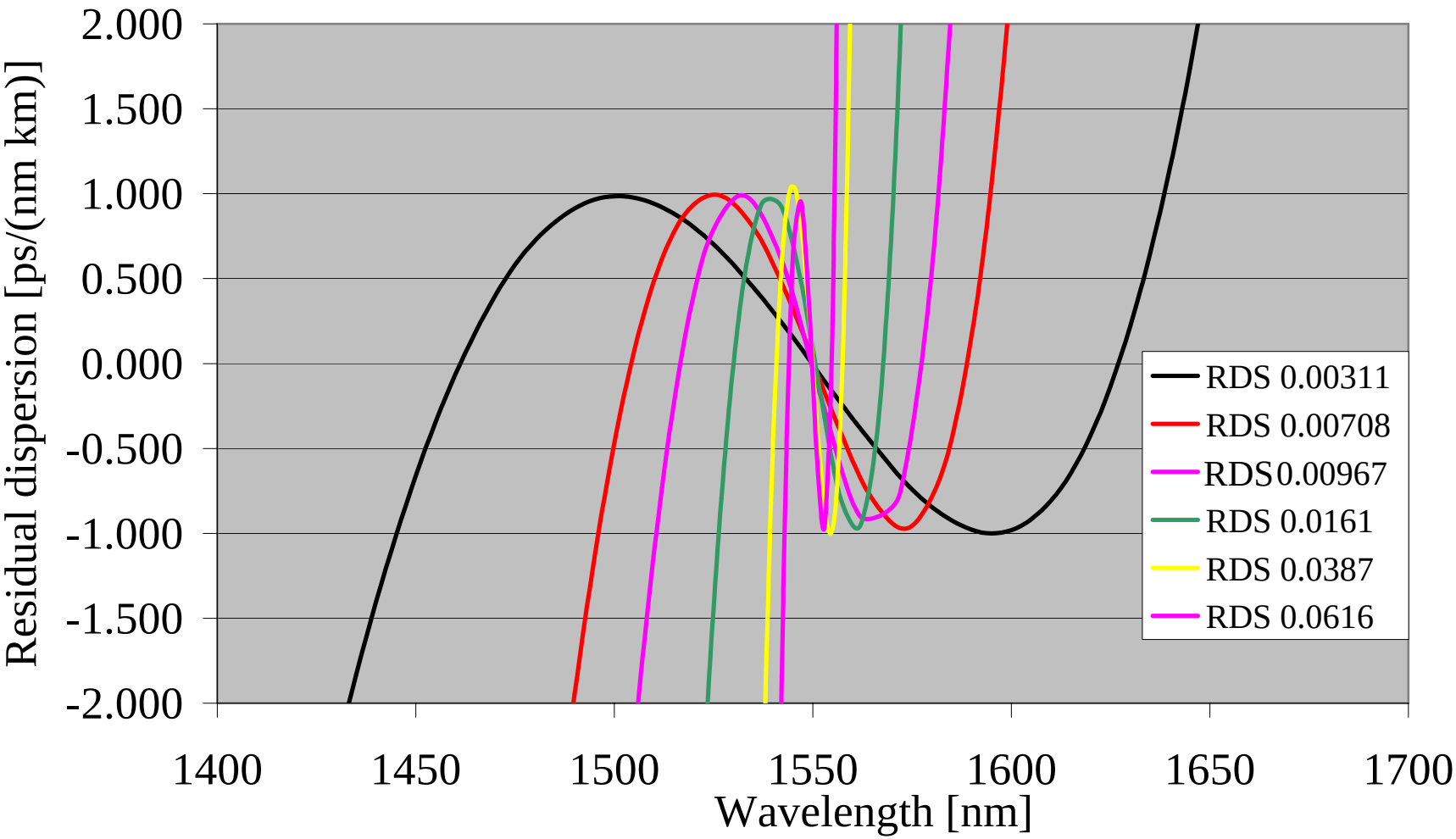
Residual Dispersion Curves for Compensation of Different RDS



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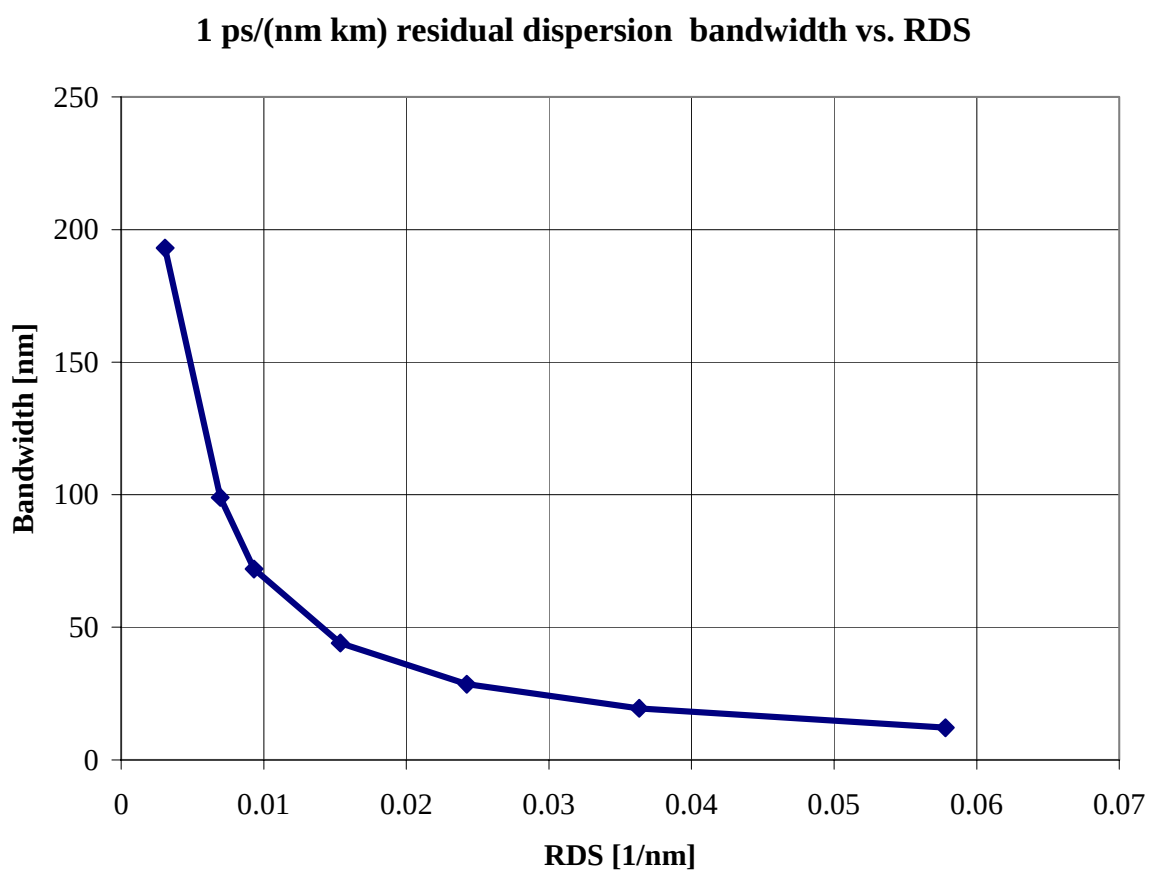
Dispersion Compensation Bandwidth Versus Transmission Fiber RDS



More details in paper P1.23 at ECOC'02 by J. Rathje et al.

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Dispersion Slope Compensating Modules, DSCM

- Broadband, very low residual dispersion
- Low loss
- Low PMD and no PDL
- No MPI (Multi-Pass-Interference)
- Passive, no temperature control
- Robust, simple, fiber compatible, based on singlemode fiber
- Commercial available for > 5 years and >100.000 modules deployed

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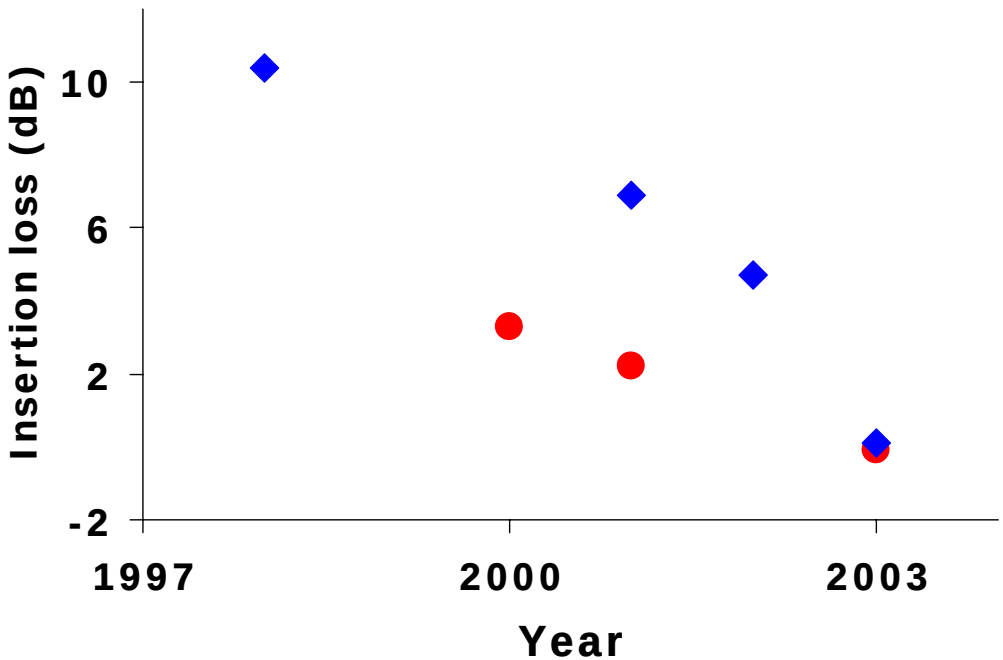
Insertion loss of DSCM for 100 km fiber

	1998	2000	2001	2002	2002*
TrueWave® RS		3.3 dB	2.2 dB		0 - -2 dB
Standard SMF	10.4 dB		6.9 dB	4.7 dB	0 - -2 dB



* Including Raman amplification, data sheet published at ECOC 2002

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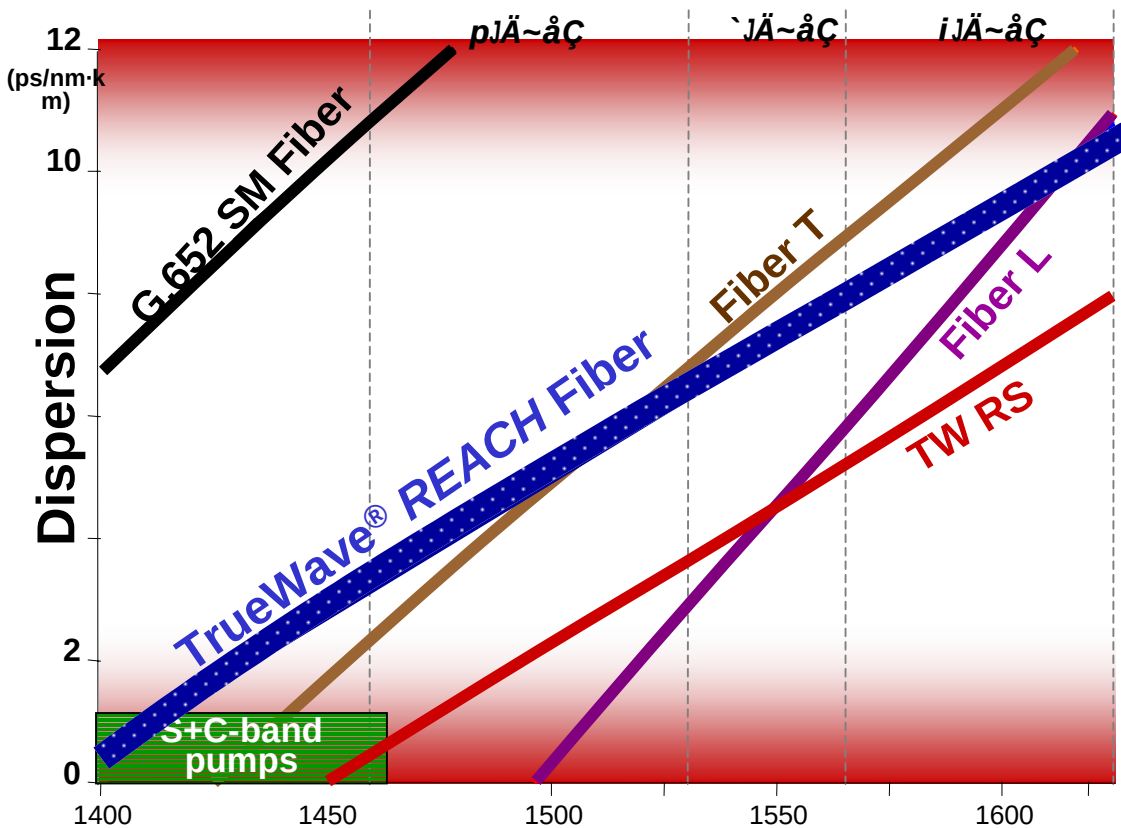
Transmission fiber

Broader Bandwidth



Too high

- More DCF Cost
- Greater DCF PMD
- Amp noise and cost from DCF loss
- Poor 40 Gb

Need fiber to open S-, C- and L-bands

Too low

- FWM limits channel spacing
- FWM distorts Raman pumps

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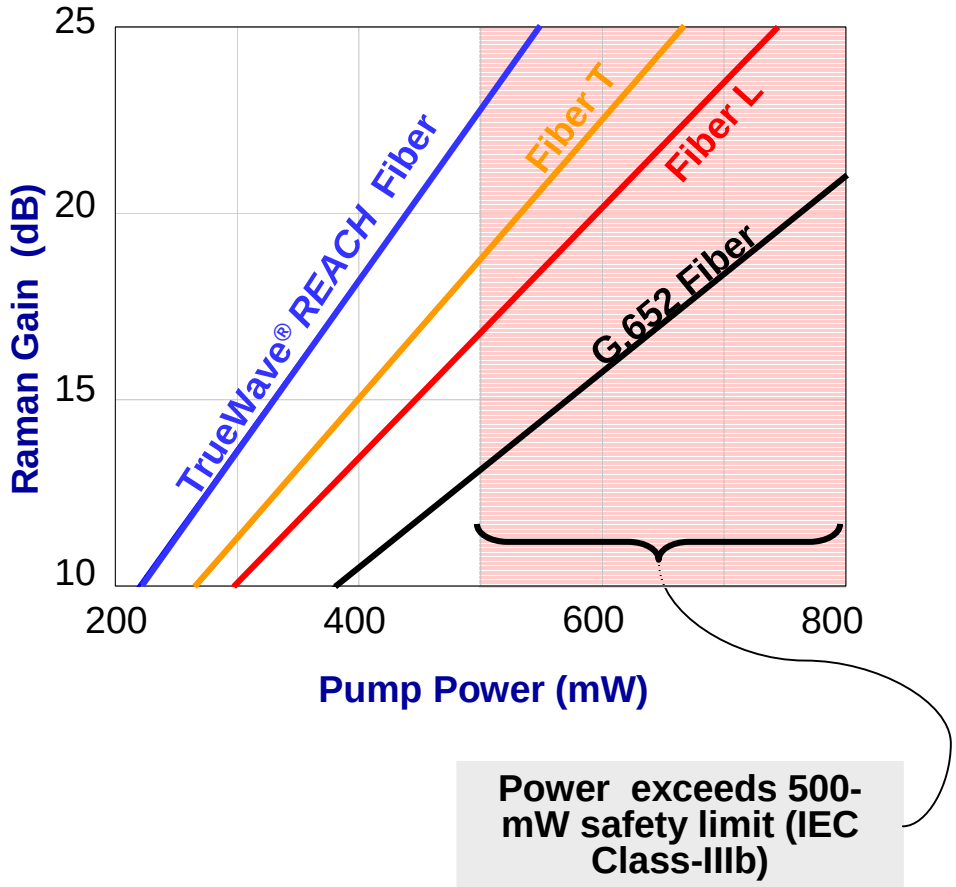
More Raman Gain from a Moderate Effective Area Fiber



TrueWave *REACH* Fiber's moderate Aeff:

- **Reduces pump cost**
- **Increases laser safety**

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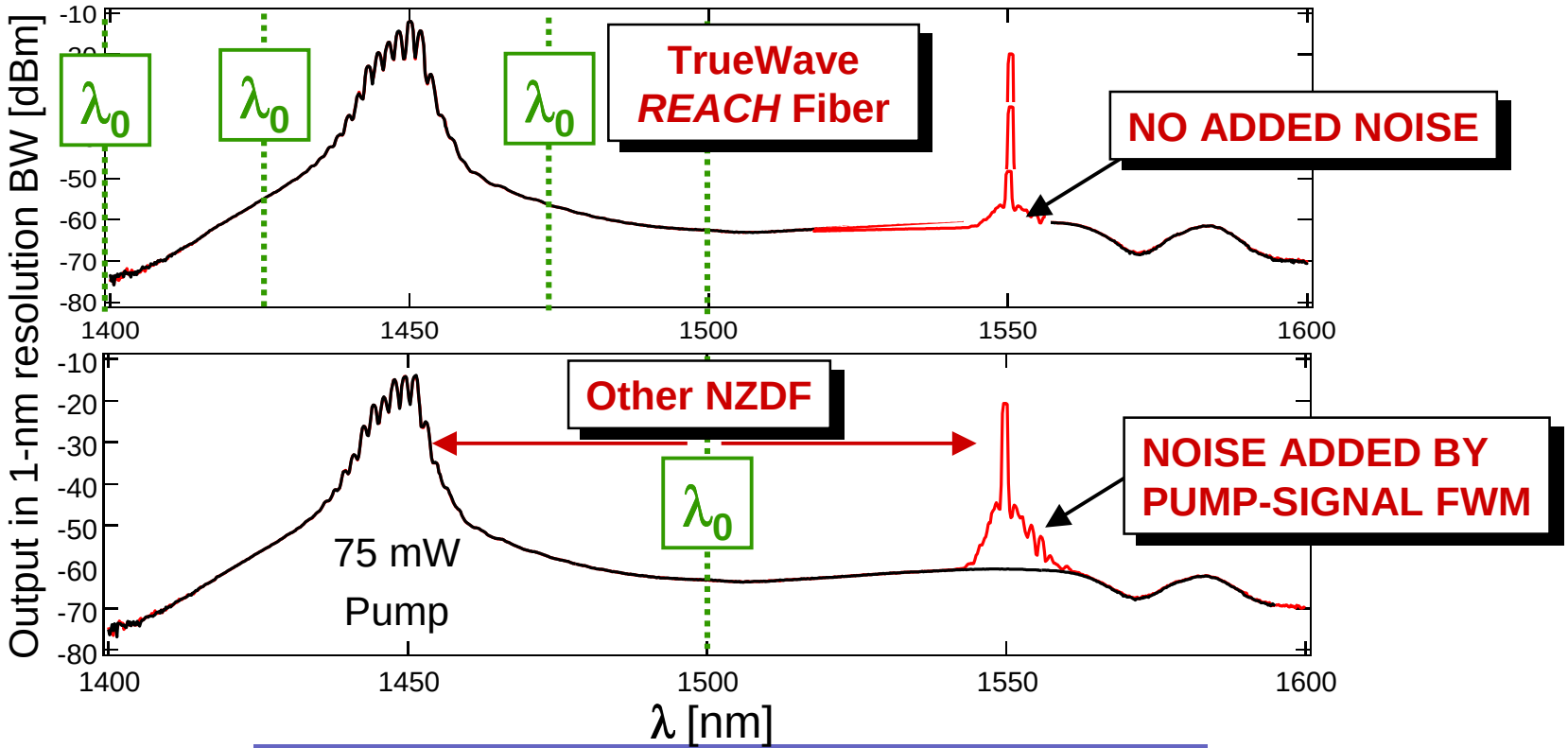
No Raman Pump Noise



TrueWave® *REACH* Fiber moves λ_0 and Eliminates Raman Pump Mixing Noise

See 020109analysis.pxp

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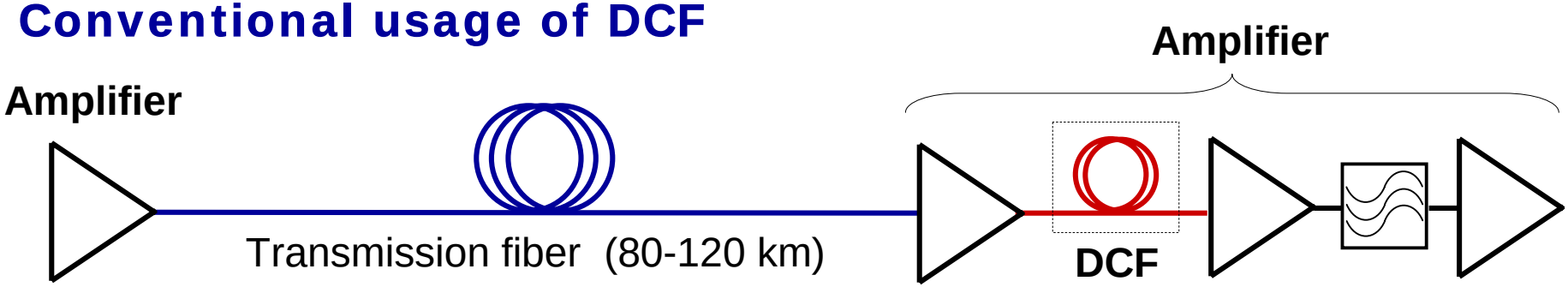
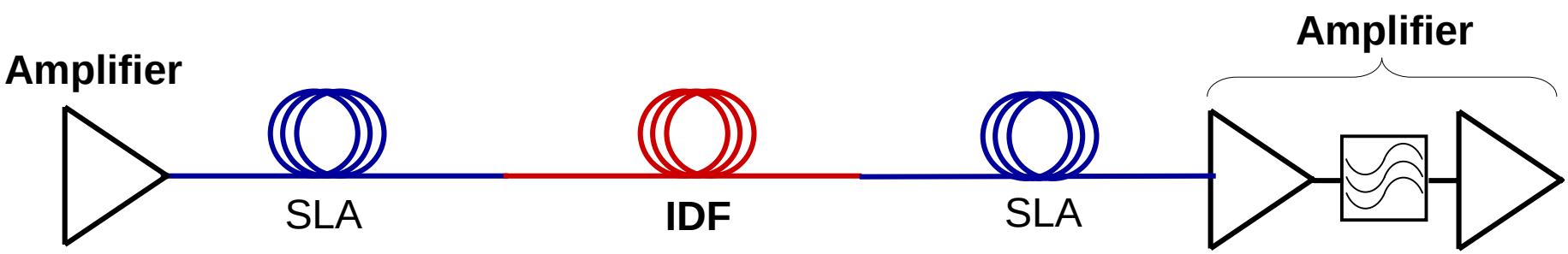
DCF's for Cabled Applications: Dispersion managed spans

Terrestrial Applications of DCF

Conventional usage of DCF



DCFs for cabled applications: Ultrawave™



Amplifiers could be EDFA's, Hybrid Raman/EDFA or Raman only

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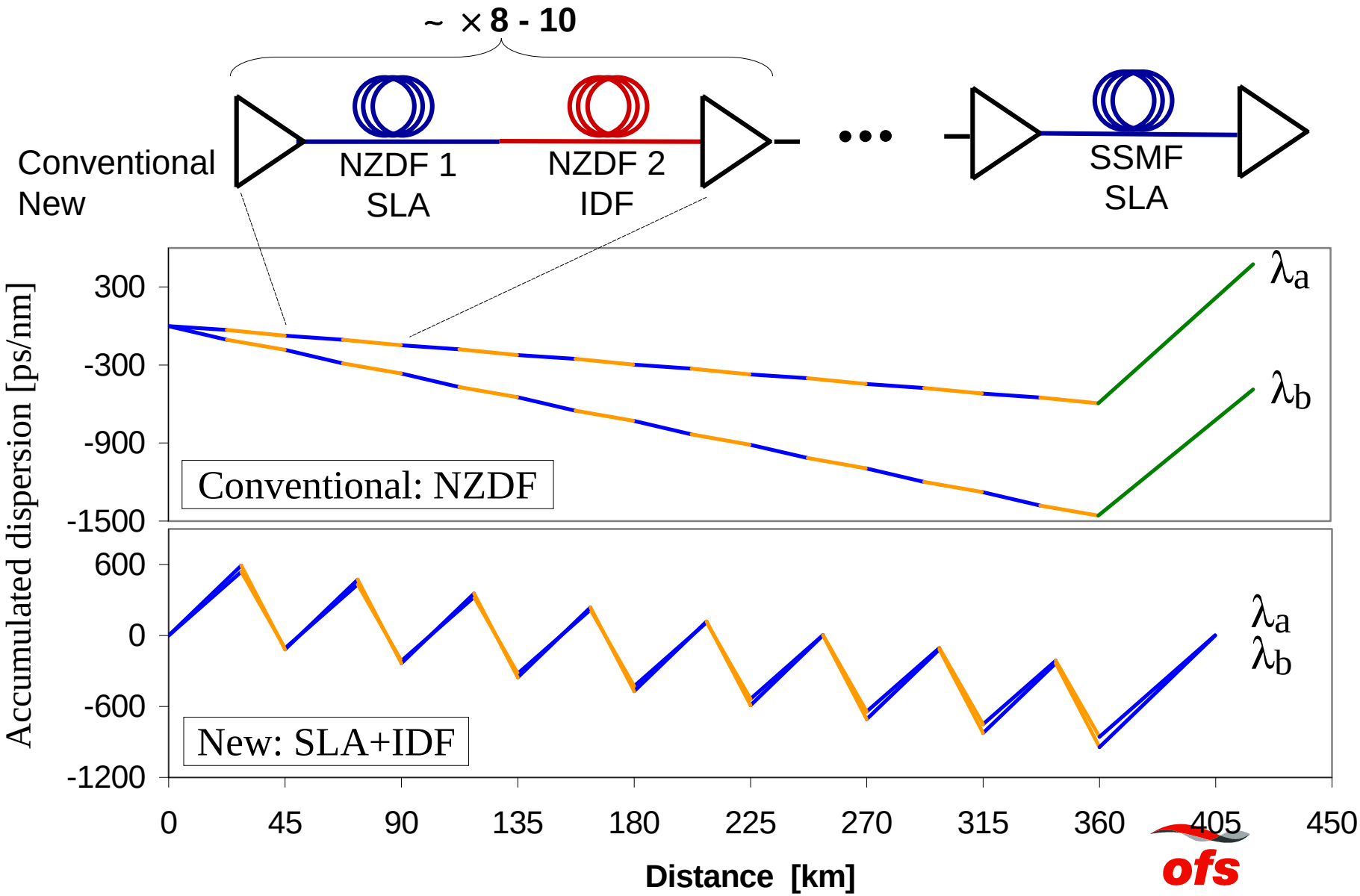
Submarine applications: old and new dispersion maps



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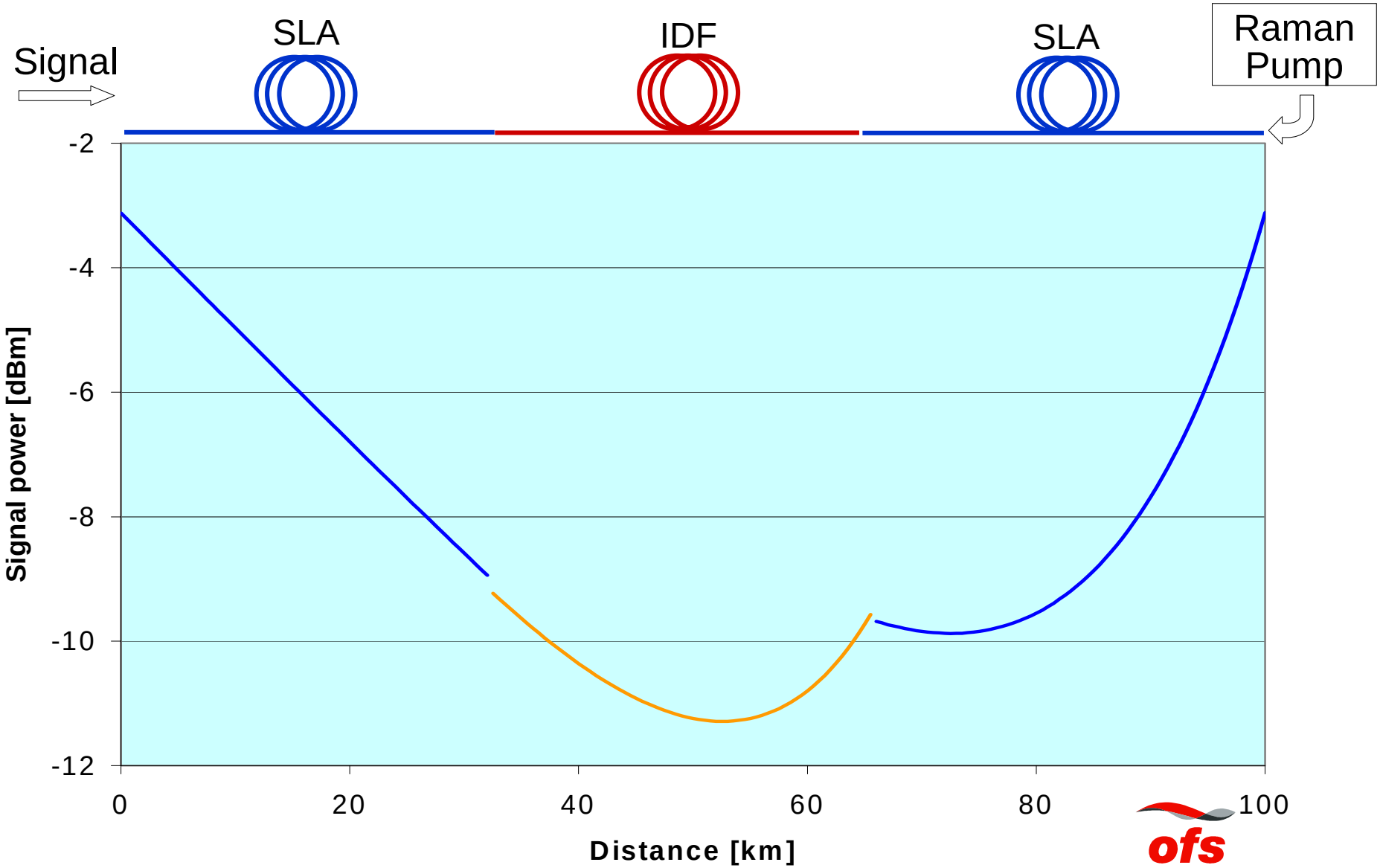
Signal Power Evolution in Raman Pumped "ABA Map"



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Estimation of Nonlinear Properties: Equivalent Effective Area

Equivalent effective area of hybrid fiber spans:

”The effective area of a single Dispersion-Shifted fiber that produces the same nonlinear phase shift as the hybrid span.”

Nonlinear phase shift given by:

$$\frac{2\pi}{\lambda} \int_0^L \frac{n_2(z)}{A_{eff}(z)} P(z)\, dz$$

The equivalent effective area thus includes effects of total span loss including splice losses.

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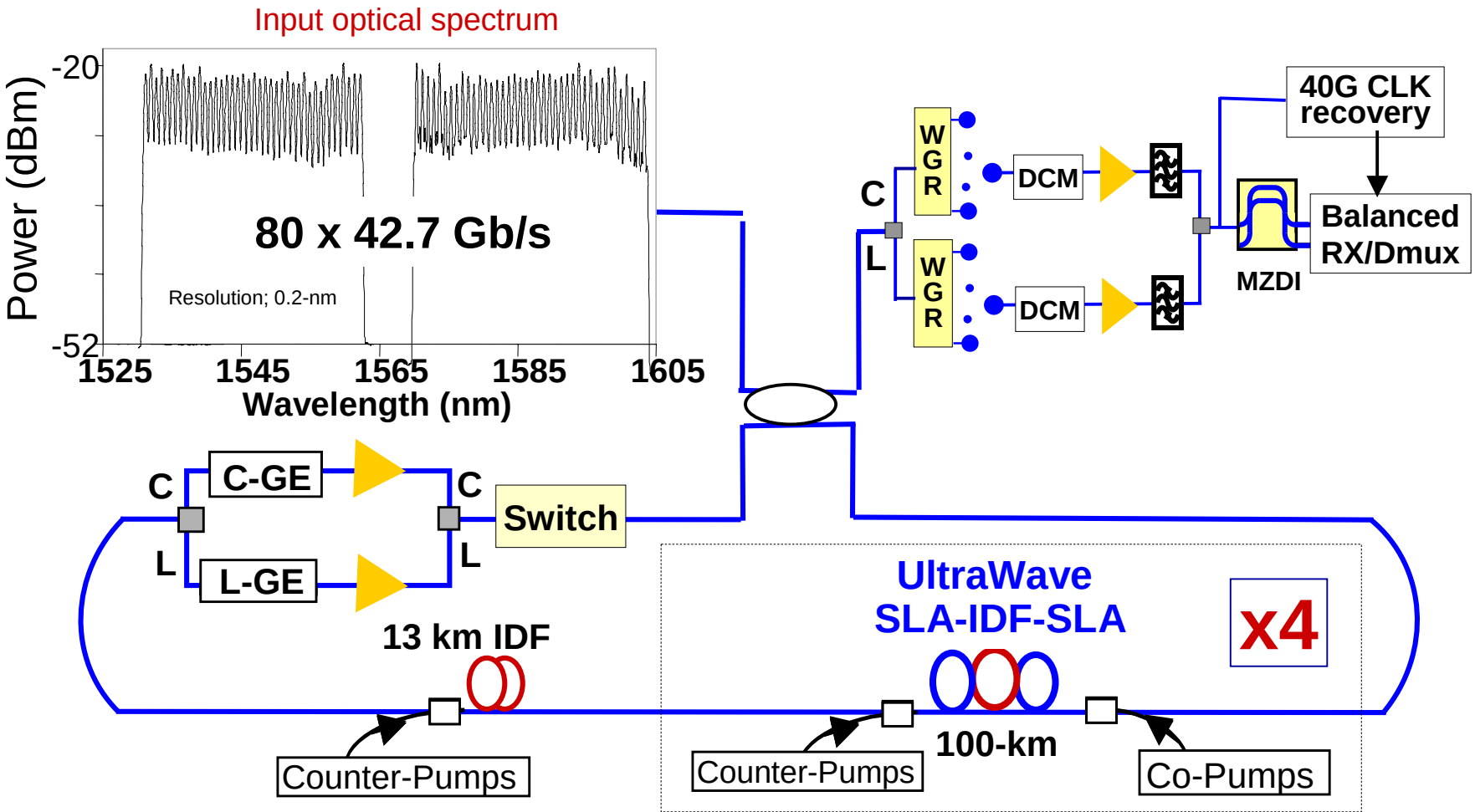
Latest World Record Results (ECOC 2002)
16.6 Pb/s*km (3.2Tb/s x 5200 km)



13 x 400km = 5200km

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DCF used as Raman Amplifier: DCRA

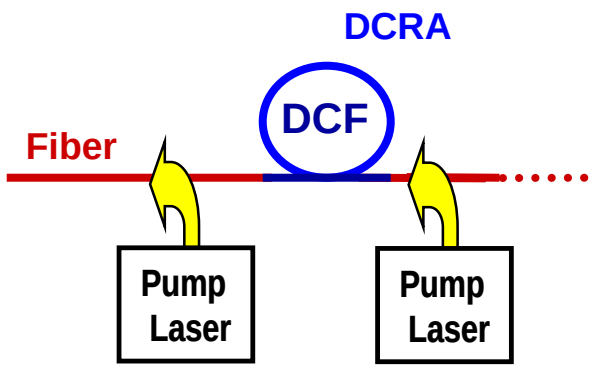
Discrete Raman Amplification in DSCM

- DCF is an excellent gain medium for discrete Raman amplifiers
  - Discrete Raman amplification requires few km of fiber
  - Small effective area and high Ge concentration gives high Raman gain efficiency
- Gives additional flexibility in system
- Saves space
- Potentially low cost!

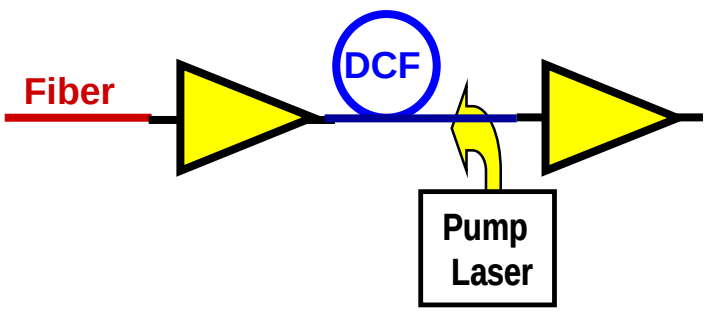
Applications of Discrete Raman Amplifiers

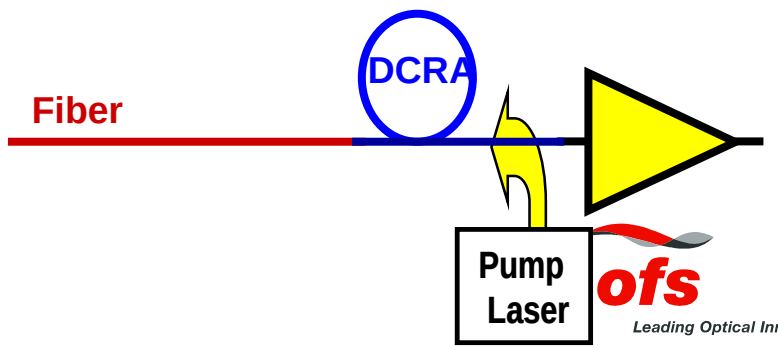
Replacing EDFA

Gain bandwidth not limited to EDFA bands



Combined with EDFA, reduce complexity





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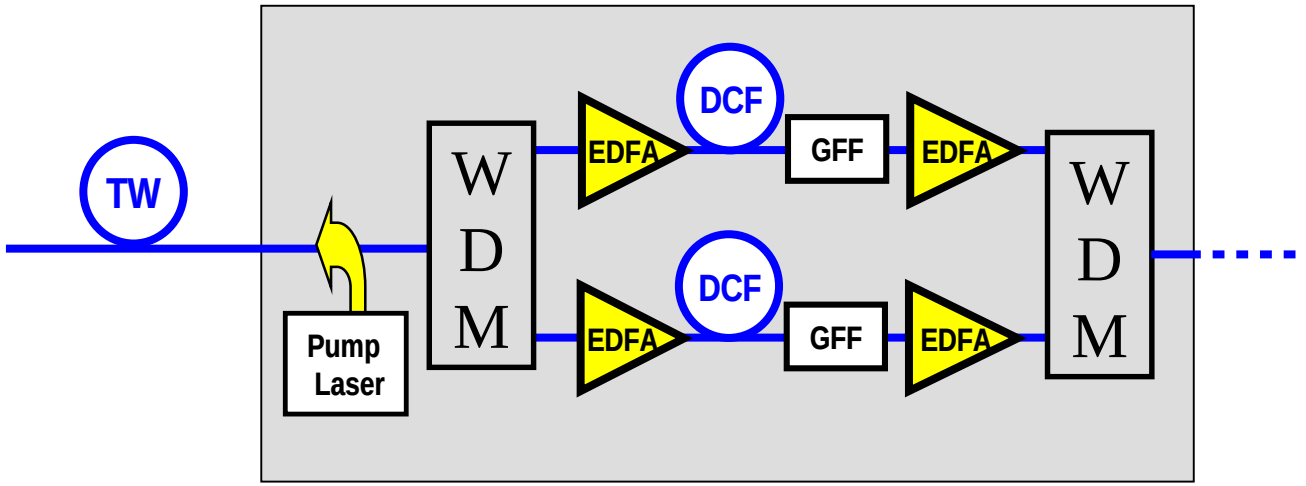
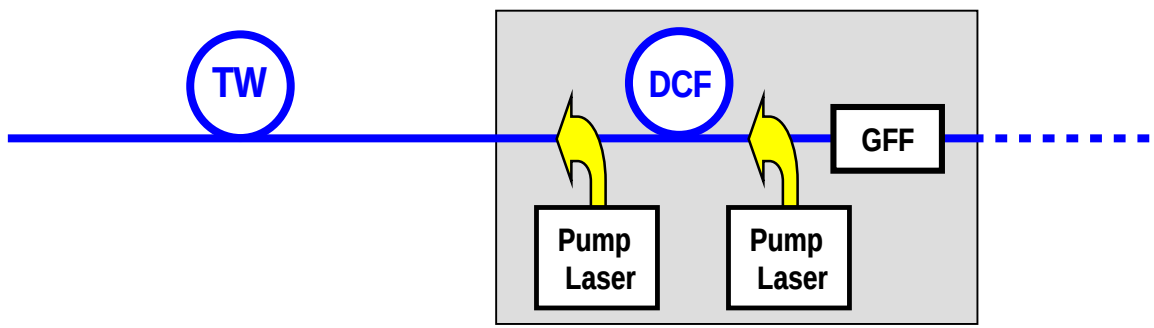
Advantage of All Raman C+L-band

Traditional split C+L-band



All Raman C+L-band



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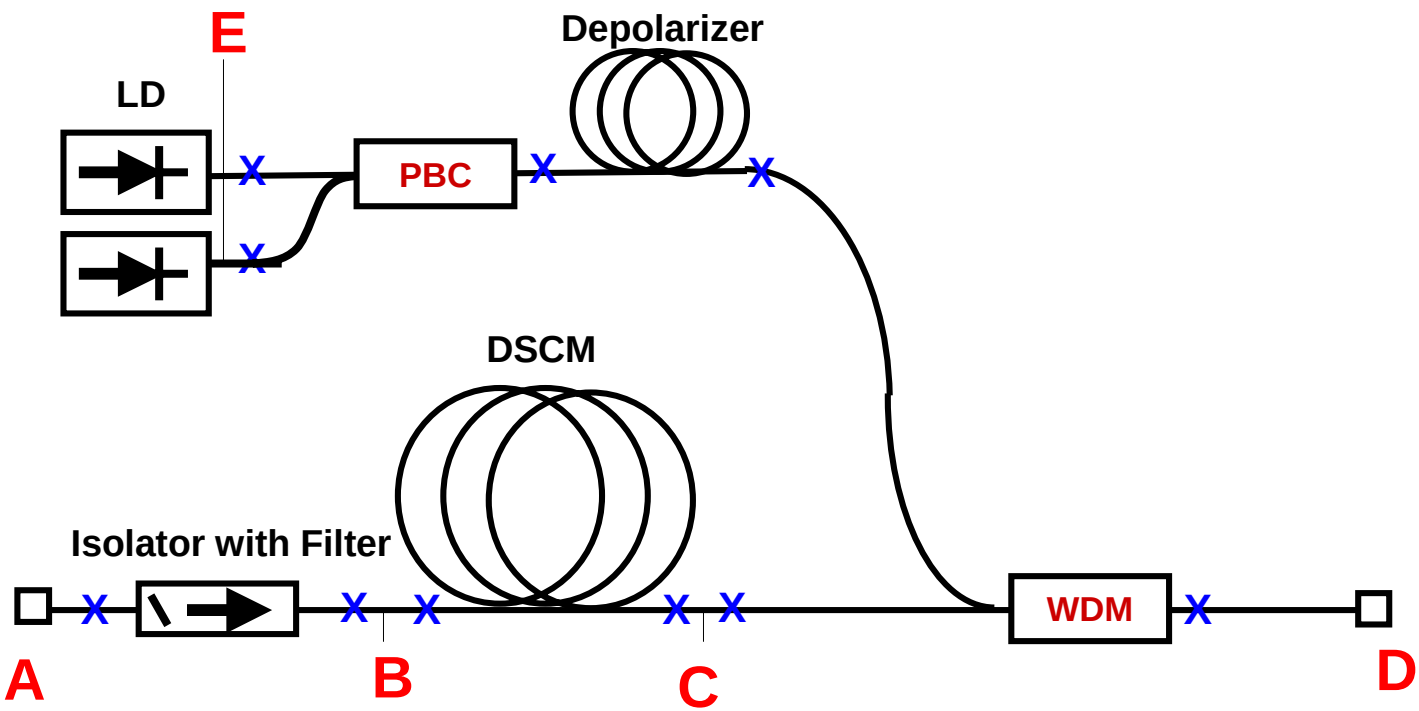
Schematic of OFS Raman pumped DSCM



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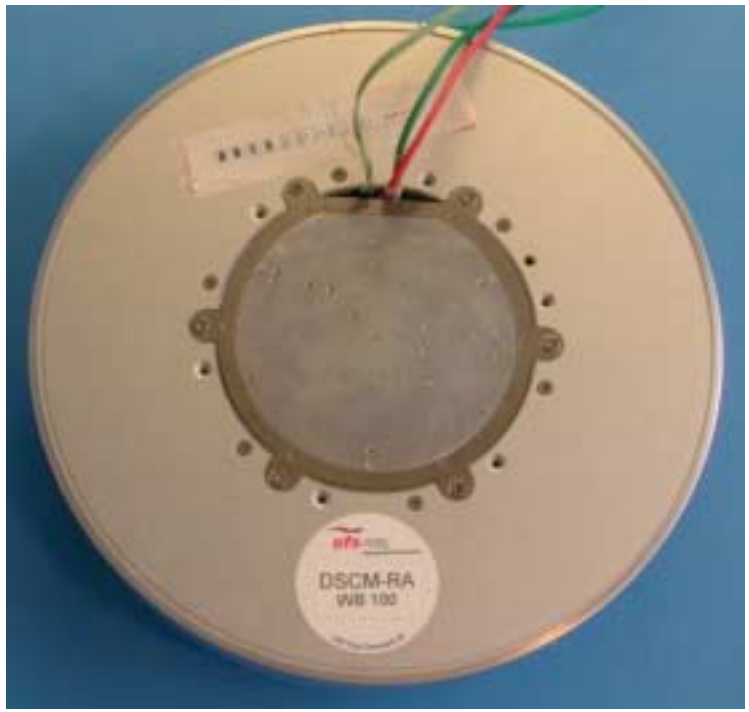
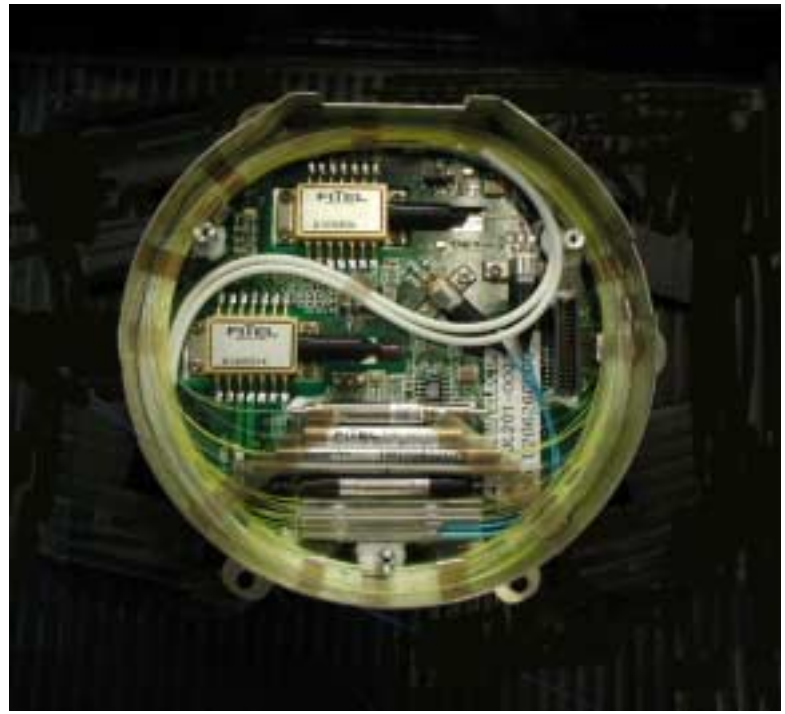
Raman pumped DSCM: DCRA





- First DSCM with integrated Raman pump module
- Raman gain counteracts the insertion loss of DSCM, resulting in a module with no insertion loss

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Raman measurements

Fiber Raman characterization

Parameters having influence on Raman gain

- Raman gain coefficient, C_R
- Effective area, A_{eff}
- Fiber loss, α
- Backscattering coefficient, κ
- Nonlinear coefficient, n_2/A_{eff}
- Dispersion coefficent, D
  - Through length of fiber used in DCM

Used to simulate gain, NF, MPI and SPM

Production statistics for DCF's and transmission fibers

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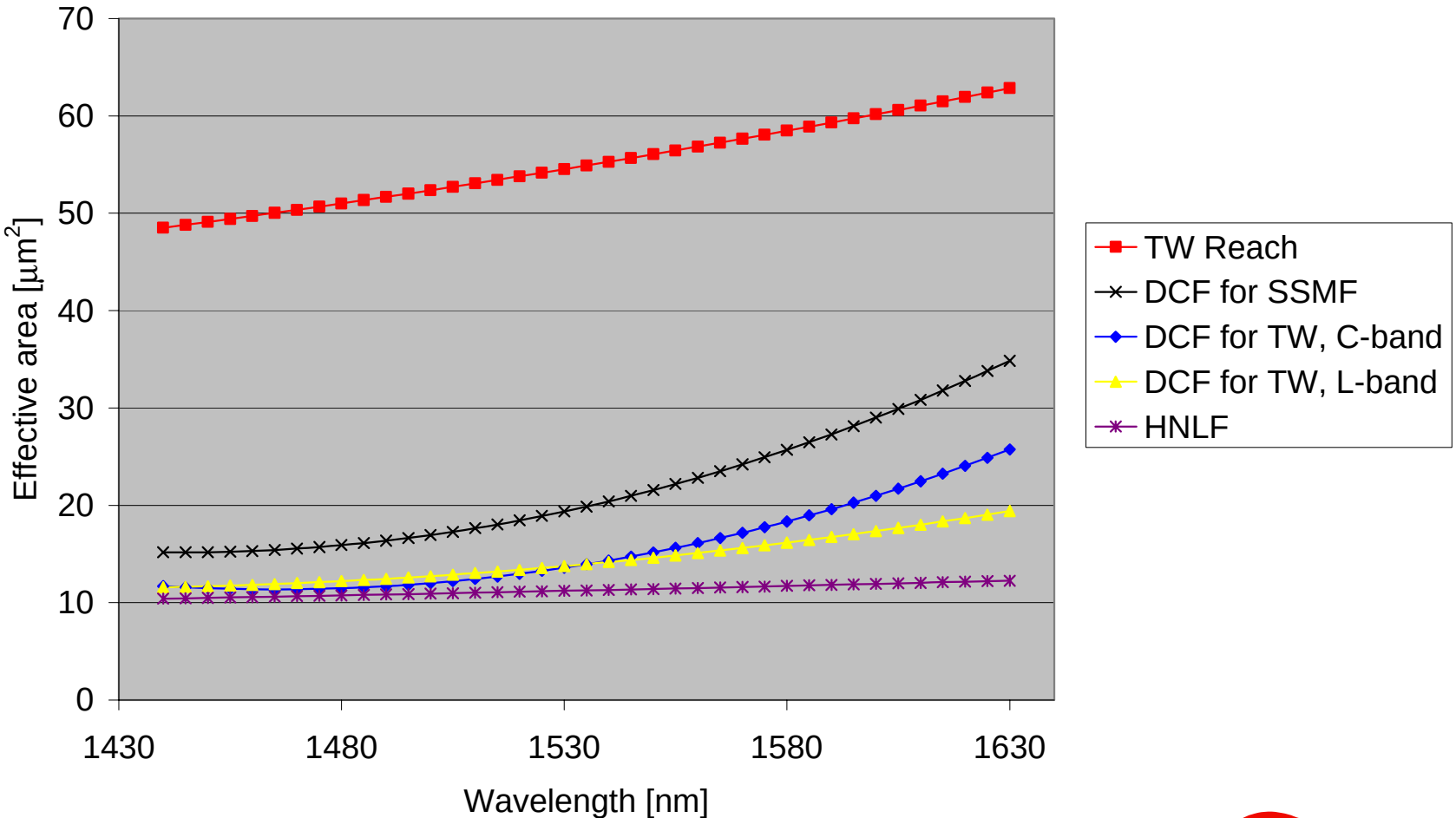
Effective Area



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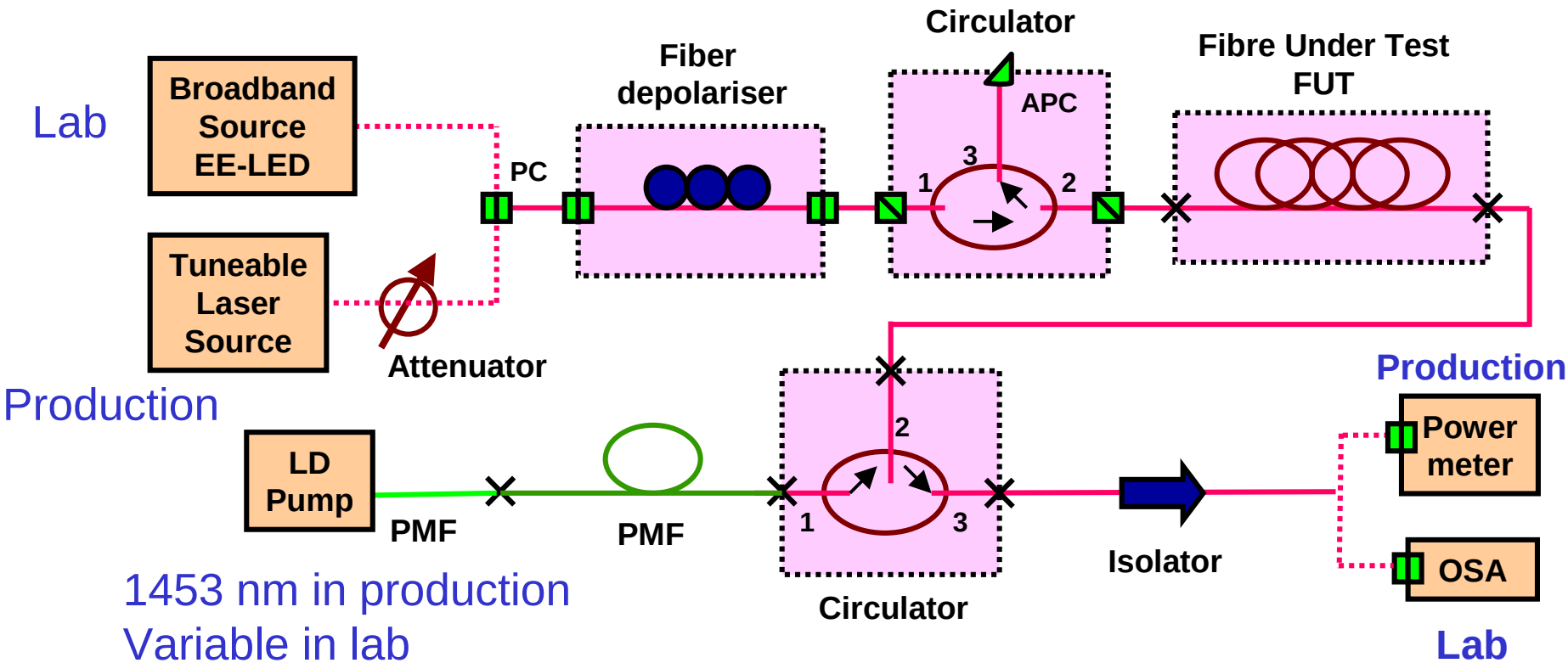
Raman gain coeff. measurement setup



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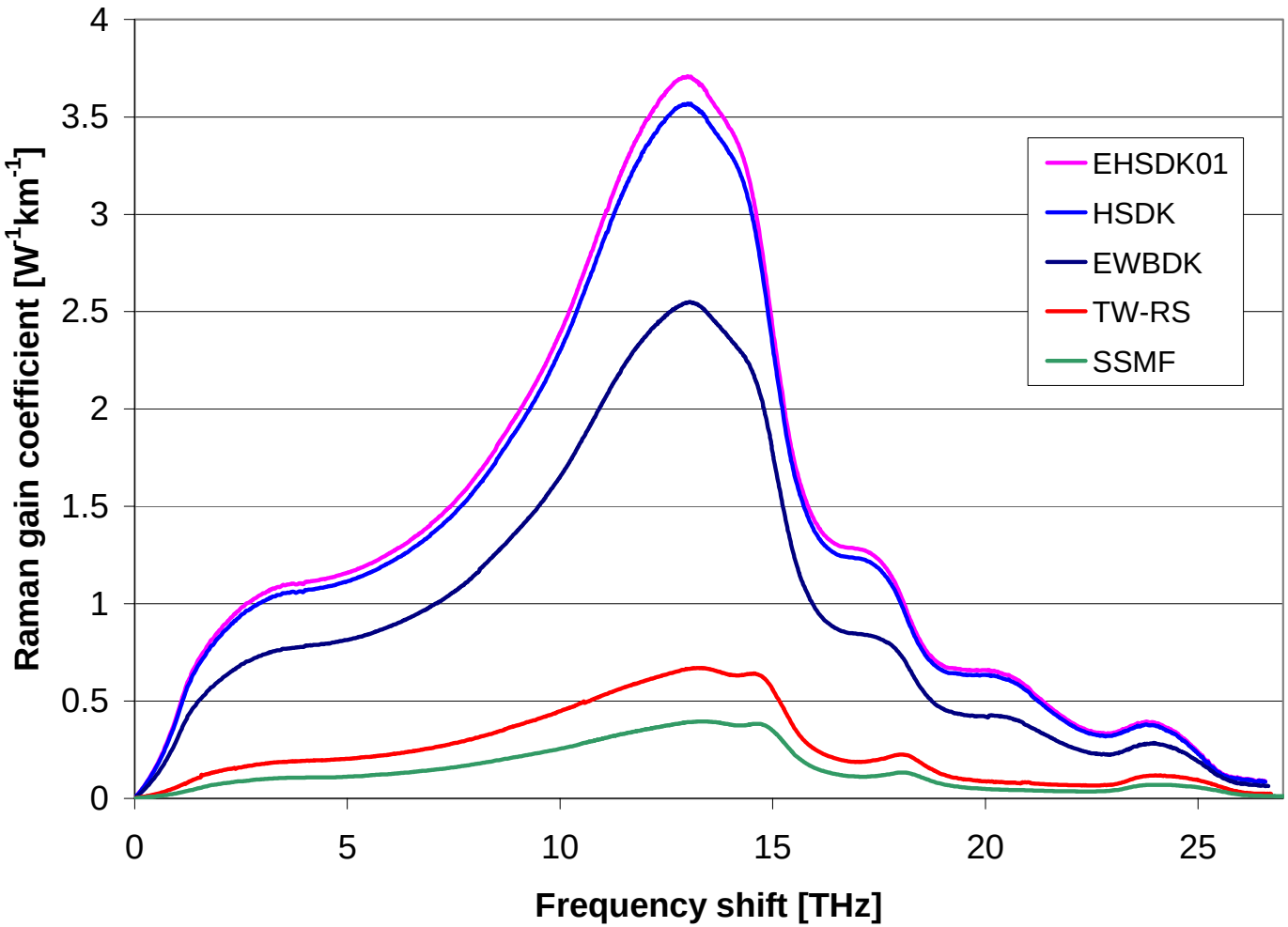
Typical Raman gain coefficient data
Pump @1453 nm



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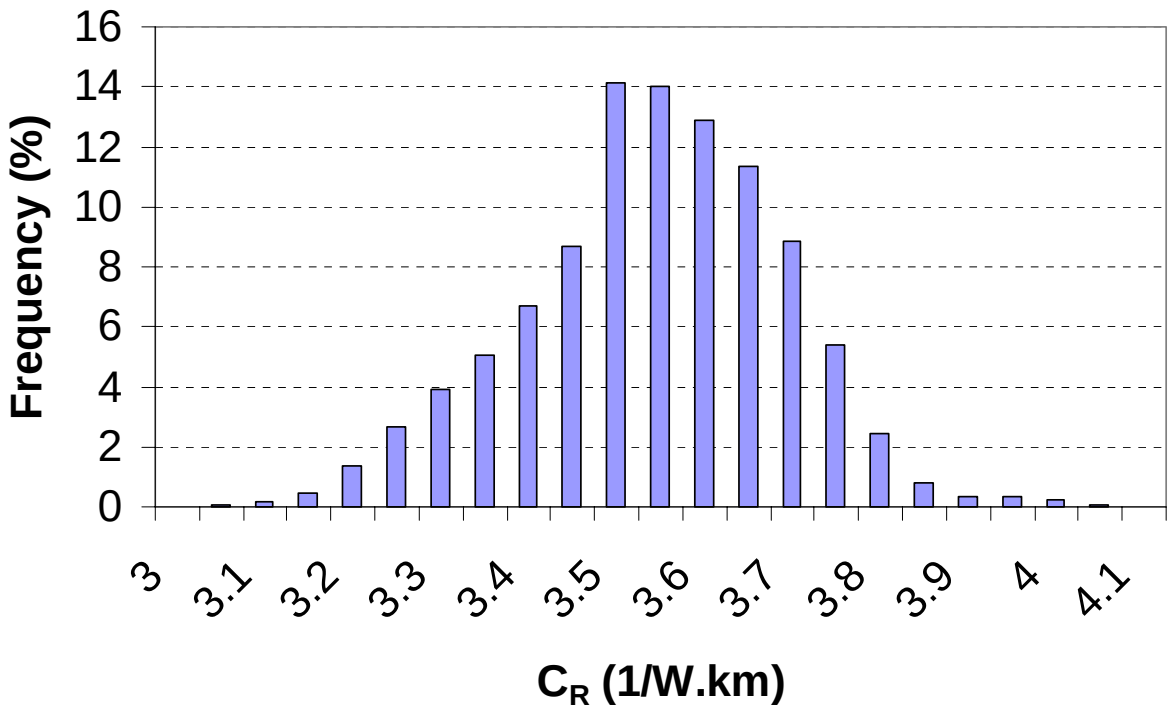
DCF Raman gain coefficient
EHS for TWRS compensation: C_R production statistics



$C_{R,\ Avg}$: 3.51 /km.W
$C_{R,\ stdev}$: 4.2%

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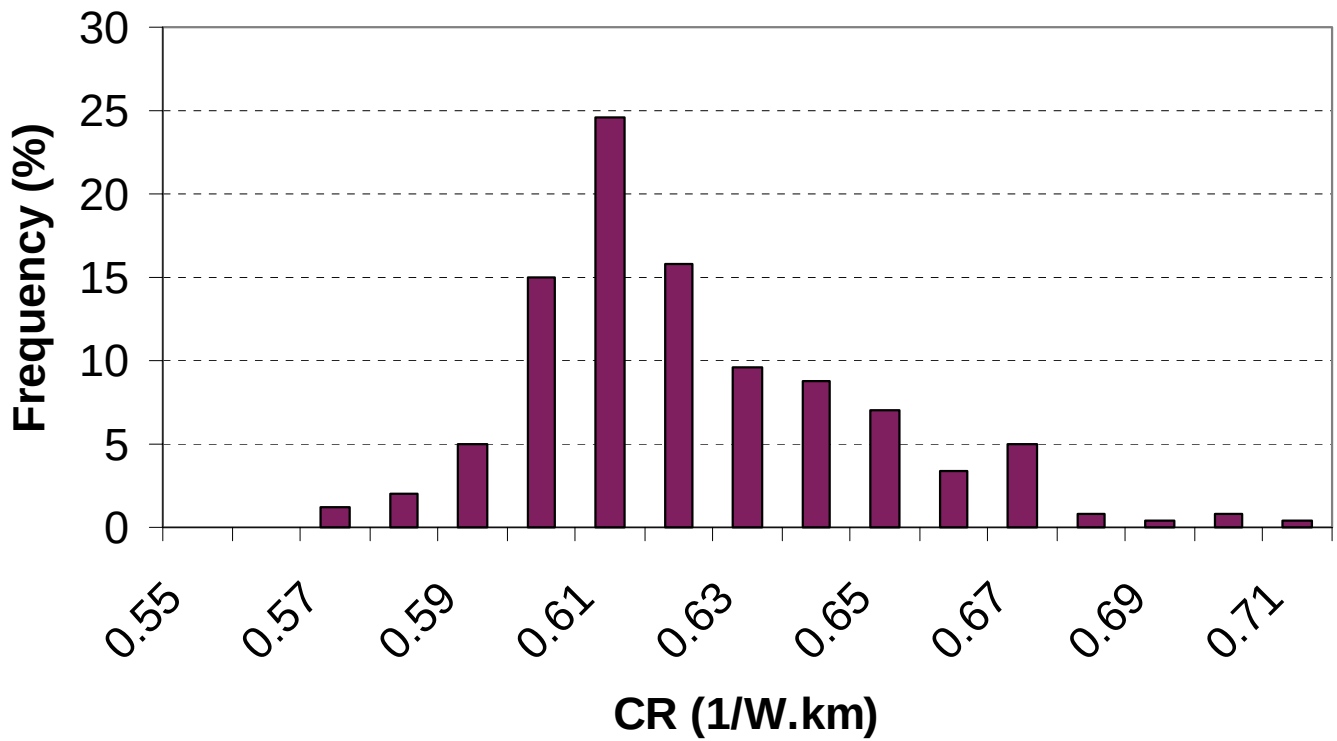
For comparison: TW Reach



$C_{R,\ Avg}$: 0.62 /km.W
$C_{R,\ stdev}$: 4.0%

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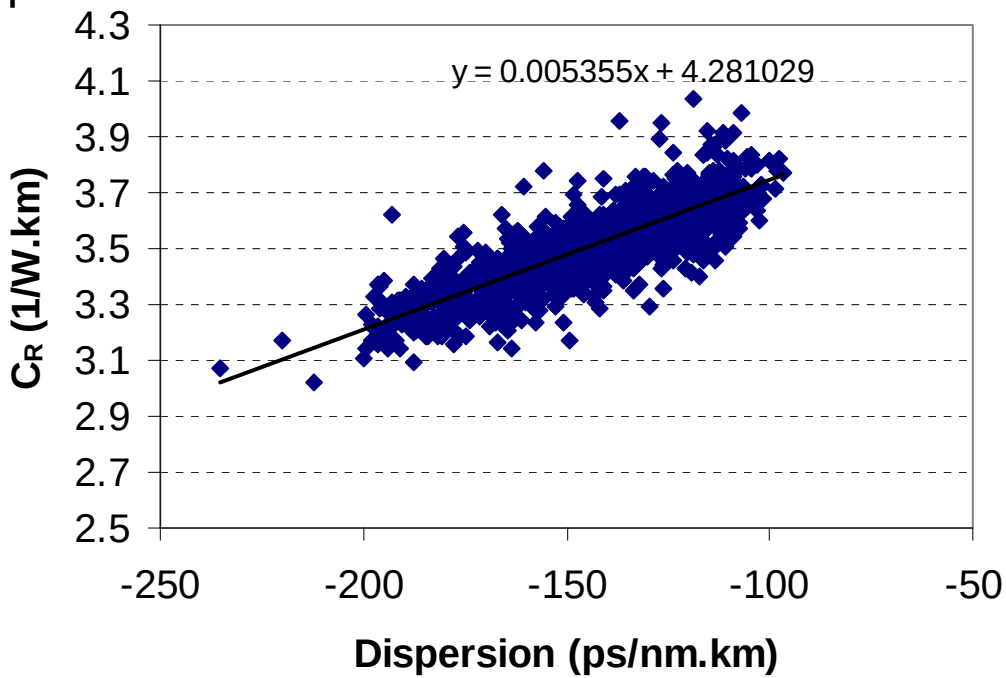
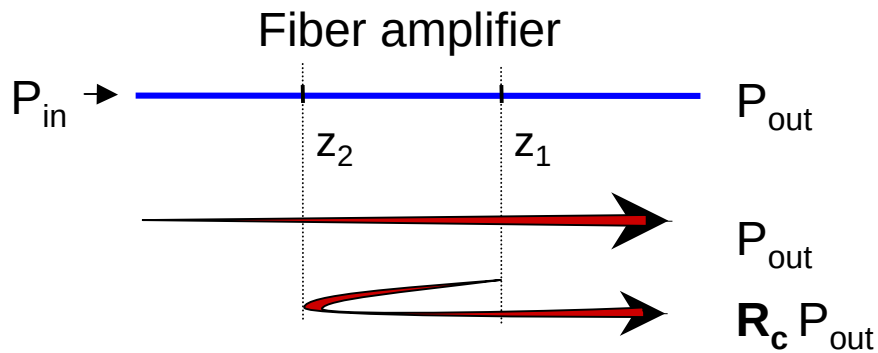
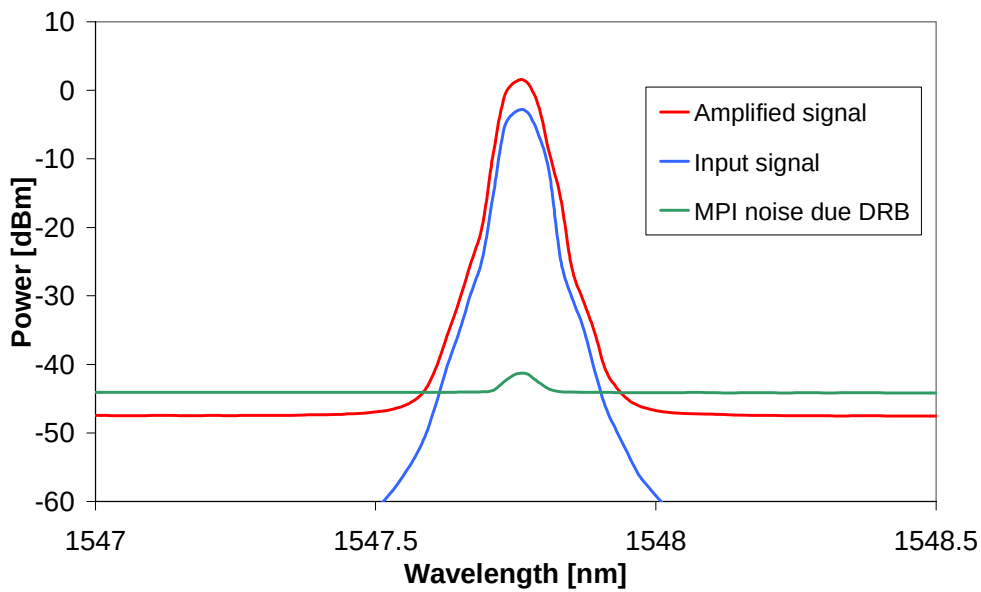
Fiber variations and pump power requirements

- For DCF's, Raman gain efficiency, C_R, varies (as it does for transmission fiber)
- In addition, the length of DCF in a module varies (with the dispersion coefficient)
- Both lead to variations in pump power requirements



Raman amplifier evaluation





S.A.E. Lewis, S.V. Chernikov and J.R. Raylor: *"Characterization of Double Rayleigh Scatter Noise in Raman Amplifiers"*, IEEE Phot. Tech. Lett., vol. 12, pp. 528-530, 2000

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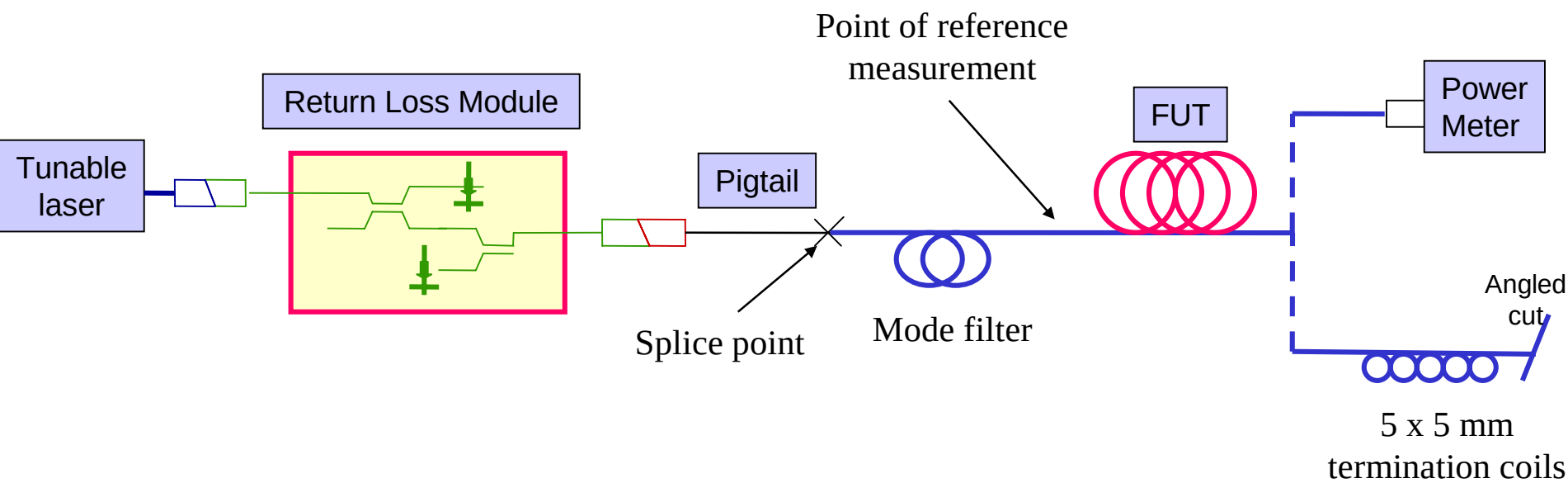
Measuring Rayleigh Backscattering



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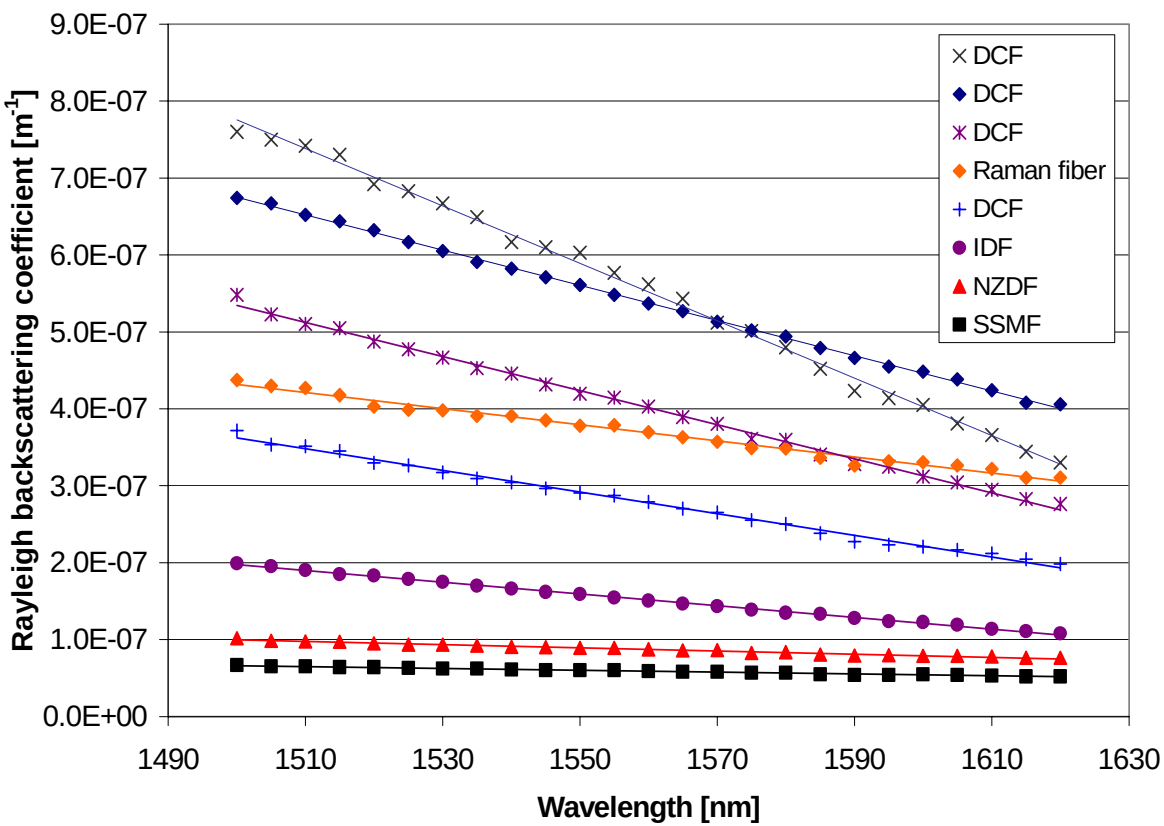
Rayleigh backscattering coefficient, κ

Rayleigh backscattering leads to MPI
κ for DCF up to 10 times higher than transmission fibers
But DCF shorter

$$\frac{dP_{RBS}(\lambda,z)}{dz} = \alpha_{RS}(\lambda)B(\lambda,z)P_{Signal}(\lambda,z) = \kappa(\lambda,z)P_{Signal}(\lambda,z)$$



$B(\lambda,z)$ is the capture fraction

$\kappa = \alpha_{RS} B$ is the Rayleigh backscattering coefficient

$$\kappa \propto \frac{\alpha_{RS,SiO_2} + K_{Ge}\Delta n^{+} + K_{F}\Delta n^{-}}{\lambda^2 A_{eff}}$$

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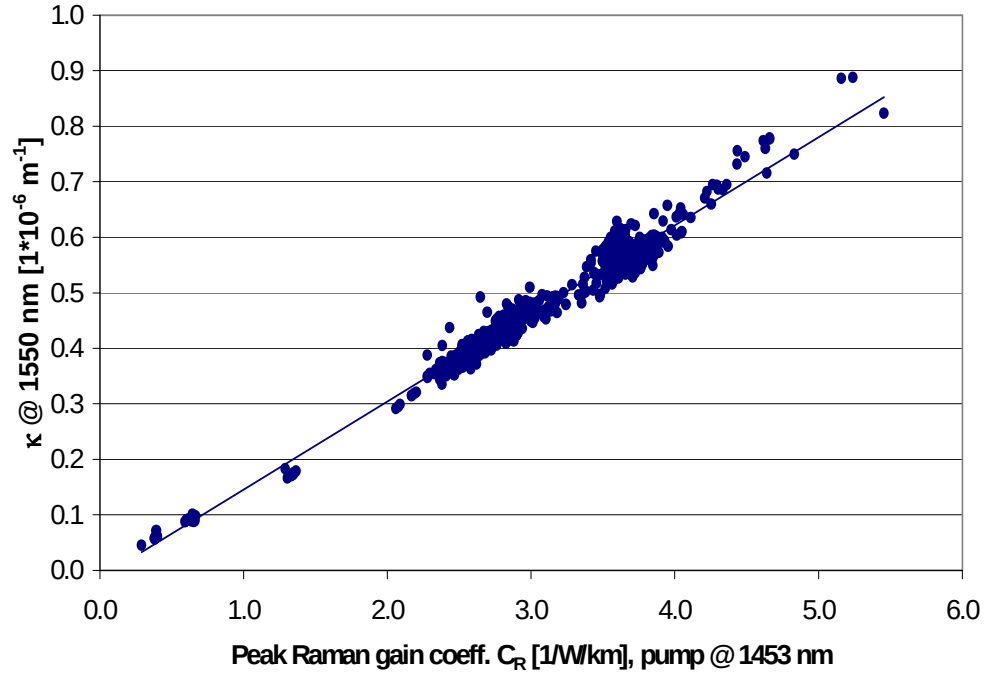
Kappa vs. $C_R = g_R / A_{eff}$



- **Distinct linear correlation between κ and C_R**

$$g_R \approx C_1 g_{SiO_2} + C_2 \Delta n^+ + C_3 \Delta n^-$$

$$\kappa \propto \frac{\alpha_{RS,SiO_2} + K_{Ge}\Delta n^+ + K_F \Delta n^-}{\lambda^2 A_{eff}}$$

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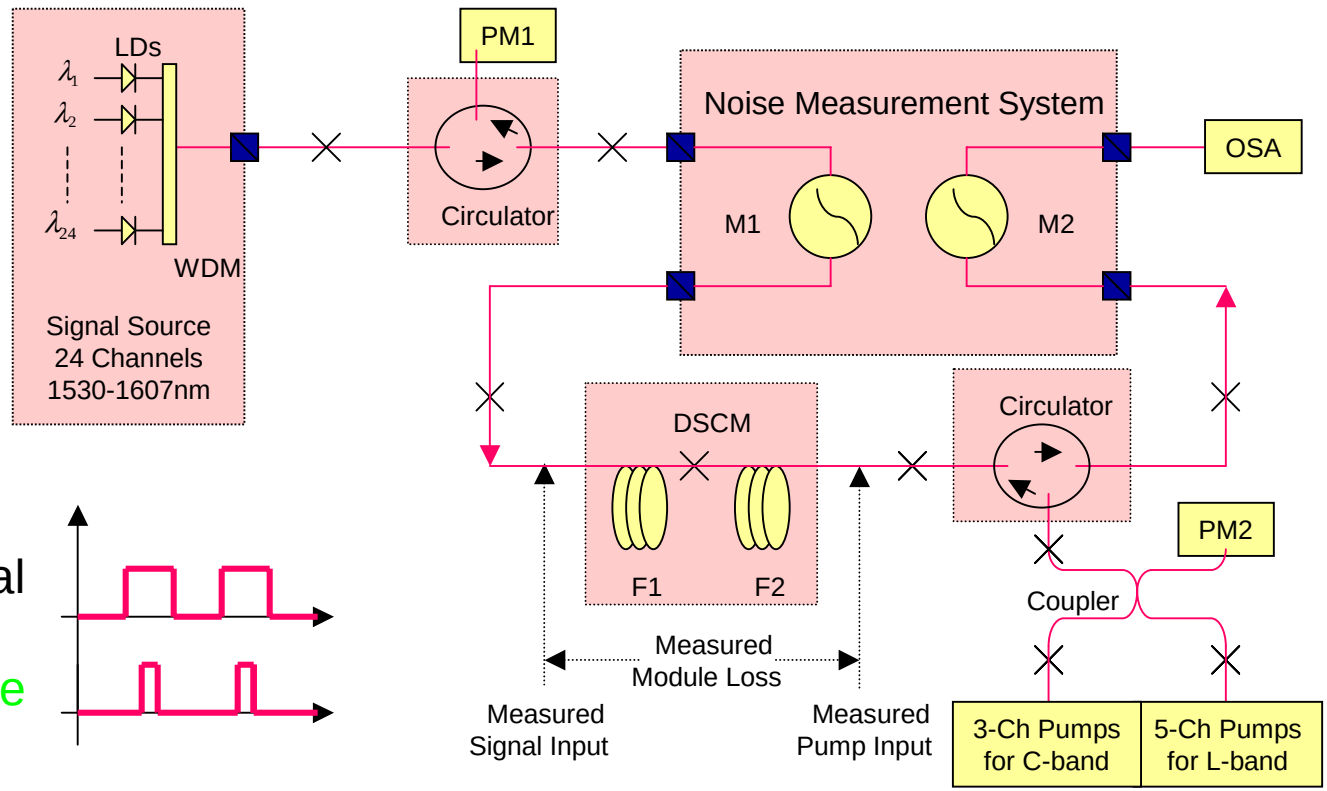
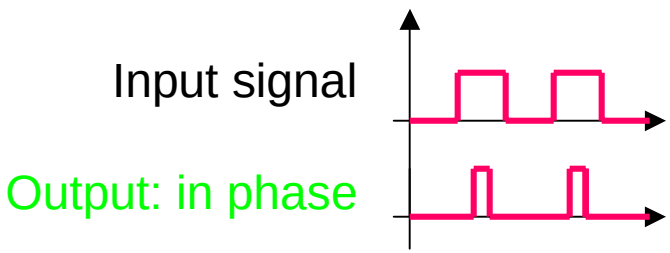
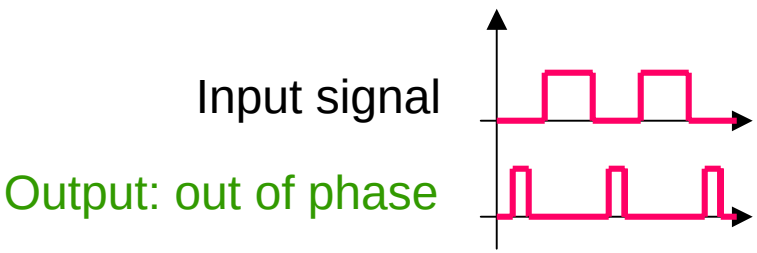
Setup for Raman amplification evaluation: Time domain extinction technique







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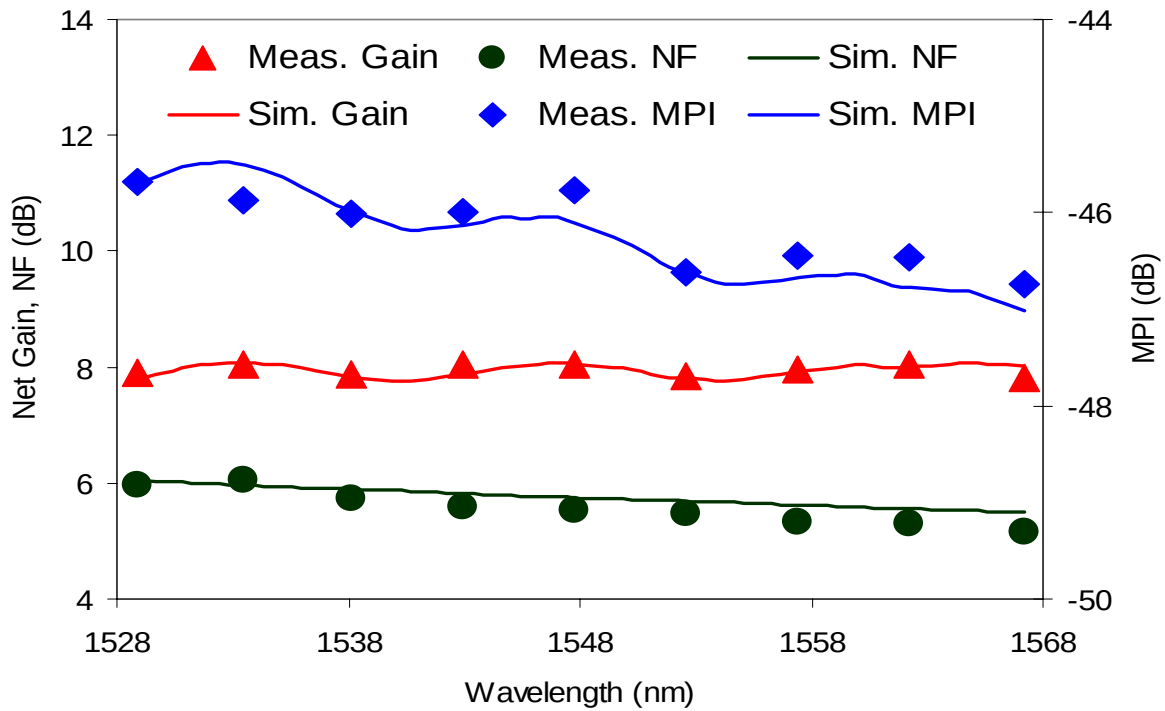
Predicting MPI in Raman amplifiers



Knowing κ, the effective area A_{eff} and the Raman gain coefficient C_R we can predict the gain, NF and MPI in Raman amplifiers

Y. Qian, C. G. Jørgensen, P. B. Gaarde, B. Pálsdóttir and B. Edvold, *"C-band discrete Raman amplification with simultaneous dispersion and dispersion-slope compensation for NZDF"*, Proceedings of OAA 2002

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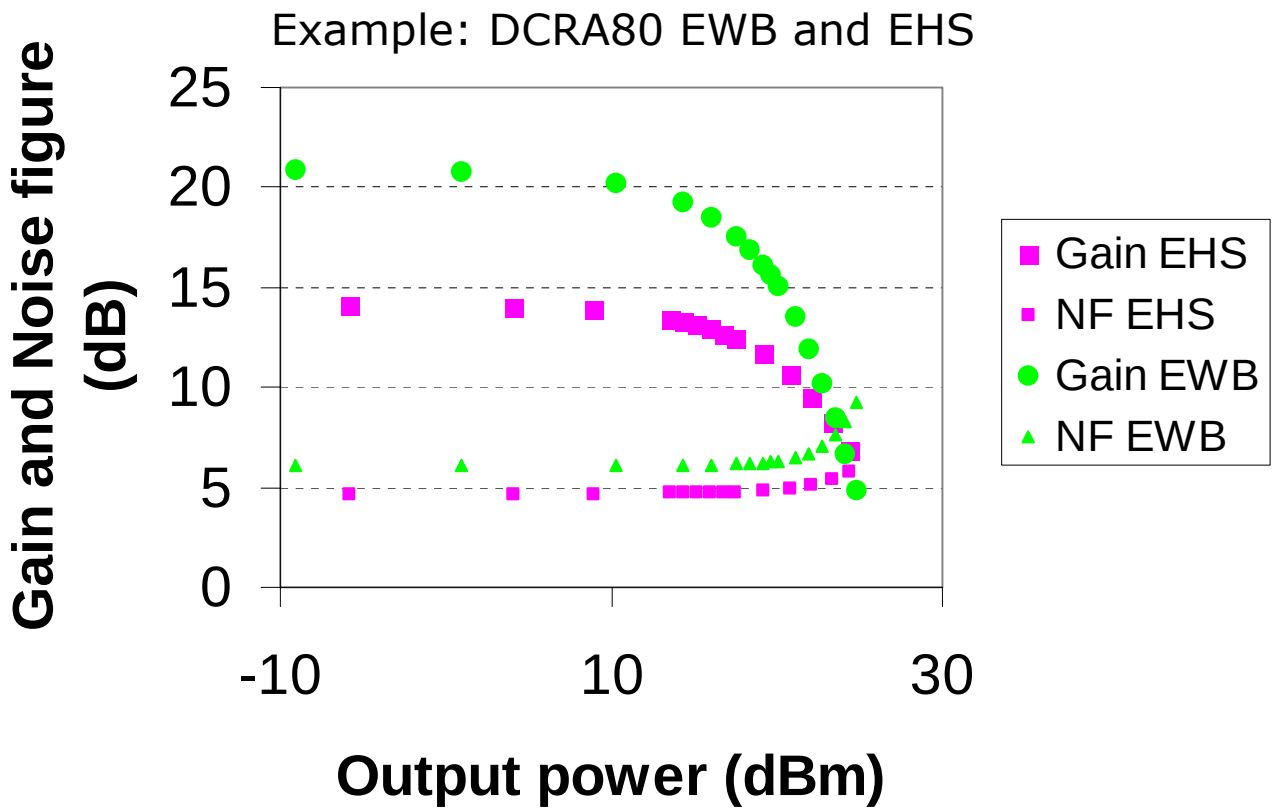
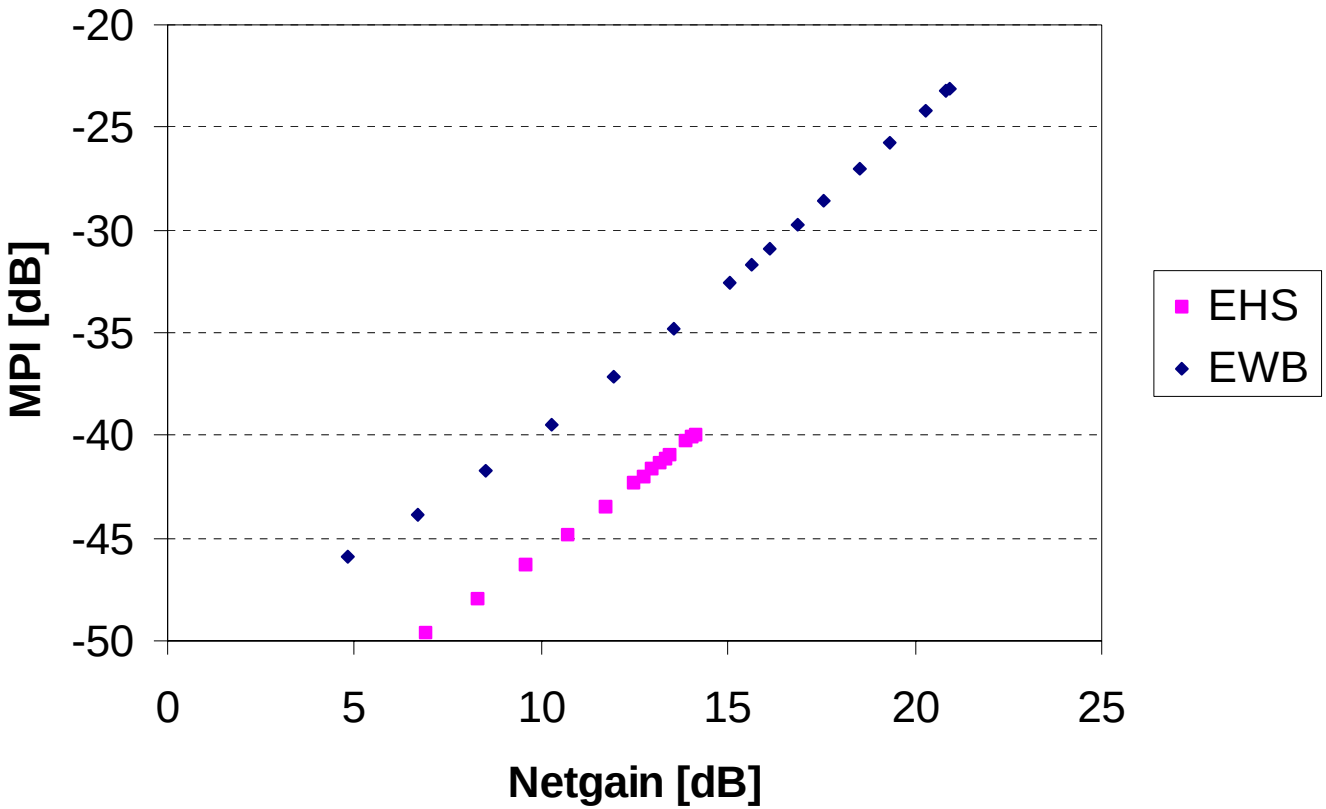
Difference between DCF's for SSMF and TW

Current DCF products optimized for dispersion compensation only:
DCRA for TW
- DCF too short for short links

DCRA for SSMF
- DCF too long



MPI in DCRA80 for SSMF and TW-RS



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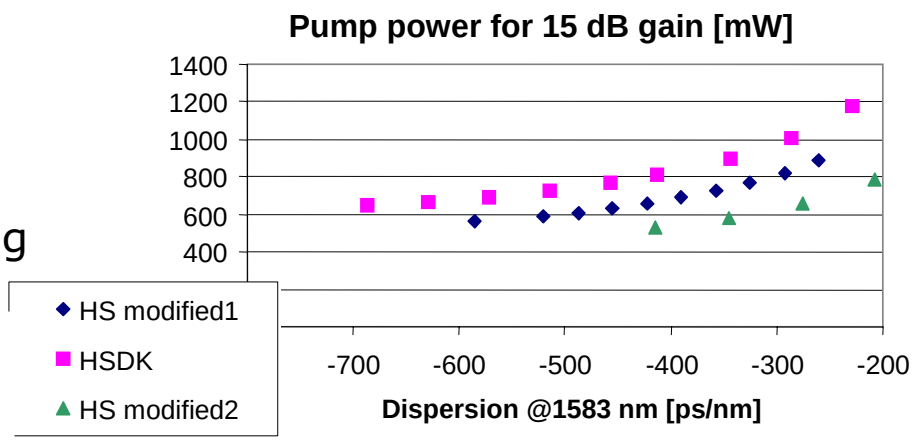
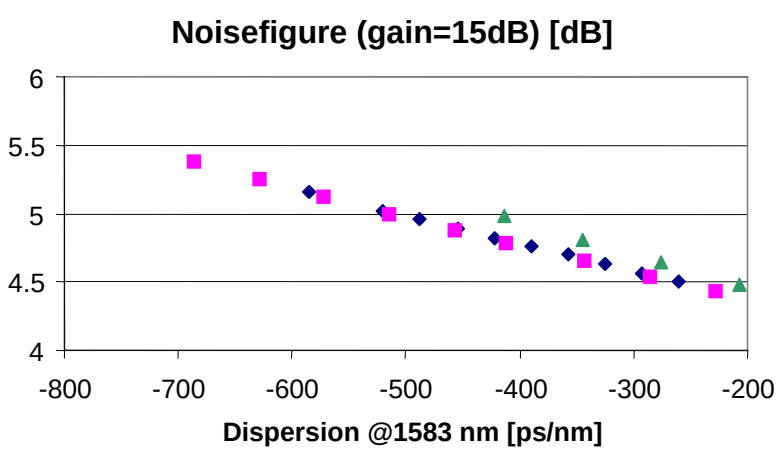
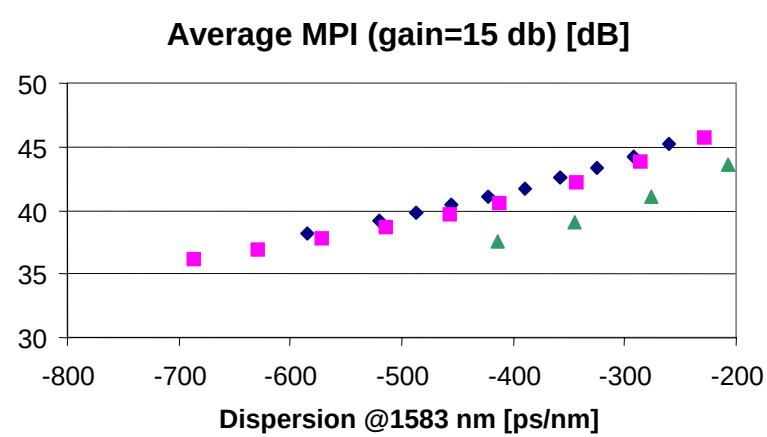
TW-DCRA: fibers optimized for both dispersion compensation and amplification

Fiber design parameters:

- Dispersion properties (slope)
- Gain efficiency
  - Raman gain coefficient
  - Loss at pump and signal
- Minimize MPI
  - Low Rayleigh backscattering
- Fiber length
  - Long to increase gain
  - Short to minimize MPI



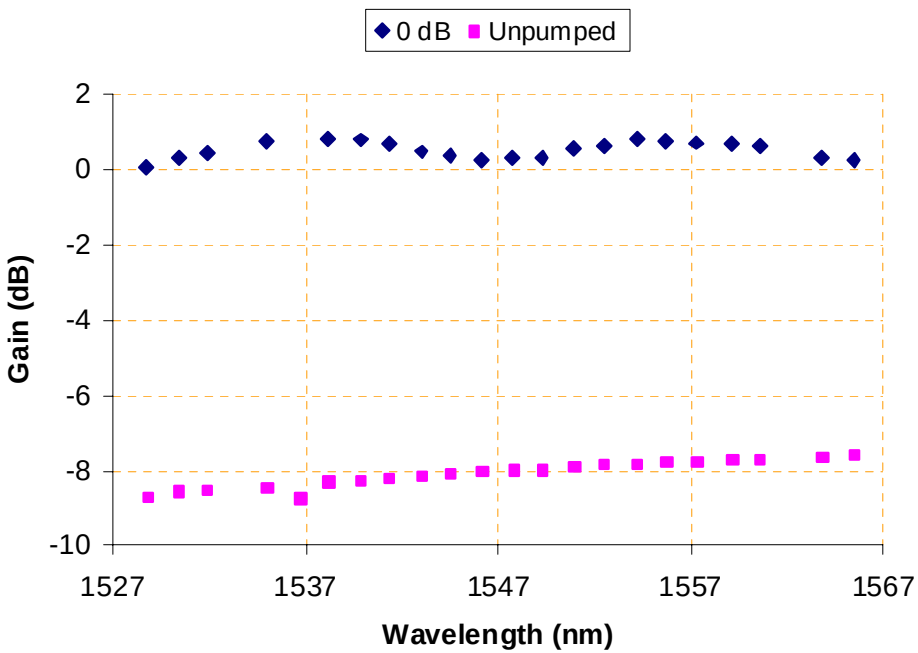


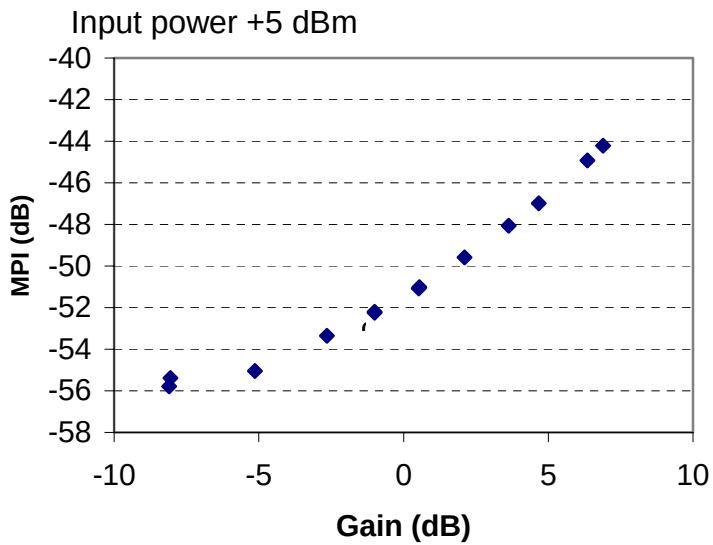


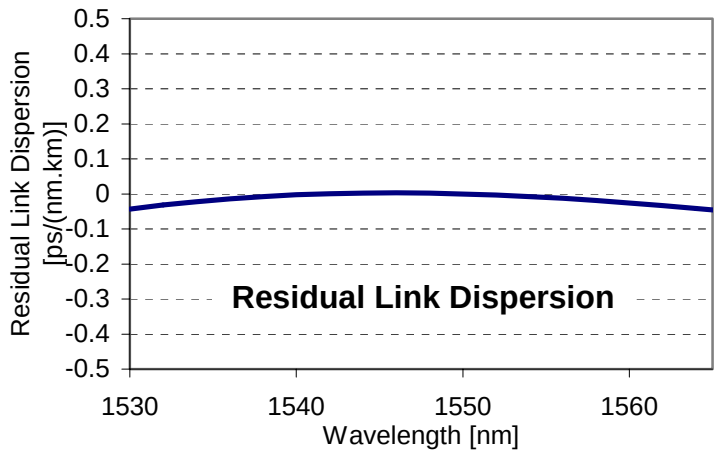
DCRA for 100 km SSMF
Input power 15 dBm

Example: DSCM for 100km of G.652 Fibre

- PDG < 0.15 dB
- Gain ripple ~ 0.75 dB
- MPI < -50 dB







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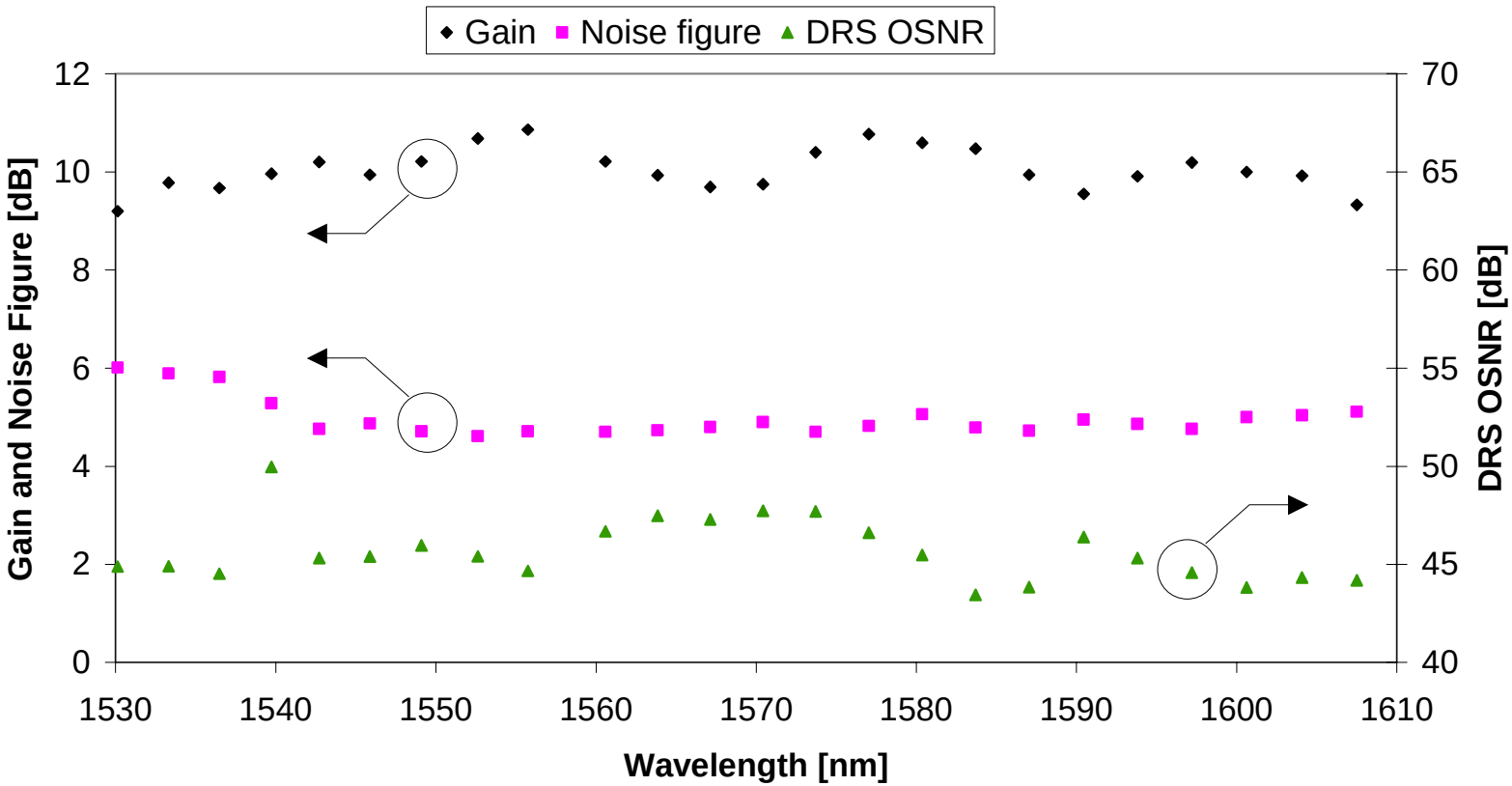
Measurement Results C+L-band Module Bi-Directional Pumping (100 km TW-Reach)

Pump wavelength [nm]	1428	1445	1467	1484	1491	1507	Total
Direction	co	co	counter	counter	counter	counter	
Pump power [mW]	360	360	86	0	138	98	1042



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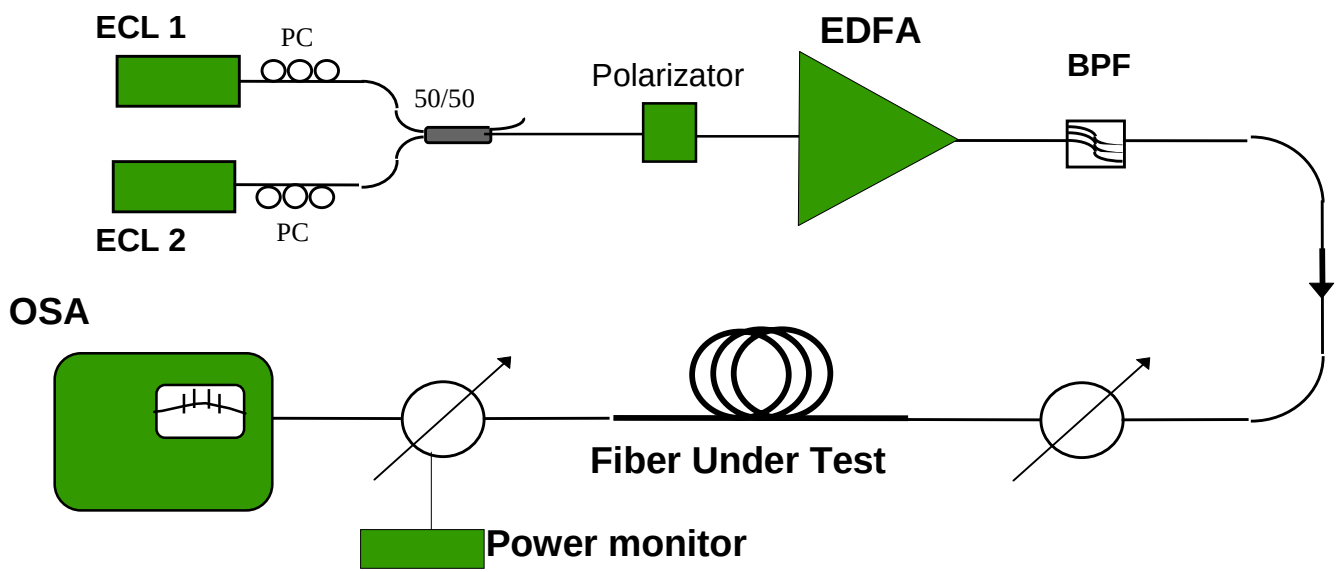
Nonlinear response: n_2 / A_{eff}

Dual frequency beat signal



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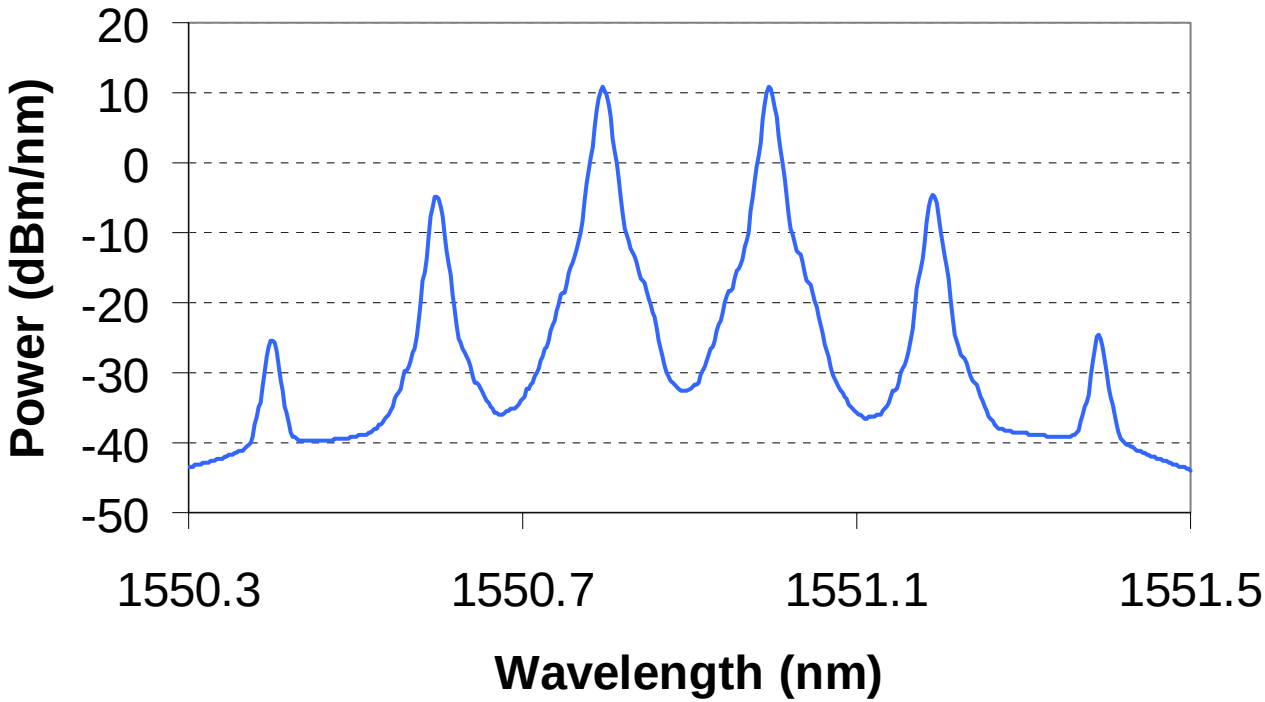
Nonlinear response: n_2 / A_{eff}

Nonlinear phase shift is determined from intensity of first order beat products relative to signal.



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Measurement Results n_2

Fiber type	n_2/A_{eff} $x10^{-9}$ W^{-1}	A_{eff} μm^2	n_2 $x10^{-20}$ m^2/W
SSMF	0.27	85	2.30
TW-RS	0.42	55.1	2.33
DCF	1.30	19.4	2.52
HNLF	2.50	12	3.0

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Highly non-linear fiber (HNLF)

”Standard” HNLF parameter values (1550 nm)

Loss
- 0.75 - 0.85 dB/km
- $L = 5$ km $\Rightarrow z_{eff} \approx 3.3$ km
- $L \rightarrow \infty \Rightarrow z_{eff} \rightarrow 5.4$ km

Effective area/MFD
- 11 – 12.5 μm2
- 3.8 - 3.94 μm

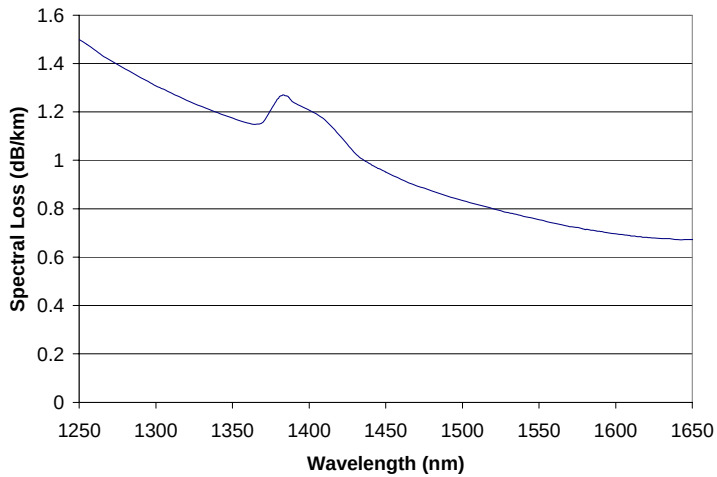
Cut-off
- 1140 - 1220 nm

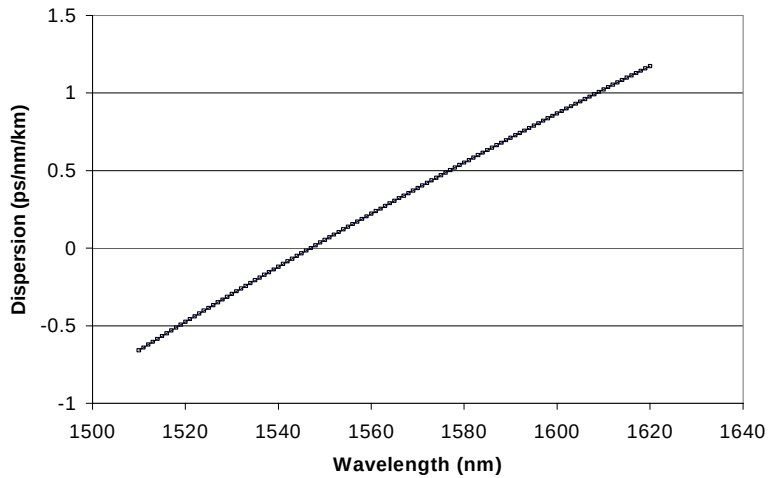
Non-linear coefficient
- $n_2 \approx 3.0 \times 10^{-20}$ m^2/W
- $\Rightarrow \gamma = 2\pi n_2/(A_{eff}\,\lambda)$
- $= 0.010 - 0.0105$ $W^{-1}\,m^{-1}$

Dispersion
- Selected

Dispersion slope*
- 0.017 - 0.019 $ps/nm^2/km$

PMD
- < 0.2 $ps/\sqrt{km}$





* Zero dispersion close to 1550 nm

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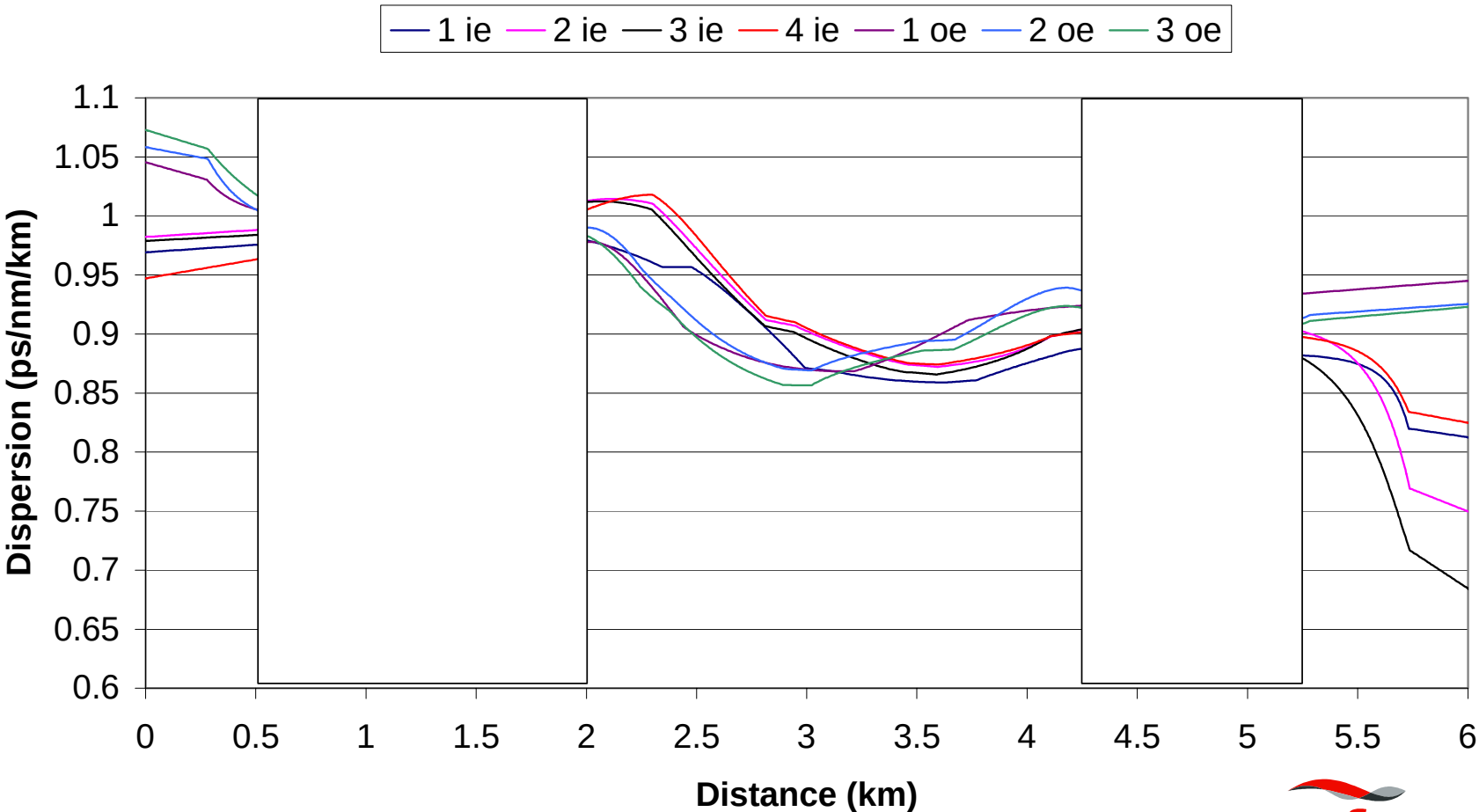
”Standard”: Dispersion uniformity (2)



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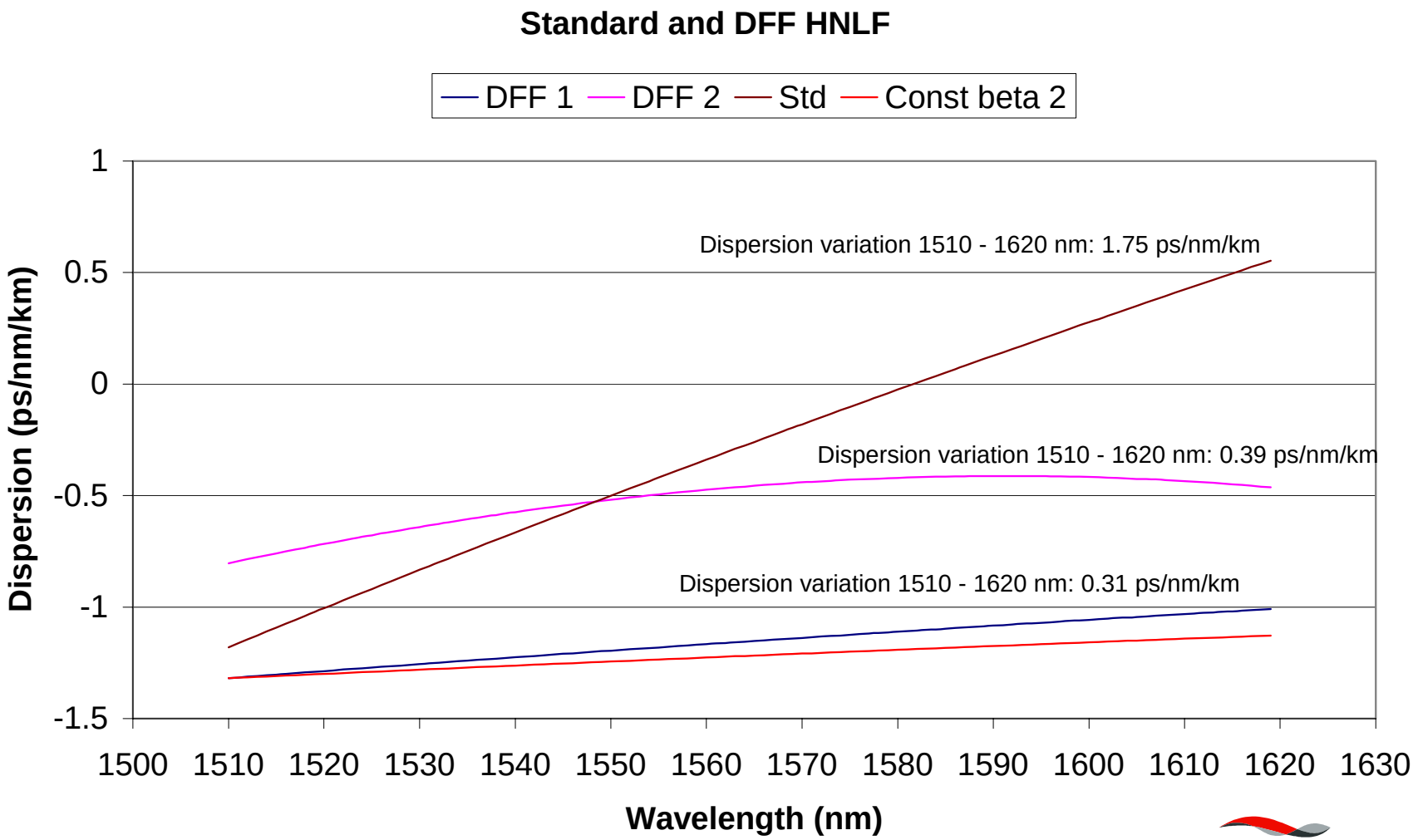
Development: Dispersion flattened HNLF (2)



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Optical regenerator

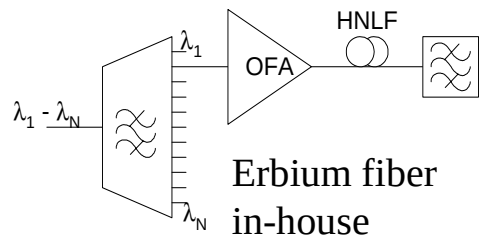
Highly non-linear fiber

* $\gamma \approx 10\ W^{-1}km^{-1}$
* $A_{eff} \approx 12\ \mu m^2$

All-optical 2R regenerator

* P: 100 - 200 mW
* L_{HNLF} : 2 - 4 km

OFA control
PCB developed

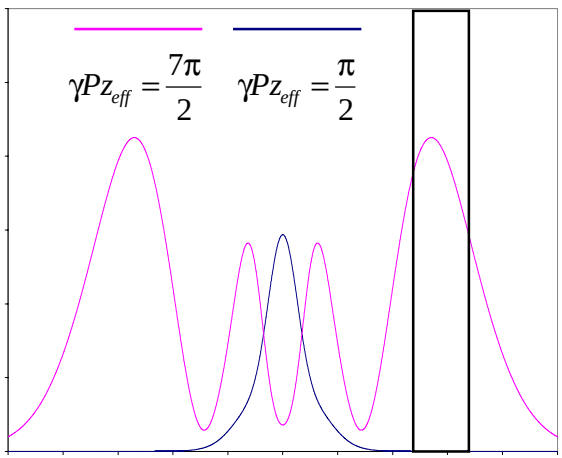
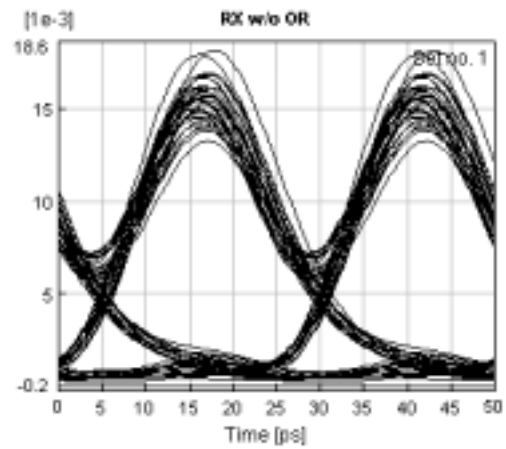
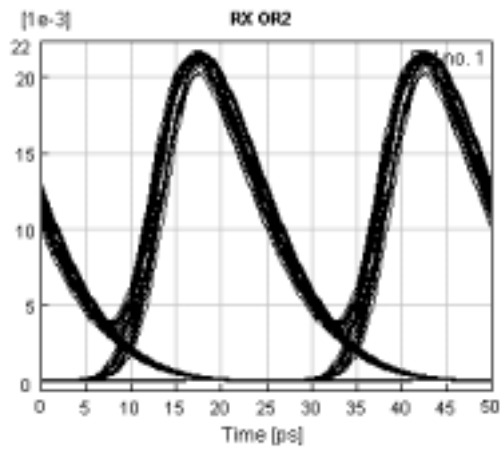


Erbium fiber
in-house

VPI simulation tool available
System simulation

* RX OR
* In-line OR

Example of eye opening improvement by RX-OR

* 40 Gb/s
* Two-stage RX-OR

Pulse spectrum HNLF output