SubOptic2013 from ocean to cloud

MASTERCLASS TUTORIAL 9

Submarine Optical Fibre and Cable: Foundation of Undersea Communication Networks

Moderator: **Gary Waterworth (Alcatel-Lucent)**

Presenters: **Sergey Ten (Corning Incorporated)**

Florence Palacios (Alcatel-Lucent)

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Presenter Profile

Sergey Ten was born in Russia and received his MS from Moscow State University and Ph.D. in Physics from the University of Arizona. He joined Corning Inc. in 1997 concentrating on the physics of light propagation in optical fibers. Sergey worked for Tyco Submarine Systems Ltd. in 2000-2001 and in 2001, he re-joined Corning Inc. as the manager of the transmission test bed group. He has authored 50 journal and conference articles and 11 patents in the field of optical communications. Currently, he is concentrating his efforts on the development of new fibers for telecom and non-telecom applications.

- Name: Sergey Ten
- Title: Manager, New Business and Technology Development
- Email: TenS@corning.com

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Agenda

1. INTRODUCTION: OPTICAL FIBER AND EVOLUTION OF ITS ATTRIBUTES DRIVEN BY PROGRESS IN SUBMARINE TRANSMISSION SYSTEMS
2. TRANSITION FROM DISPERSION MANAGED OPTICAL FIBER SOLUTIONS FOR 10 GB/S SYSTEMS TO SINGLE FIBER SOLUTIONS FOR COHERENT 100 GB/S SYSTEMS
3. ADVANCED ULTRA LOW LOSS AND LARGE EFFECTIVE AREA FIBER DESIGNS AND THEIR ADVANTAGES FOR 100 GB/S COHERENT SYSTEMS

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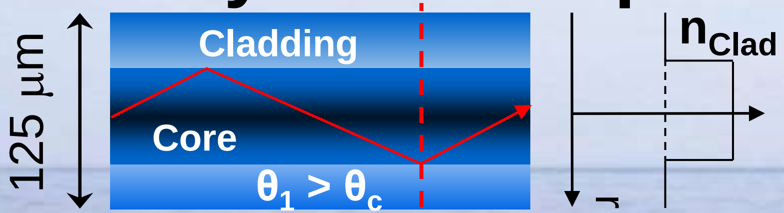
Optical fiber: principle of operation and the history of development



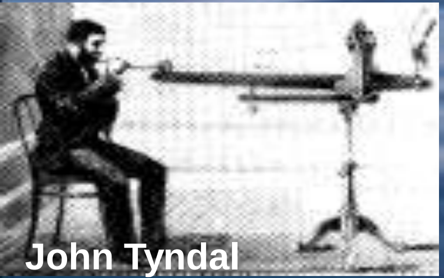
$n_{Core} > n_{Clad}$

1854 — John Tyndal: total internal reflection

1966 — C. Kao: prediction of 20 dB/km loss for silica fiber. Nobel Price in 2009

1972 — Corning demonstrates optical fiber with <17 dB/km attenuation

1988 — First transatlantic deployment of optical fiber (TAT-8)



John Tyndal

Charles Kao

P. Schultz, D. Keck, R. Maurer

http://www.corp.att.com/history/milestone_1988.html

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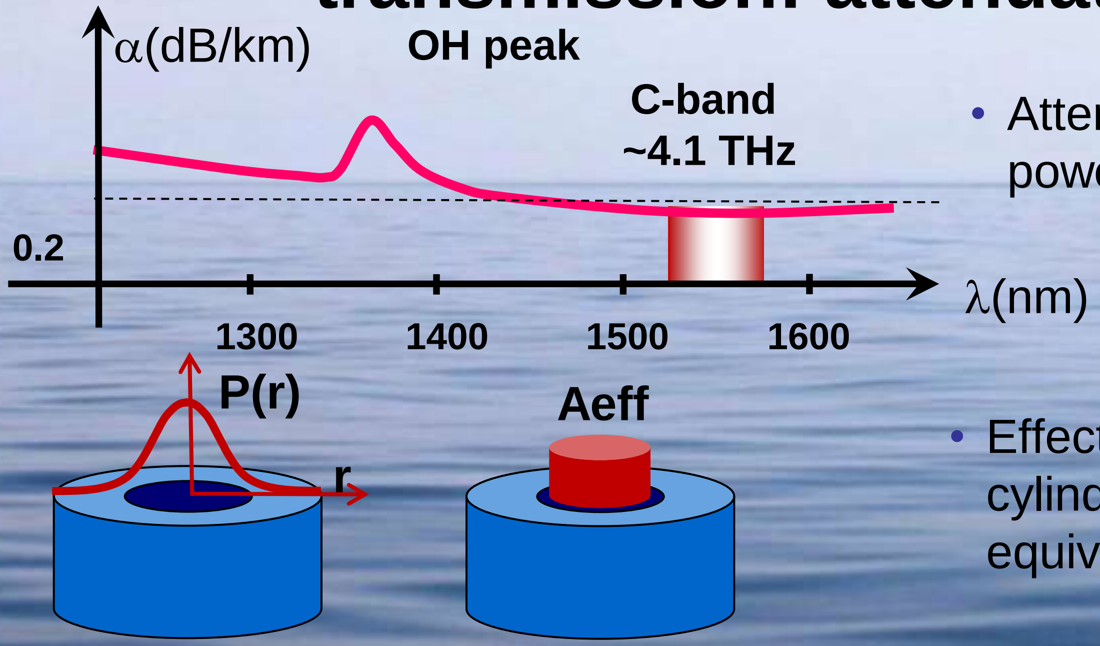
Optical fiber parameters critical for optical transmission: attenuation and Aeff



- Attenuation is reduction of optical power decay with distance
- Effective area Aeff is the area of a cylindrical beam of light carrying power equivalent to the power of optical mode

Both attenuation and Aeff are critical to achieving higher optical signal to noise ratio (OSNR)

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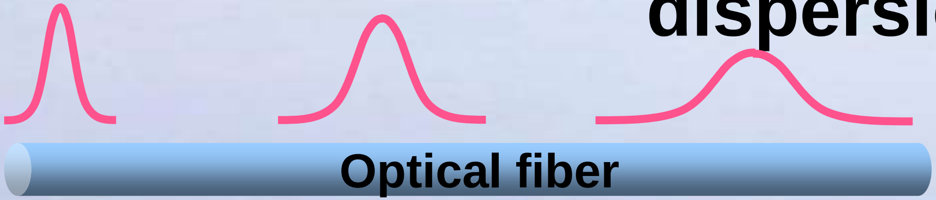
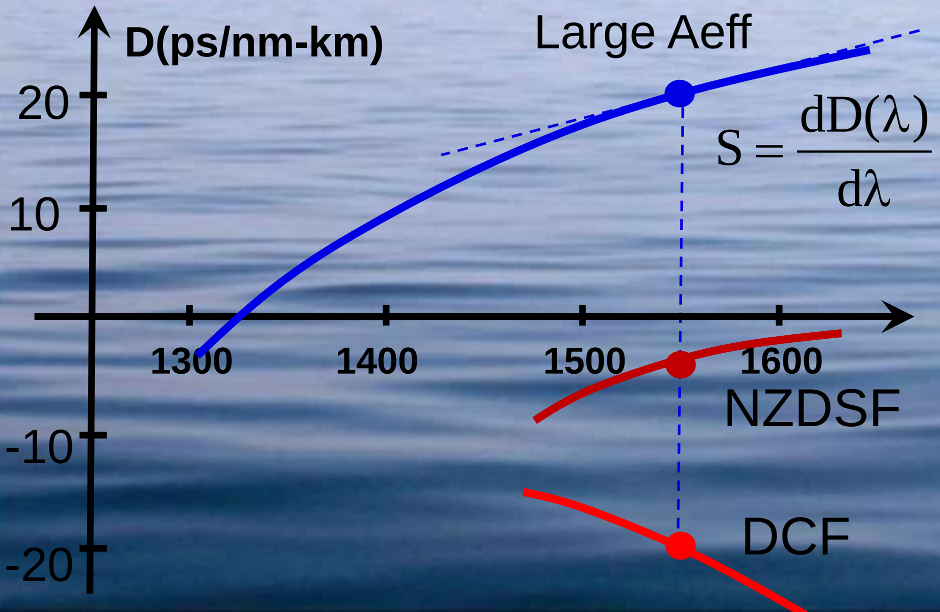
Optical fiber parameters: dispersion and dispersion slope



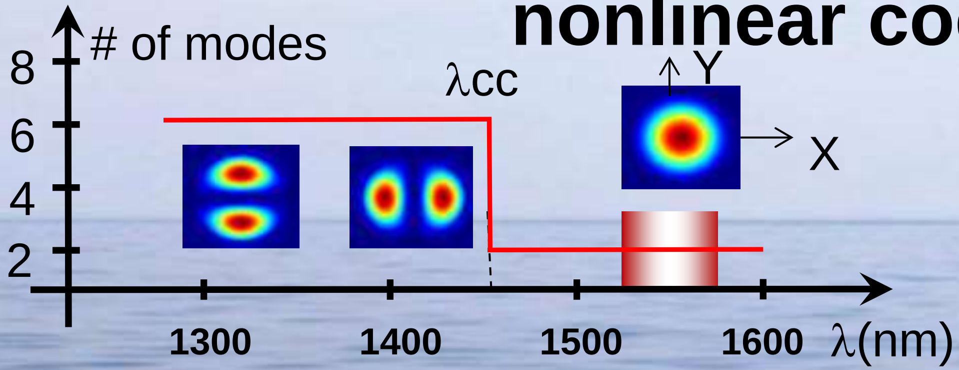


- Dispersion coefficient shows how fast optical pulse broadens in optical fiber
- At 10 Gb/s dispersion must be compensated especially at trans-oceanic distances!
- Dispersion slope shows how fast dispersion changes with wavelength

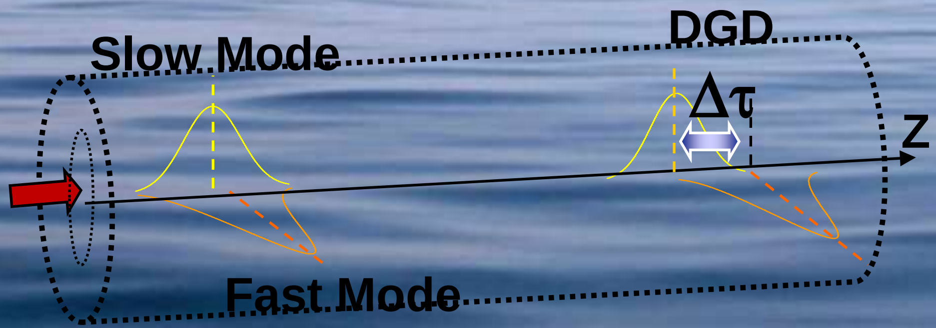
NZDSF – non-zero dispersion shifted fiber

DCF - Dispersion compensating fibers

Optical fiber parameters: cutoff, PMD and nonlinear coefficient n_2



- Below cable cutoff wavelength optical fiber supports several modes
- All submarine system operate with single mode fiber i.e. $\lambda_{cc} < \lambda_{signal}$



- Polarization Mode Dispersion (PMD) is caused by different group velocities of X and Y polarizations
- Nonlinear coefficient n_2 shows change of index of refractive with signal power

$$n(P)=n_0+n_2P/Aeff$$

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Transmission system innovation has been a driver for optical fiber

Transmission System

1988

First transatlantic optical cable (TAT-8)
- 1310 nm laser Tx
- 295 Mb/s single channel
- Regeneration at every span

1996

First optically amplified cable (TAT 12-13)
- 1550 nm laser Tx
- Erbium doped fiber amplifier (EDFA)
- 5 Gb/s single channel

~2000

First optically amplified WDM cable
- EDFA with >10 nm bandwidth in 1550 nm band
- Multiple NRZ or RZ 10 Gb/s channels

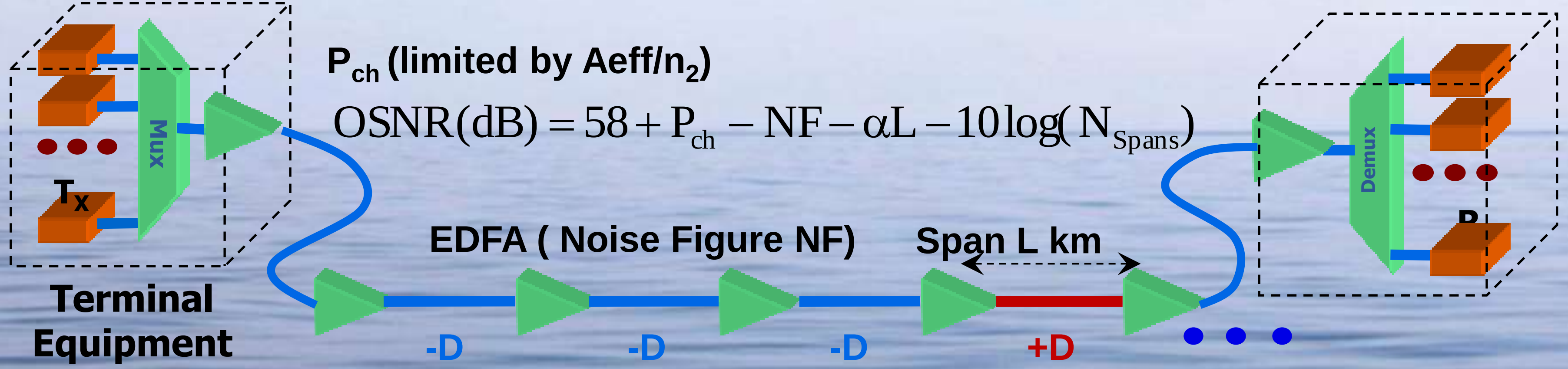
Optical Fiber

1988 Key Attributes:
- Single mode at 1310 nm
- Low attenuation and chromatic dispersion at 1310 nm
- High proof test

1996 Key Attributes:
- Low attenuation at 1550 nm
- Zero chromatic dispersion at 1560 nm
- High proof test

~2000 Key Attributes:
- Low attenuation at 1550 nm and larger Aeff
- Lower slope of chromatic dispersion in signal band
- High proof test

Optically amplified 10 Gb/s DWDM submarine system requirements



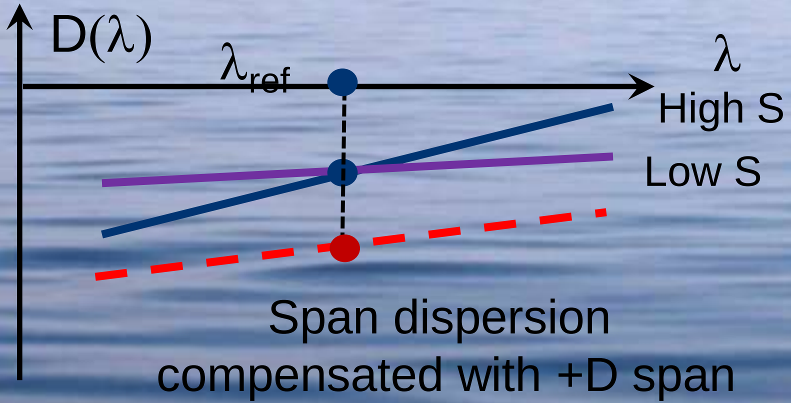
$$\mathrm{OSNR(dB)} = 58 + P_{ch} - \mathrm{NF} - \alpha L - 10\log(N_{Spans})$$

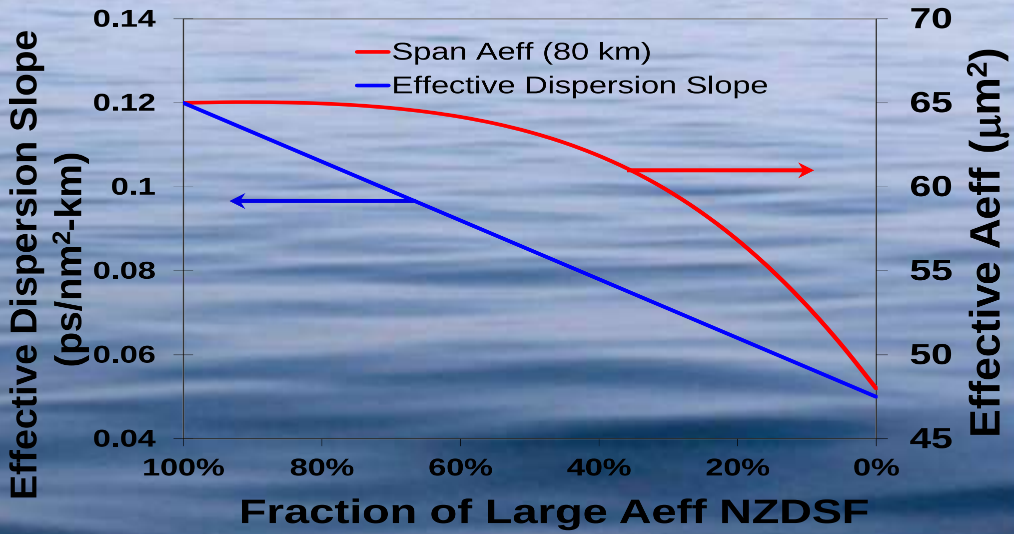
$$\mathrm{OSNR(dB)} \propto 10\log(A_{eff} / n_2) - \alpha L(\mathrm{dB}) - 10\log(N_{Spans})$$

Must achieve:

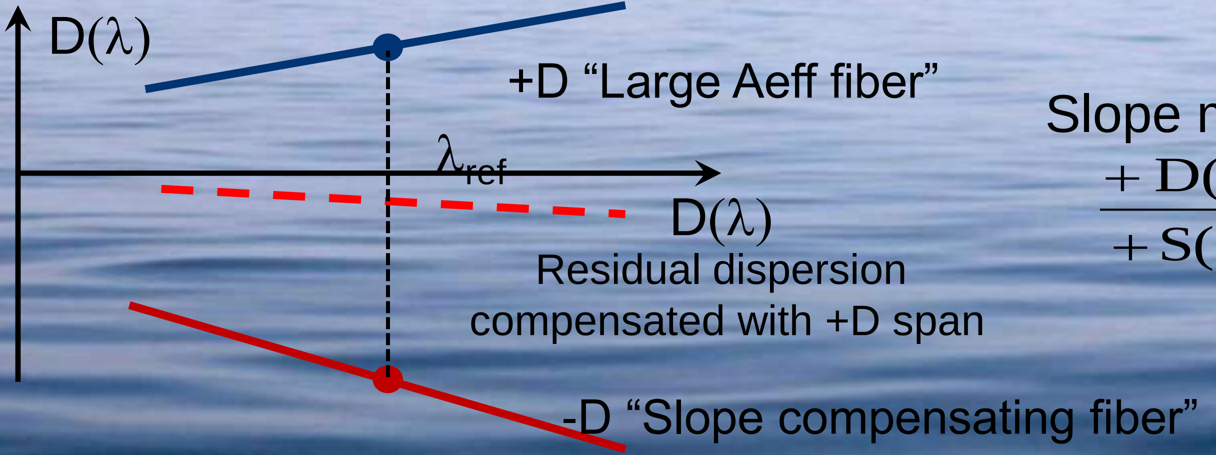
- Sufficiently high OSNR at the receiver
- Precise dispersion compensation for all channels
- Low PMD

None-zero dispersion shifted fibers compensate dispersion but not slope





Dispersion managed fiber solution provides broadband dispersion compensation



Slope matching condition

$$\frac{+D(\lambda_{ref})}{+S(\lambda_{ref})} = \frac{-D(\lambda_{ref})}{-S(\lambda_{ref})}$$

Broadband compensation simplifies terminal equipment

Fiber types used for 10 Gb/s DWDM repeatered submarine systems

Fiber Solution	*Corning Fiber*	*Attenuation (1550 nm) [dB/km]*	*Dispersion (1550 nm) [ps/nm-km]*	*Dispersion Slope [ps/nm²-km]*	*Aeff [mm^2]*	*Distance (km)*
Dispersion managed fiber	**Vascade® L1000**	**0.187**	**+18.5**	**+0.06**	**100**	**Trans-Pacific 9000 km**
	Vascade® S1000	**0.235**	**-38.0**	**-0.12**	**27**	
Low Dispersion Slope NZDSF	**Vascade® LS+**	**0.201**	**-3.0**	**+0.05**	**48**	**Trans-Atlantic and regional ≤6000 km**
Large A_{eff} NZDSF	**Vascade® LEAF®**	**0.200**	**-4.0**	**+0.12**	**65**	
Hybrid	**Vascade® Hybrid**	**0.202**	**-3.5**	**0.085**	**63**	

Transmission system innovation has been a driver for optical fiber

Transmission System

~2000

First optically amplified WDM cable

- EDFA with >10 nm bandwidth in 1550 nm band
- Multiple NRZ or RZ 10 Gb/s channels

Optical Fiber

Key Attributes:

- Low attenuation at 1550 nm and larger Aeff
- Lower slope of chromatic dispersion in signal band
- High proof test

~2013

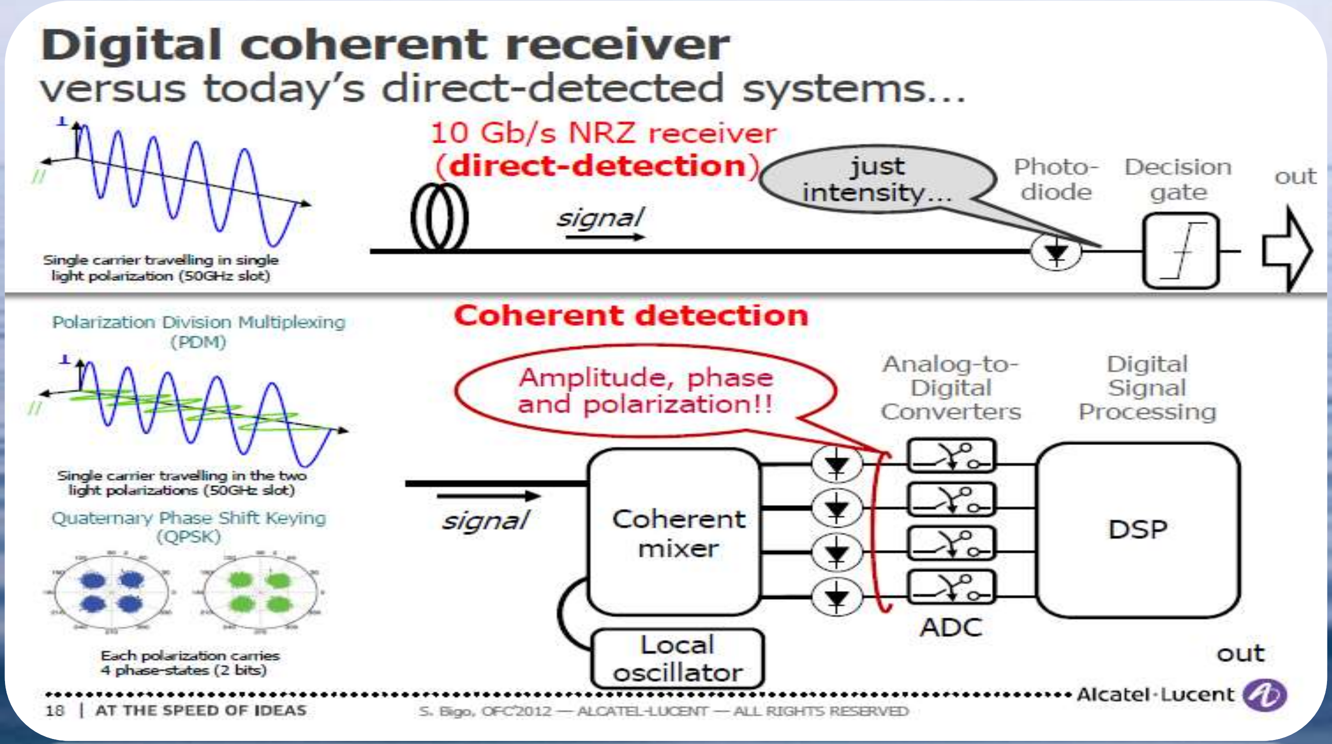
Coherent , optically amplified DWDM systems

- Coherent detection, Polarization Multiplexing and QPSK modulation
- Multiple 100 Gb/s channels

Key Attributes:

- Ultra low attenuation at 1550 nm and very large Aeff
- No dispersion management
- High proof test

Transmission system evolved from 10 Gb/s direct detection to 100 Gb/s coherent



S.Bigo, Tutorial at OFC 2012 OThA3.1

Key implications of coherent 100 G transmission to optical fiber

10 Gb/s OOK Direct detection	*100 Gb/s QPSK coherent*	*Implication for 100 G fiber solution*
Chromatic dispersion must be compensated. Nonlinearity depends on the dispersion map	Electronic dispersion compensation limited by ASIC capability. +D map is optimal	No dispersion management in the cable is required.
PMD should be small fraction of bit period. Challenge for very long systems	PMD is compensated. 75 ps DGD compensation demonstrated	No need to improve PMD specifications
Need ~8.5 dB OSNR for OOK at BER=10^{-3}	*Need ~14.5 dB OSNR for PM-QPSK at BER=10^{-3}*	*Need fiber solution that has ultra low loss and low nonlinearity*

$$OSNR(dB) \propto 10\log(A_{eff}/n_2) - \alpha L(dB) - 10\log(N_{Spans})$$

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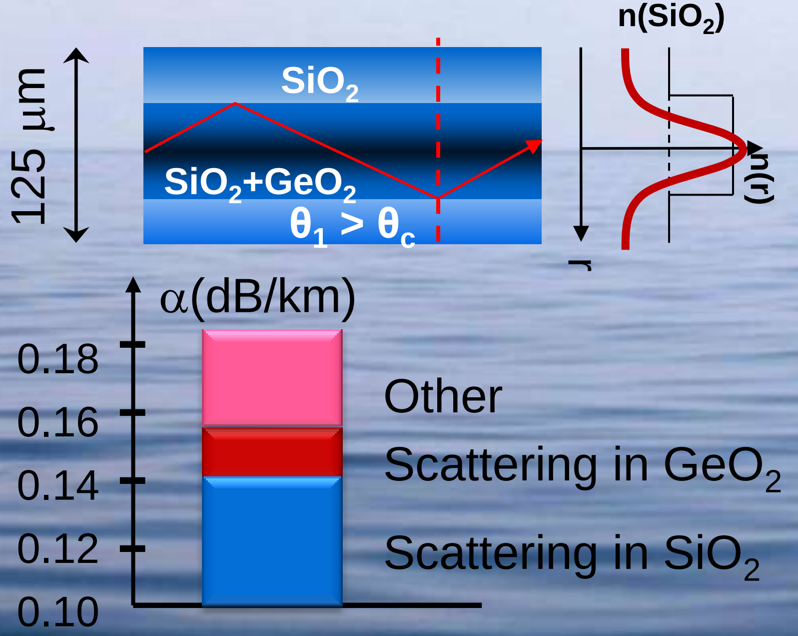
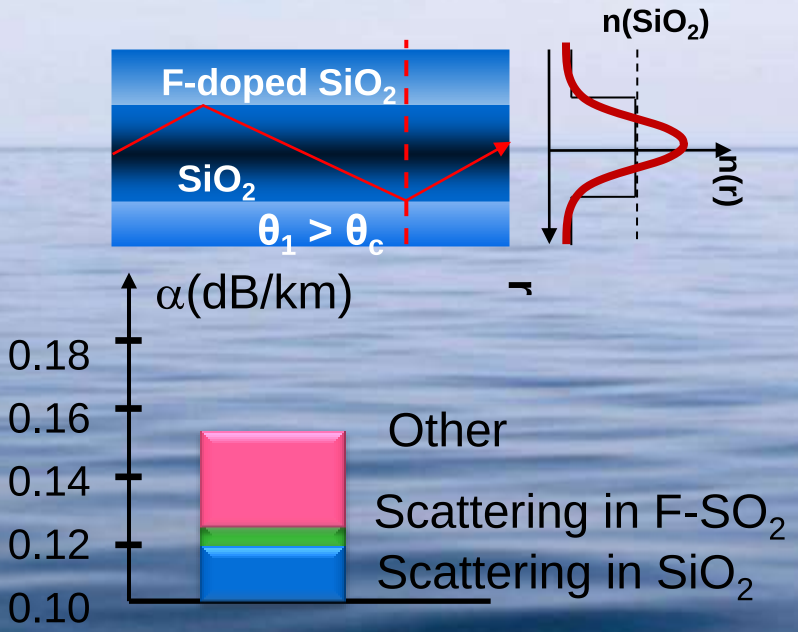
Design of ultra low loss, large Aeff fiber: Material choice is critical for lowest loss





Other sources of attenuation include IR , UV and impurities residual absorptions (e.g. metals) and waveguide imperfections

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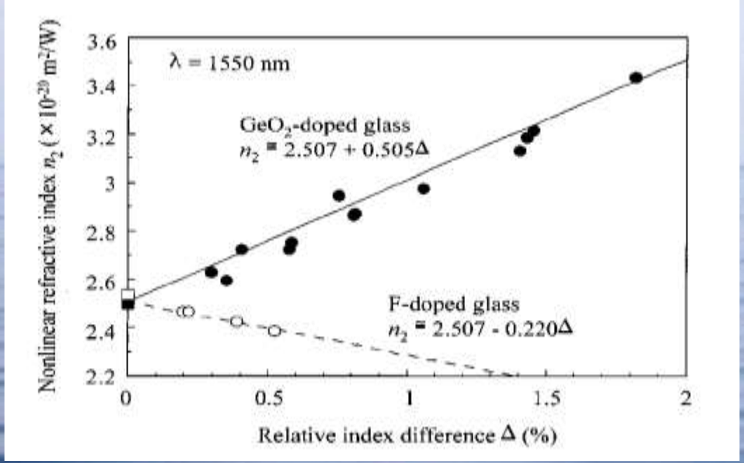
Additional benefits of Pure Silica Core design: Lower nonlinearity and latency



Telegeography 2011

$$V_g = \frac{c}{n_g} \qquad \tau = \frac{L}{V_g}$$

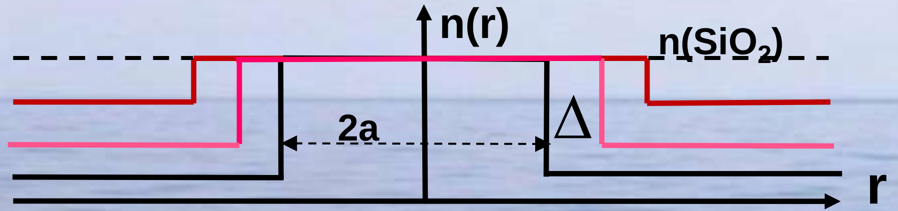
- PSC fibers have lower n_2 coefficient (~9%) for practical designs
- Additional advantage over SiGe fibers

- PSC fibers have approximately 0.4% lower group index than SiGe fibers
- For transatlantic route this may result in 240 μs lower round trip time

K. Nakajima and M. Ohashi, PTL v.15 p. 492

Design of ultra low loss, large Aeff fiber: Refractive index profile

Single Mode Requirement

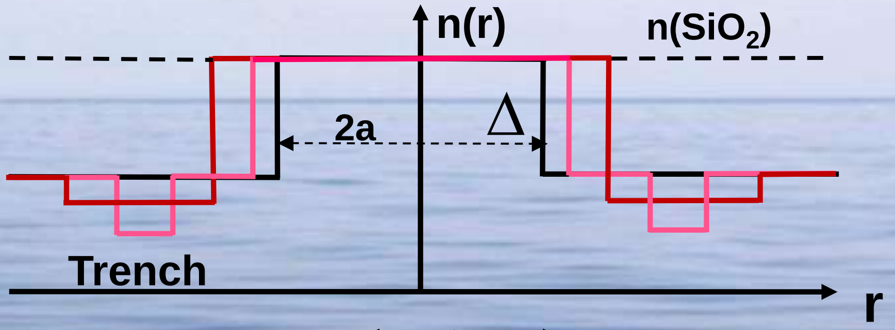


$$V = \frac{2\pi a}{\lambda}\sqrt{n_{Core}^2 - n_{Clad}^2} < 2.4$$

$$\lambda_C = \frac{\pi a}{1.4}\sqrt{2\Delta n_{Core}} < \lambda_{Sig}$$

- Core radius is limited by single mode requirement i.e. $\lambda_{Cutoff} < \lambda_{Sig}$
- λ_{Cutoff} is high for most large Aeff fibers (ITU-T G.654 category)

Macrobend Requirement



$$\alpha_{MacroBend} = F(a, \Delta, R) \qquad R = R_{spec}$$

- Macrobend spec imposes another limitation on Aeff
- Trench and depress cladding enable larger Aeff for the same macrobend

M. Bigot-Astruc, ECOC 2008, MO4.B1

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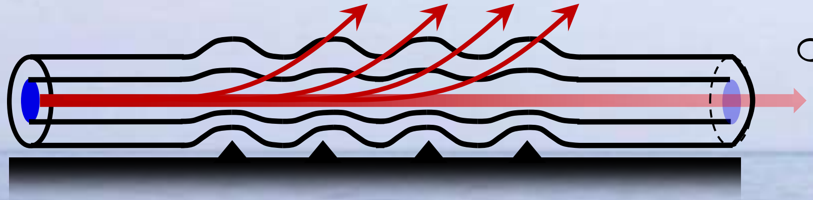
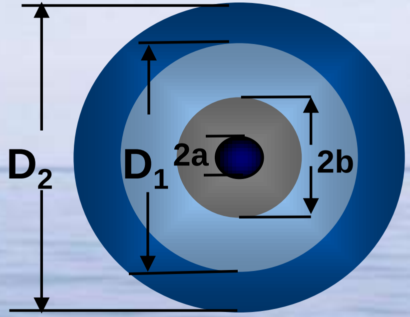
Design of ultra low loss, large Aeff fiber: Advanced coating reduces microbend loss

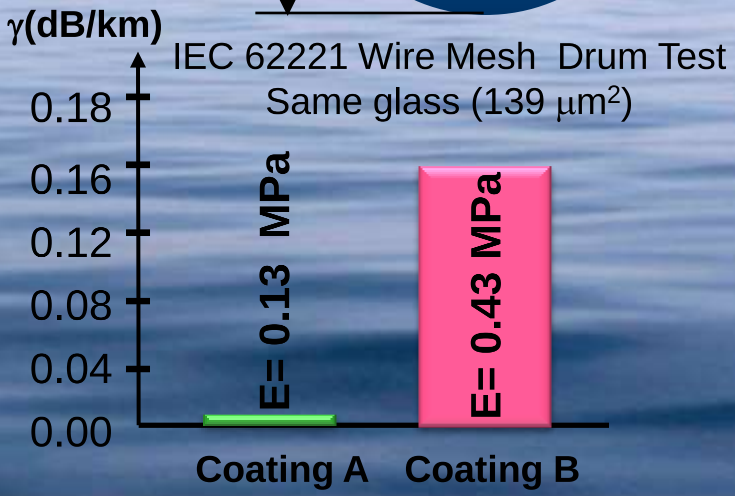


$$\propto e^{-\gamma z}$$

$$\gamma \propto \frac{a^4}{b^6 \Delta^3} E^{3/2}$$



- Microbend loss caused by perturbations of the cladding that are transferred to the core
- Microbend loss can be reduced by using primary coating with lower elastic modulus E



S. Bickham, OFC 2011, OWA5

Large Aeff fibers: reported results and commercial products

Fiber Manufacturer	*Fiber type*	*α(1550 nm) (dB/km)*	*Aeff (μm^2)*	*Dispersion (ps/nm/km)*	*Reference or comment*
Corning	**PSC**	**0.160**	**150**	**20.7**	**OFC 2013 papers OTu2B, PDP 5A.6**
Sumitomo	**PSC**	**0.154 (min - 0.149)**	**130**	**20.7**	**OFC 2013, PDP5A7**
OFS	**SiGe**	**0.183**	**150**	**20.6**	**J.X. Cai et. al JLT, vol 30, p.652 (2012)**
Draka	**SiGe**	**0.185**	**155**	**21.7**	**OFC 2011 paper OMR2.**
Corning EX2000	**PSC**	**0.162**	**112**	**20.2**	**Commercially available** *http://www.corning.com*
Sumitomo Z+ fiber	**PSC**	**0.168**	**112**	**20.5**	**Commercially available** *http://global-sei.com/*
OFS UltraWave SLA	**SiGe**	**0.185**	**106**	**19.5**	**Commercially available** *http://ofsoptics.com*
Draka LongLines	**SiGe**	**<0.190**	**120**	**20.3**	**Commercially available** *http://communications.draka.com/*

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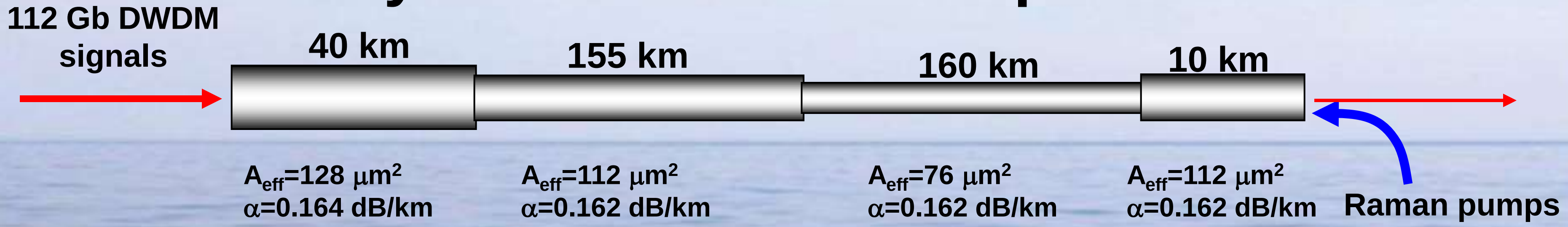
Unrepeatered systems benefit from PSC fiber: variety of different Aeff helps further!



ECOC 2010, paper We.7.C.5

Fiber	*Fiber type*	*α(1550 nm) (dB/km)*	*Aeff (μm²)*	*Dispersion (ps/nm/km)*	*Reference or comment*
EX3000	PSC	0.160	150	20.7	OFC 2013 papers OTu2B, PDP 5A.6
EX2000	PSC	0.162	112	20.2	Commercially available
EX1000	PSC	≤0.174	76	18.5	http://www.corning.com/

- Attenuation is the most important fiber attribute for long unrepeatered systems
- Availability of large Aeff enables Raman and nonlinearity optimization

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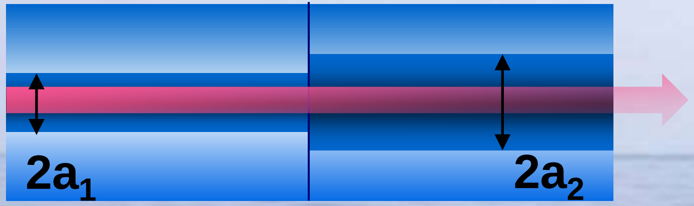
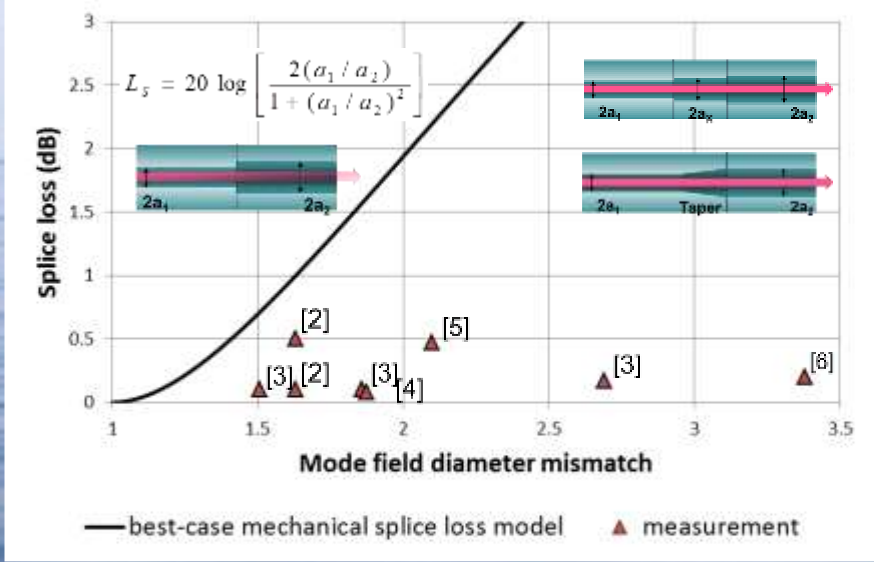
Practical considerations: splicing large Aeff with smaller Aeff fibers (e.g. EDFA pigtail)

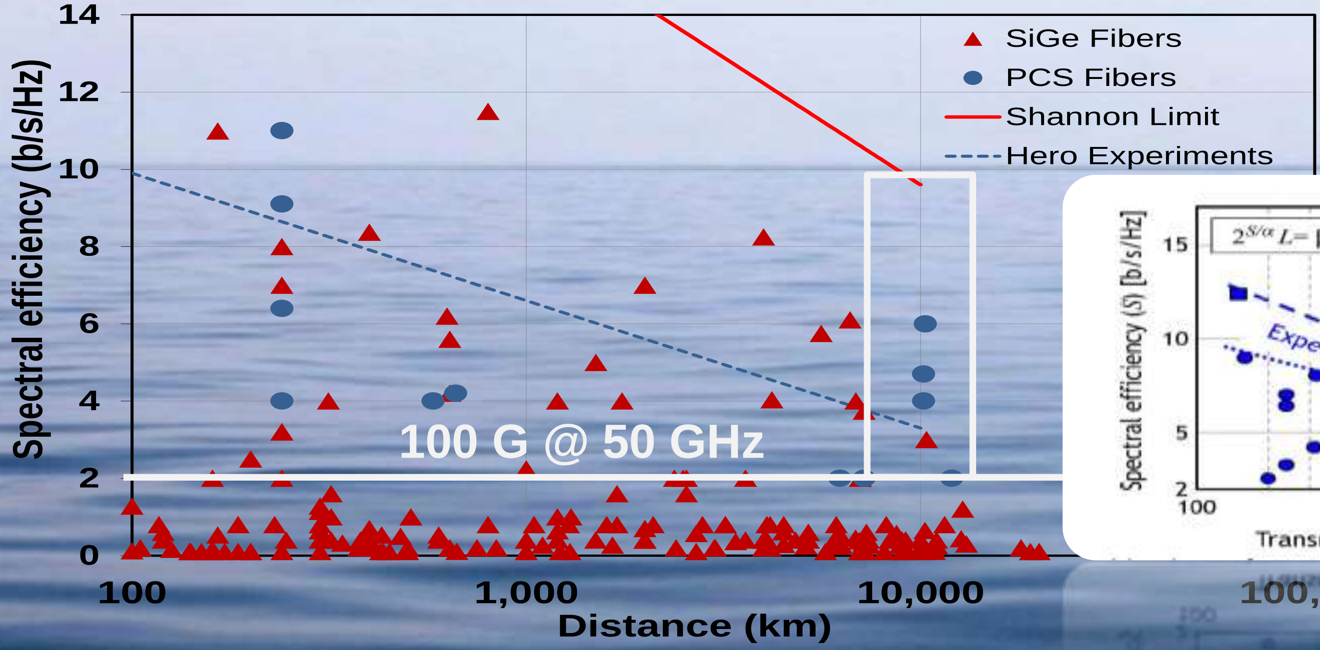


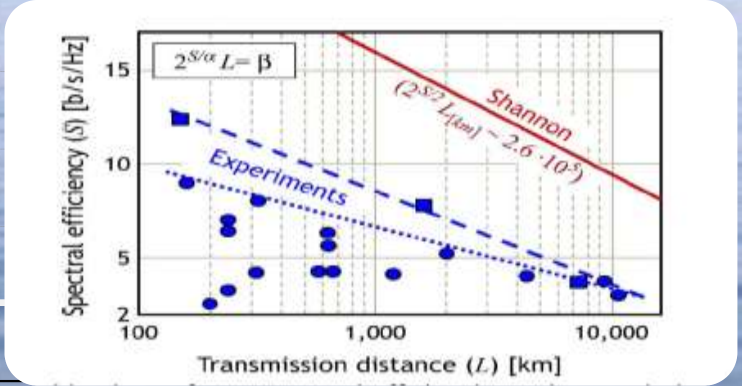
- Mechanical splice loss formula [1] predicts increasing splice loss with smaller Aeff fibers, leads to argument of optimal Aeff
- Bridge fiber and optimized splice recipes are known techniques to reduce splice loss



1. D. Marcuse, Bell Sys. Tech. J. 56 pp. 703-718 (1977)
2. H. Escobar OFC 2003, paper TuS1
3. E.M. O'Brien et al, Electron. Lett. 35 pp. 168-169 (1999)
4. B.S. Wang et al, Proc. SPIE 6781 pp. 678130[1-14], (2007)
5. L. Grüner-Nielsen, Opt. Fiber. Technol 6 pp. 164-180 (2000)
6. M. Takahashi, Furakawa Review, 31 pp. 1-6 (1997)

PSC large Aeff area fibers are used to achieve record results





P. Winzer PTL v. 23 p 851 2011

Ultra Low Loss Extra Large Aeff fibers are required to achieve industrial margin in trans-Pacific links and grow spectral efficiency beyond 2 b/s/Hz

Summary

- Advanced submarine systems rapidly transition towards 100 G systems that use coherent detection that enables chromatic dispersion compensation through signal processing
- Dispersion managed fiber solutions are being replaced with ultra low loss fibers with large Aeff that provide higher OSNR required by 100 G
- Advanced fibers with attenuation ≤0.16 dB/km and Aeff≤150 μm^2 have been demonstrated. They achieve higher OSNR, lower latency and enable transpacific distances at 100 G with industrial margin

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Presenter Profile

Florence Palacios was born in Auchel in northern France and received her Master's Degree in engineering from "SupOptique" (Orsay, France) in 1997, ranking first in the class. She specialized in Optics and Photonics, earning a DEA from Université Paris-Sud XI in the same year. She joined the Alcatel-Lucent Submarine Networks team in Calais in 1999 as Project Manager for new fiber qualifications. Her project management responsibilities were extended to the development of new cables and associated jointing accessories, becoming manager of the development project team. In 2012, in addition to her Project Management responsibilities, she was appointed manager of the cable optical transmissions team and is now more particularly concentrating on the qualification of the new generation of optical fibers for submarine cables.

- Name: Florence PALACIOS
- Title: Fibers and Raw Materials Manager, Project Coordination
- Email: florence.palacios@alcatel-lucent.com

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Fiber management in submarine cable

1. SUBMARINE CABLE DESIGN
2. OPTICAL PERFORMANCES
3. FIBER QUALIFICATION PROGRAM
4. APPLICATIONS TO FIBERS FOR NEW GENERATION SYSTEMS
5. SUMMARY

Submarine cable design

- Submarine cable functions are:
  - To offer the best possible optical performance, i.e. a mechanical assembly to house and protect as much as possible the optical fibers
  - To provide an insulated electrical path for repeater powering, if any or to monitor permanently the status of the transmission system and to localize cable breaks
  - To ensure a 25 year lifetime in all of its functions (optical – electrical – mechanical)

The cable is a packaging
It houses and protects the transmission medium (fiber) for its design life

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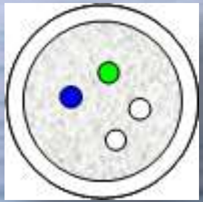
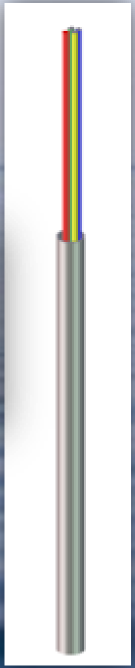
Submarine cable design

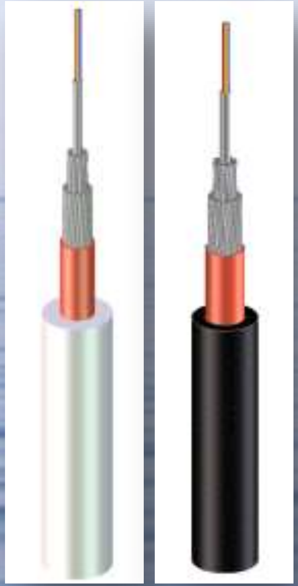
- Submarine cable design – Fiber housing
  - Loose design, ensuring minimum strain and long lifetime - Maintains fiber attenuation and PMD at fiber intrinsic performances
  - Several possible design options:
    - Stainless steel tube
    - Plastic tube
    - Copper tube
    - Internal cavity
    - With jelly filling, possibly with hydrogen barrier…





Submarine cable design

- Submarine cable design – Composite Conductor (CC) and Insulation
  - Mechanical protection design for the CC
    Several possible design options:
    - Steel wires vault
    - 3 divided steel segments vault
    - single layer tension member
  - Copper tape - Electrical conductor for repeater powering, maintains the vault in place
  - Natural polyethylene insulation layer (R) / Black polyethylene insulation layer (UR) – Possibly multi-layer insulation



Submarine cable design

- Submarine cable design – Types of Protection

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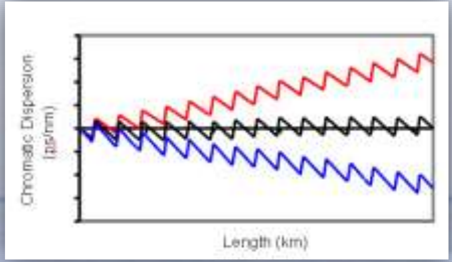
Optical performances

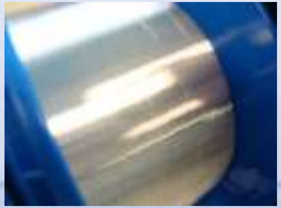
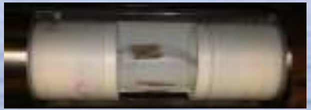
- Optical performances to be checked:
  - Attenuation in agreement with power budget needs:
    - Fiber attenuation in cable (dB/km)
    - Splice losses (dB)
  - Chromatic dispersion in agreement with CD map (CD managed systems)
  - Polarization mode dispersion in agreement with specification



For new generation systems (full +D)
Optimal attenuation performance is the key parameter

Qualification program

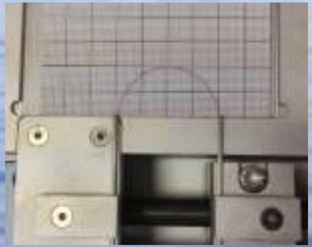
- Fiber qualification program in submarine cable includes:
  - Tests performed on bare/colored, uncabled fibers (bending, coating tests…)
  - Tests performed on optical module/cable (cabling, thermal, ageing…)
  - Tests performed on jointing accessories (cable joint box, beach/land joint…)

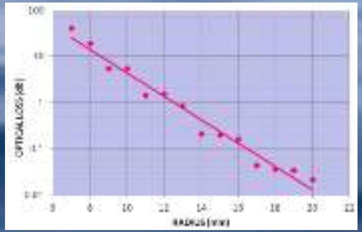



Primary goal is to ensure that the fibers are not affected by the cable manufacturing process and that the cable design delivers good cabled fiber performance

Qualification program

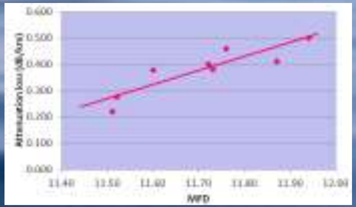
- Macro-bending sensitivity:
  - To check the behavior of fibers when submitted to localized bends (such as a curvature inside a joint)
    - Test method according to ITU-T G650 or IEC 60793-1-47 or internal test method based on these references and adapted to submarine products as need be
    - Measurement of fiber optical loss versus bending radius (range depending on fiber sensitivity and application) – Data extrapolation
    - Tests performed on fiber full sensitivity range (MFD, λc…)
    - Acceptance limit depending on what increment of attenuation is acceptable in power budget for fiber cabling/jointing – ideally 0, i.e. order of magnitude of measurement accuracy





Qualification program

- Micro-bending sensitivity:
  - To check the behavior of fibers when submitted to micro-bending stress (caused by fiber crossovers, fiber packaging…)
    - Test method according to IEC 62221 or internal test method based on this reference and adapted to submarine products as need be
    - Measurement of fiber loss when wound under tension on a specially designed spool fitted with a mesh – Comparison to fiber wound at free (near 0) tension on spool with soft surface
    - Tests performed on fiber full sensitivity range (MFD…)
    - Acceptance limit depending on what increment of attenuation is acceptable in power budget for fiber cabling – ideally 0, i.e. order of magnitude of measurement accuracy



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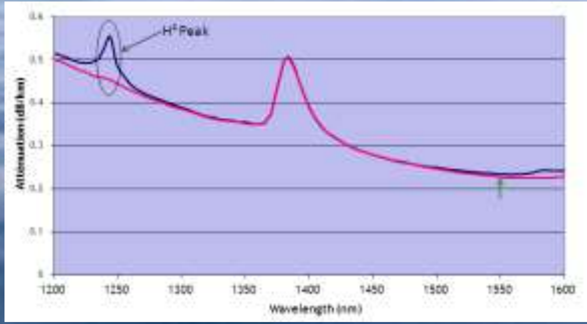
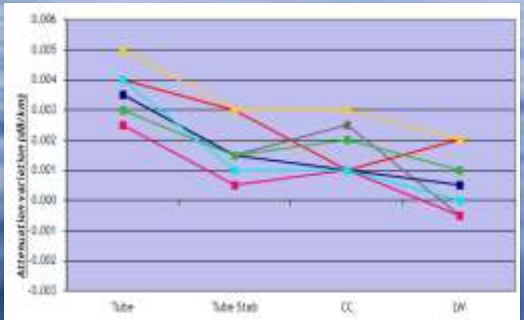
Qualification program

- Sensitivity to hydrogen:
  - To check the behavior of fibers when exposed to hydrogen environment
    - Test method generally used consists in soaking the fibers to saturation then going through full desorption
    - Change in attenuation at 1550nm measured after test
    - Acceptance limit is set depending on a number of factors, such as design requirements, cable level of protection vs. Hydrogen, taking into account measurement accuracy



Qualification program

- Cabling test:
  - To check the behavior of fibres during the cabling process from incoming tests to completed cable stage, under standard manufacturing conditions and practices
    - Manufacture of long length LW cable prototype – Depending on fiber sensitivity, cable armoring included
    - Attenuation variations at 1550nm checked at each manufacturing step (reference: fiber attenuation at near zero tension) - PMD measured
    - Acceptance limit depending on what increment of attenuation is acceptable in the power budget for fibre cabling – ideally zero, i.e. order of magnitude of measurement accuracy



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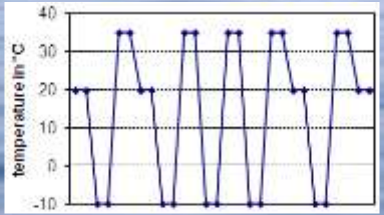
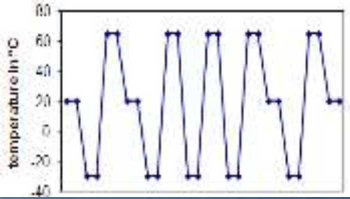
Qualification program

- Thermal cycling test:
  - To simulate operation and storage on fibers in cable at extreme temperatures
    - Test method according to ITU-T G976 or IEC 60794-1 or internal test method based on these references and adapted to submarine environment as need be
    - Test performed on fibers in completed cable (LW) - Cycles simulating storage, cycles simulating operation
    - Change in attenuation measured at 1550nm during operation cycles and after storage cycles
    - Acceptance limit depending on what increment of attenuation is acceptable in the power budget for fibre on the seabed or after storage – ideally zero, i.e. order of magnitude of measurement accuracy





Qualification program

- Accelerated ageing test:
  - To check the performance of the system over 25 years at 3°C (or seabed temperature) through accelerated ageing
    - No internationally recognized test methods for submarine cable ageing so a proprietary assessment method is generally used
    - Test performed on fibers in completed cable (LW)
    - High temperature to accelerate ageing and simulate 25 years
    - Change in attenuation at 1550nm measured after the test
    - Acceptance limit depending on what increment of attenuation is acceptable in the power budget for fibre on the seabed for the system lifetime – ideally zero, i.e. order of magnitude of measurement accuracy

Qualification program

- Coating qualification:
  - Qualification tests dedicated for new coatings
  - Standard fiber testing methods e.g. mechanical strength (IEC 60793-1-31), coating stripping force change (IEC 60794-1-2 Method E5)… may be applied for a coating qualification of a cabled fiber
  - Coating compatibility with ink and tube / cavity filling jelly:
    - Accelerated ageing tests in filling jelly and in air
    - Fiber mechanical properties, coating integrity, ink adhesion checked before and after ageing
  - Wipe test on colored fibers

Qualification program

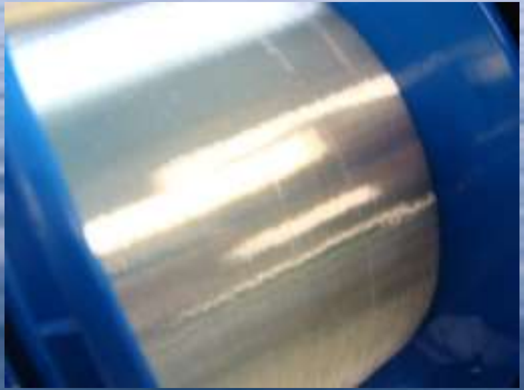
- Splice qualifications:
  - Each splice combination has to be optically qualified:
    - Optimization of splicing program for minimal splice loss
      - May depend on splicing machine used
      - Strongly depends on fiber types / mismatch
    - Optical loss measurement on range of samples
    - Acceptance limits depending on what attenuation is acceptable in power budget for fibre splicing
  - 2 types of splice protection may have to be tested:
    - Micro-molding and heat-shrink
    - Mechanical tests before and after thermal, accelerated ageing – Wrap test

Qualification program

- Tests in jointing equipment:
  - Depending on fiber sensitivity to macro-bending, it is sometimes required to add to the qualification program some tests in joints:
    - Joint assembly, with optical loss measurements at 1550nm, on several joint designs:
      - Cable submarine proprietary jointing box
      - Universal jointing box (UJ, UQJ) following UJ QTS test protocol
      - Beach / terrestrial joint
    - Acceptance limit depending on what attenuation is acceptable in power budget for joints

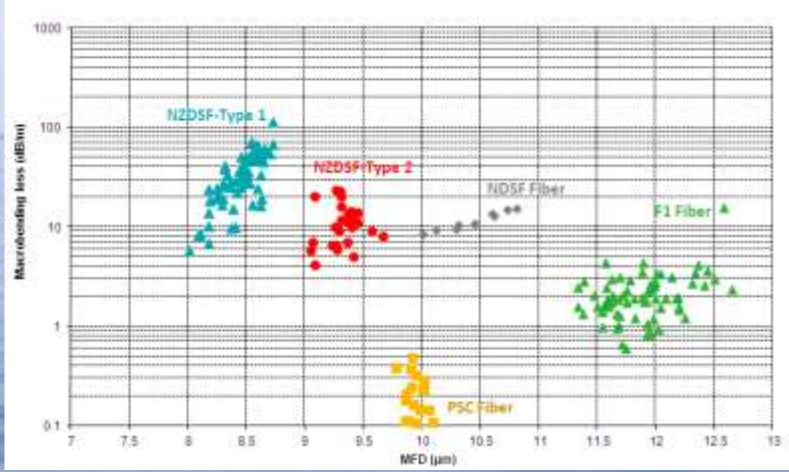
Application to fibers for new generation systems

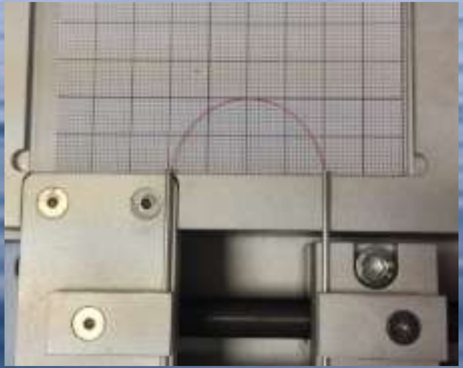
- Two families of fibers for new generation systems evaluated:
  - 1st family (F1) – Large effective area, low loss fibers
  - 2nd family (F2) – Extra-large effective area, low loss fibers



Application to fibers for new generation systems

- Macro-bending sensitivity:
  - F1 fibers sensitivity lower than NZDSF
  - F2 fiber tests on going





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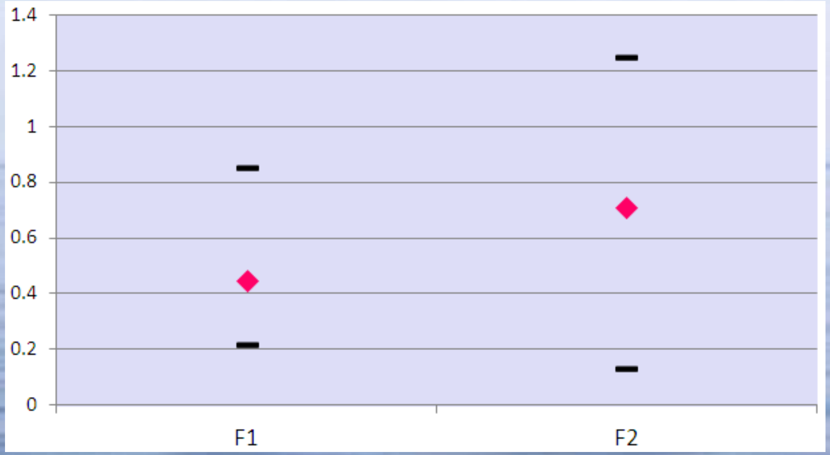
Application to fibers for new generation systems

- Micro-bending sensitivity:
  - F1 fibers sensitivity equivalent to previous fiber generation (NZDSF)
  - F2 fibers sensitivity looks higher for upper part of MFD range



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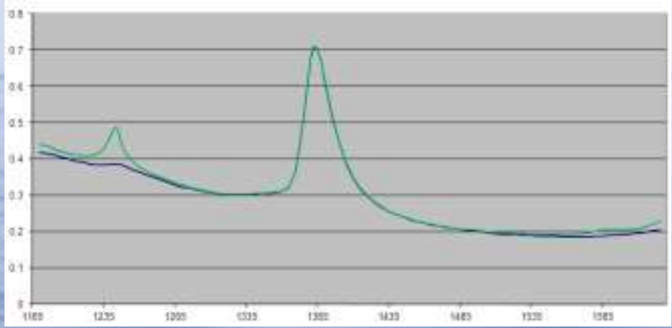
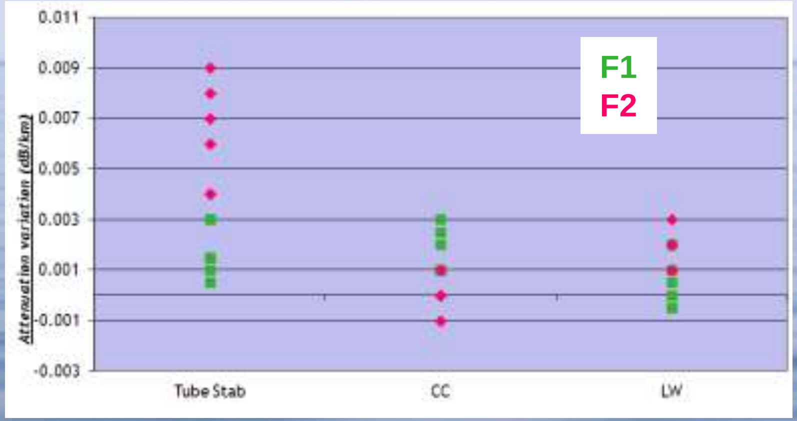
Application to fibers for new generation systems

- Sensitivity to hydrogen:
  - F1 fiber results conforming to requirement
  - F2 fiber preliminary results identical to F1



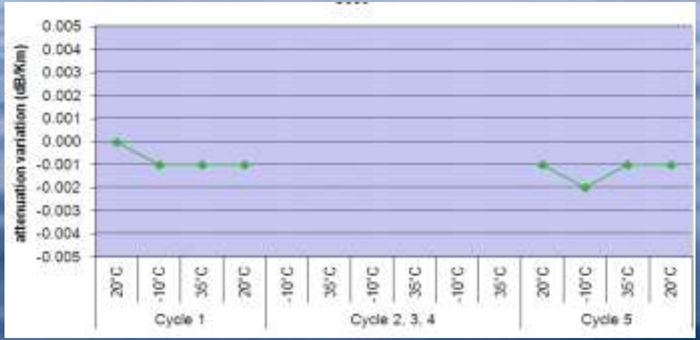
Application to fibers for new generation systems

- Cabling:
  - Higher attenuation level after tube manufacturing for F2 (more sensitive to micro-bending)
  - Nevertheless, results after insulation stage demonstrate that both F1 and F2 have a good behavior once cable completed (attenuation variations within measurement accuracy)



Application to fibers for new generation systems

- Thermal cycling:
  - F1 fiber behavior after storage cycles within measurement accuracy
  - F1 fiber behavior during operation cycles within measurement accuracy
  - F2 preliminary results seems equivalent to F1



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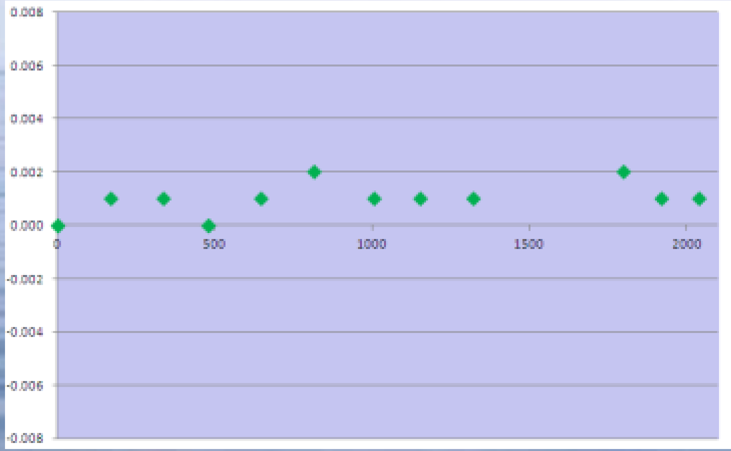
Application to fibers for new generation systems

- Accelerated ageing:
  - F1 fiber behavior after ageing test conforming to requirement
  - F2 preliminary results similar to F1



Application to fibers for new generation systems

- Splice qualifications:
  - F1 and F2 fiber performances identical when spliced with themselves
  - F2 splice loss higher than F1 when spliced to PSC fiber – This is explained by the higher MFD difference between these two fibers

		Average	MFD gap
F1	F1	0.03	0.9
F1	PSCF	0.08	2.6
F2	F2	0.02	0.6
F2	PSCF	0.20	3.3

Fiber management in submarine cable - Summary

- Cable role is to protect the transmission medium i.e. fibers, ensuring minimum induced strain and long lifetime – maintaining fiber attenuation and PMD at their intrinsic performances
- To guarantee this function for 25 years lifetime, under very different environmental conditions, a comprehensive testing program has to be conducted, each time a new fiber (glass, coating) is introduced on market
- Fibers for new system generations, whose challenge is to get the minimum attenuation level inside cable, give satisfactory results, with attenuation variations within measurement accuracy

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Thank You! Questions?

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