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Winter College on Fibre Optics, Fibre Lasers and Sensors

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Limits of Fiber-Optic Communications Systems

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Limits of Fiber-Optic Communications Systems

An introduction to nonlinear processes in Fiber Optic Communications Systems

Goals:

Present an overview of the basic physical mechanisms that limit fiber optic system performance

Understand physical limits of fiber capacity

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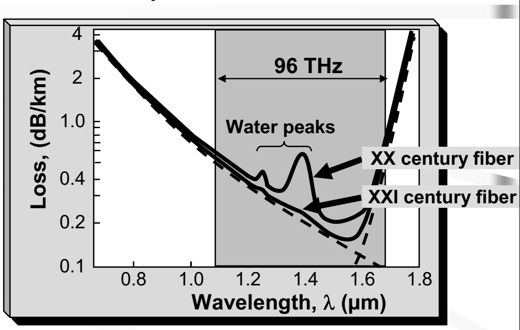
Transmission Capacity of Optical Fibers

Capacity = BxL (Bit rate x Distance)

- **Coaxial (copper) cable:**
  25 Mb/s x km
  Limited by loss
  (skin depth effect)

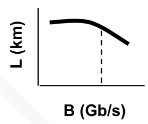
- **Optical Fiber:**
  > 1 Pb/s x km (?)
  Limited by dispersion (?)



100 THz Bandwidth (loss < 0.5 dB/km)

Over 1 million km transmission demonstrated with optical fibers.
BxL product is not a good specification for fiber capacity

How far can we go with fibers? (for a given bit rate)



Topics

- **Physical Limits from Linear Effects**
  - ***Attenuation and Dispersion limits***
- **Nonlinear optical effects**
  - ***Limits imposed by optical nonlinearities***

LINEAR EFFECTS

Effects limiting capacity of optical fiber transmission

Attenuation – Sensitivity
Chromatic Dispersion
Polarization Mode Dispersion

Attenuation/Detection limit

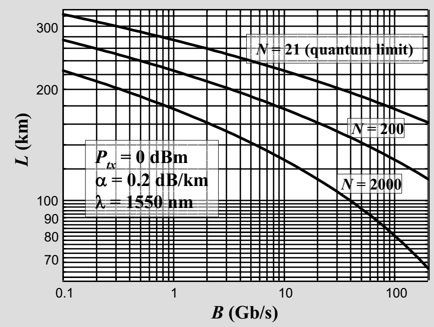
Minimum number of photons/bit at the receiver for a given error probability (BER = 10^{-9})

BER: Bit Error Rate

- **Poisson statistics**

$$p(0) = \exp(-N) = 10^{-9}$$

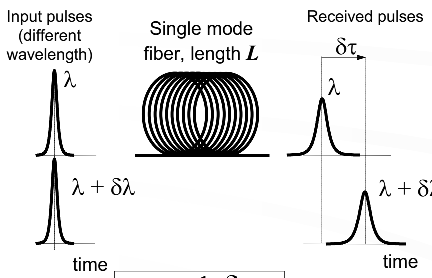
- **Quantum limit:**
  N_Q = 21 photons
- **Practical receivers:**
  N > 1000 photons
  (Sensitivity)



Maximum fiber length to receive N photons/bit for a given launched power, P_{tx}

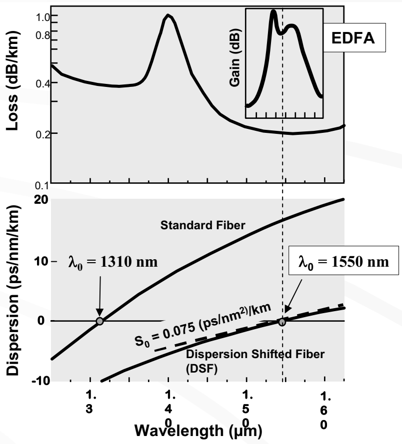
Dispersion

Measurement of Group Velocity Dispersion (GVD):



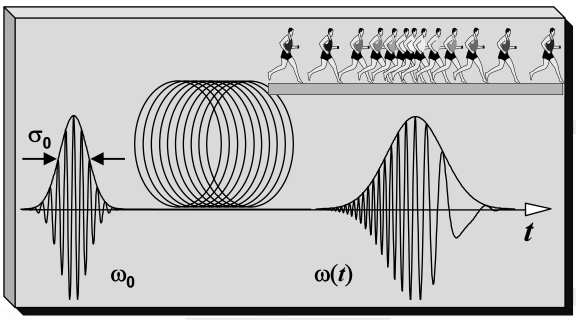
$$D = \frac{1}{L}\frac{\delta\tau}{\delta\lambda}$$

$$S = \frac{dD}{d\lambda}$$



Dispersion and Chirp

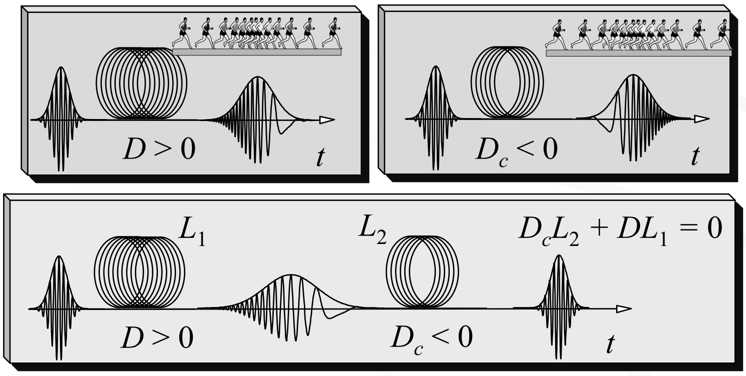
Dispersion produces a frequency chirp in the bit pulse



Instantaneous frequency $\omega(t) \approx \omega_0 - \frac{z\lambda^2 D}{2\pi c \sigma_0^4} t$

Beyond the dispersion limit

– **Dispersion Compensation**



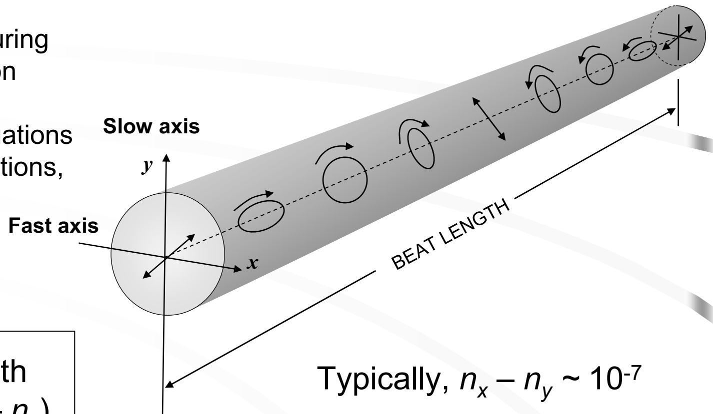
– **Dispersion Compensating fibers introduce losses (use EDFAs)**

Fiber Birefringence

Imperfections in fabrication

Stress induced during cabling, installation

Polarization fluctuations (mechanical vibrations, temperature,…)

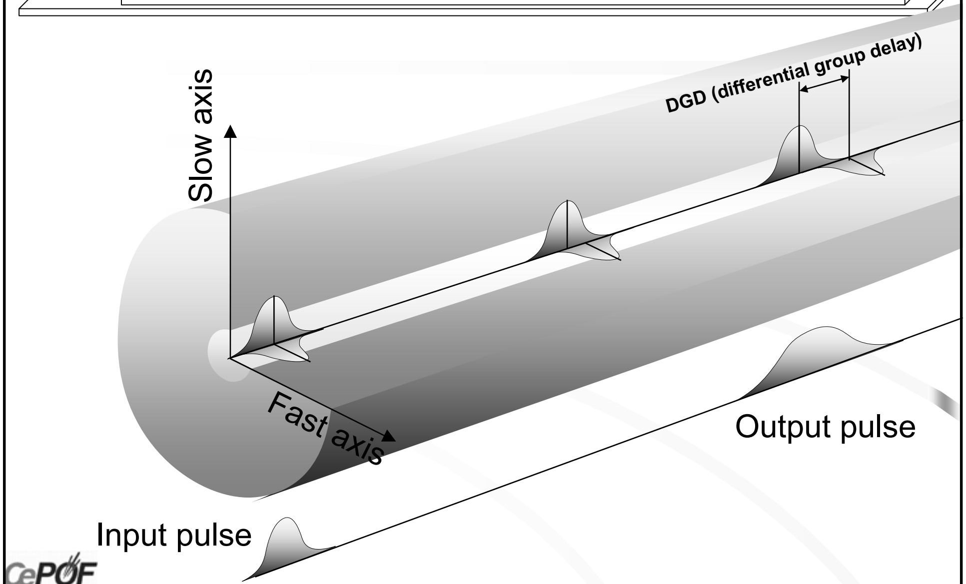


Beat Length
$L_B = \lambda/(n_x - n_y)$

Typically, $n_x - n_y \sim 10^{-7}$

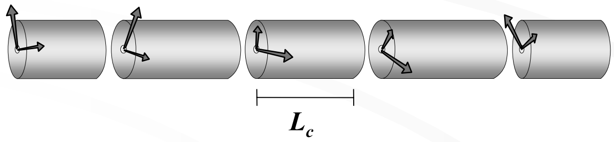
$L_B \sim 15$ m @ 1550 nm

Polarization Mode Dispersion - PMD



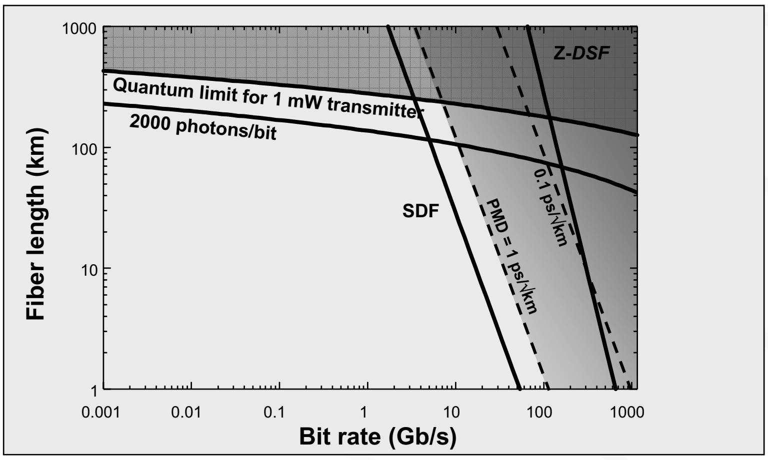
PMD in Long Fibers

- In long fibers the birefringence axes are not preserved in orientation but vary, in average, after one “coherence length” (L_c)
- DGD follows a random walk process
  (analogous to Örnstein-Uhlembeck process in Brownian motion theory)



$$DGD \propto \sqrt{LL_c}$$

Attenuation, Dispersion, and PMD Limits

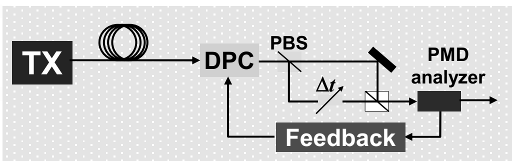


Attenuation limits for 1mW transmitter, α = 0.25 dB/km and BER < 10^{-9}
Quantum limit = 20 photons/bit
SDF = Standard dispersion fiber (D = 17ps/nm/km)
Z-DSF = Zero-Dispersion Shifted Fiber (D = 0, S = 0.07 ps/nm^2/km)

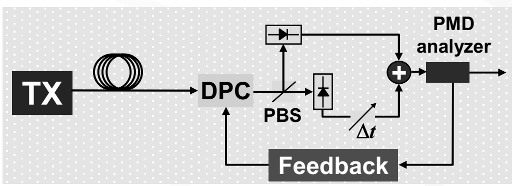
PMD compensation

Polarization state varies randomly but slowly (> minutes)

Several techniques involving feedback on Dynamical Polarization Controller (DPC)



TX: Transmitter
PBS: Polarization Beam Splitter
Δt: delay line



S. Yao, WDM, Nov. 2000

Linear effects limiting fiber capacity REVIEW

- **Attenuation – related to sensitivity of receiver**
  - **Minimum number of photons per bit for BER < 10^{-9}**
  - **Typically 2000 photons (Quantum limit: 21 photons)**
  - **Compensated by using optical amplifiers**
- **Dispersion – related to index profile and material dispersion**
  - **Pulse (bit) dispersion given by spectral width of laser**
  - **Standard dispersion fiber: D = 17 ps/nm/km @ 1550 nm**
  - **Dispersion Shifted fiber : D = 0; Dispersion Limit given by Dispersion Slope**
  - **Compensated using Dispersion Compensation Fibers (for WDM dispersion slope must also be compensated)**
- **Polarization Mode Dispersion (PMD) – related to fiber birefringence**
  - **Orthogonal polarizations travel at different speeds**
  - **Polarization fluctuates slowly with time (vibrations, temperature, stress)**
  - **PMD can be compensated using polarization controller and feedback circuit**

Nonlinear optical effects in fibers

Stimulated Scattering

SBS: Stimulated Brillouin Scattering

SRS: Stimulated Raman Scattering

Nonlinear refractive index (phase modulation)

Phase Modulation

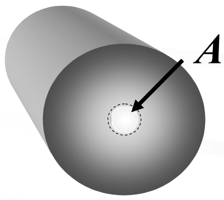
Solitons

Four Wave Mixing

Effective Area and Effective Length

- Nonlinear effects depend on light intensity (I = Power/Area)
- Effective area

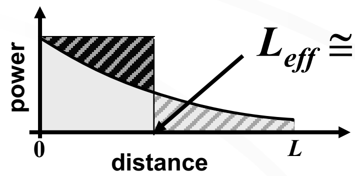
$$A_{eff} = \frac{\left[\int I dA\right]^2}{\int I^2 dA}$$



$$A_{eff} \cong \begin{cases} 80\ \mu m^2 & \text{for standard fibers} \\ 55\ \mu m^2 & \text{for DSF} \end{cases}$$

- Nonlinearities are important over a length of fiber where intensity is high
- Effective Length

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha}$$

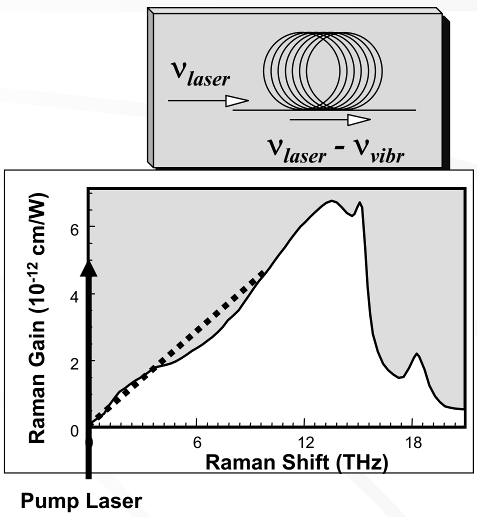


$$L_{eff} \cong \begin{cases} L & \text{for } \alpha L \ll 1 \\ 1/\alpha & \text{for } \alpha L \gg 1 \end{cases}$$

(ex., $\alpha \cong 0.22$ dB/km, $1/\alpha \cong 20$ km)

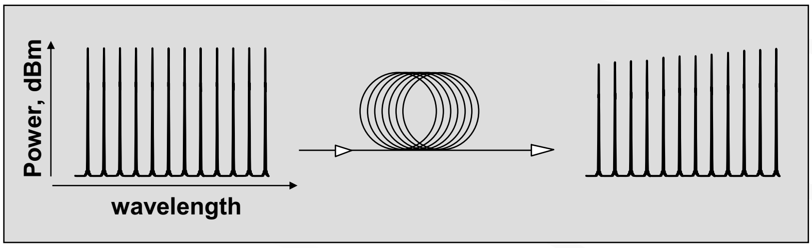
Stimulated Raman Scattering (SRS)

- Co-propagating scattering
- Coupling to molecular vibrations of silica
- High power threshold
  example: $P_{th} \cong 1.8$ W
  ($A_{eff} = 80\ \mu m^2$, L_{eff} = 20km)



Raman in DWDM systems

SRS manifests as tilting of WDM spectrum
higher loss for channels with smaller λ's

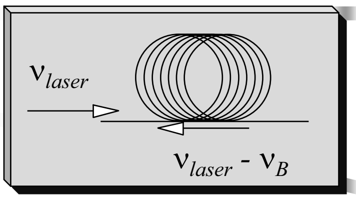


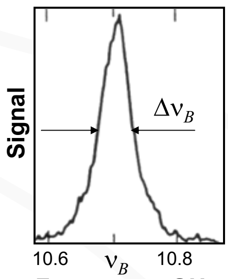
Stimulated Brillouin Scattering (SBS)

- **Counter-propagating scattering**
  - **Precludes long distance bi-directional transmission**
- **Strongest nonlinearity**

  $g \cong$ **4x10^{-9} cm/W**
- **But easy to eliminate**
  - **Threshold depends on laser linewidth**

$$P_{th} \cong 84 \frac{A_{eff}}{g L_{eff}} \left(1 + \frac{\Delta \nu_{laser}}{\Delta \nu_B} \right)$$

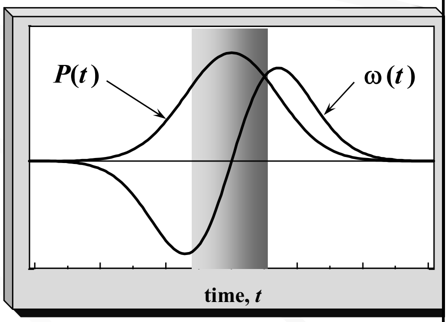




Example (20 km, 80 μm^2): P_{th} = 8.4 mW (narrow line lasers)

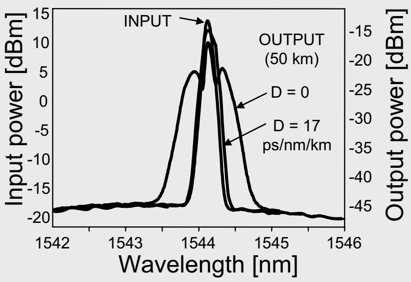
Phase Modulation

- Self phase modulation $n = n_0 + n_2 P(t)/A_{eff}$
- Cross phase modulation $n = n_0 + 2n_2 \Sigma P_k(t)/A_{eff}$
- **Modulation of phase of the wave changes instantaneous frequency $\omega(t)$**
- **Broadens pulse spectrum**
- **Accelerates pulse spreading by dispersion**

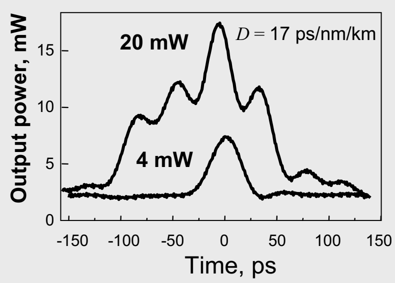


Phase modulation and dispersion

Spectral broadening is larger in fibers with lower dispersion [bad for WDM]



But pulse broadening is larger in fibers with higher dispersion [bad for high bit rate systems]



Trade off between phase modulation and dispersion (general philosophy in modern NZ-DSFs)

Limitations from Phase Modulation

- **Self Phase Modulation (SPM)**
  - ***Important in single channel systems***
- **Cross Phase Modulation (XPM)**
  - **Important in WDM systems**
  - **Phase of one channel is modulated by the power of all other channels**
    - **broadens pulse spectrum**
    - **accelerating pulse broadening by dispersion**
    - **Limits pulse duration and power ($\partial P / \partial t$)**
    - **Pulse Duration ⇒ limits the bit rate (B)**
    - **Power ⇒ limits the distance (L)**

• *Ultimate limit of DWDM systems?*

P.P. Mitra and J.B. Stark, *Nonlinear limits to the information capacity of optical fibre communications*, Nature, 411, 1027-1030 (June 2001)

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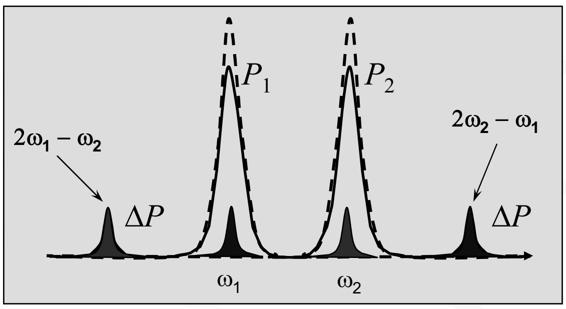
Four Wave Mixing (FWM)

- **Most important effect for WDM systems with low dispersion**
- **Due to nonlinear refractive index**



- **Reduces the transmitted power in each channel**
- **Produces cross talk**

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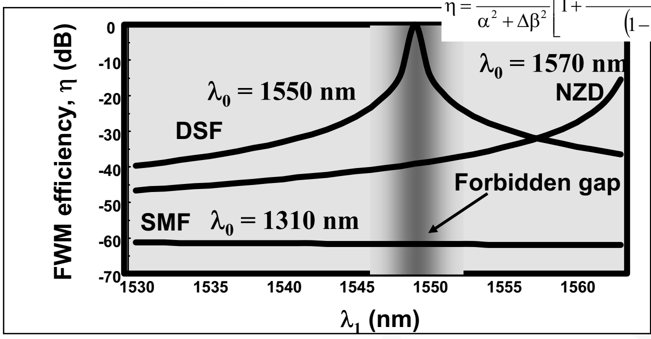
FWM and dispersion

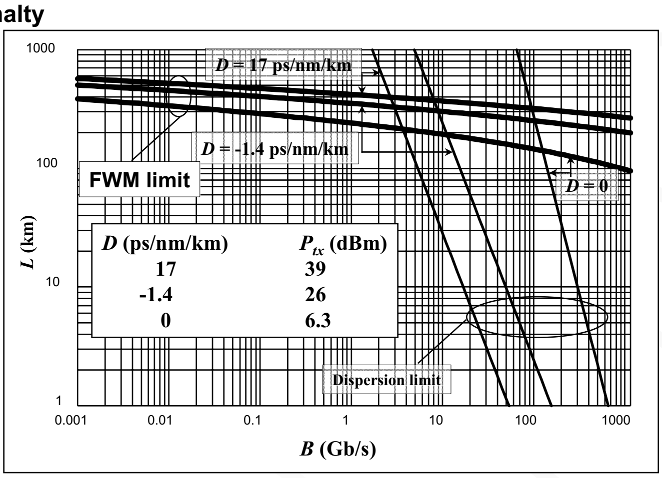
- FWM efficiency is larger in lower dispersion fibers
- Region around zero dispersion wavelength (λ_0) extremely difficult for DWDM ("forbidden gap")
- Non-Zero Dispersion Shifted (NZD) fibers alleviates the problem

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left[1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{\left(1-e^{-\alpha L}\right)^2}\right]$$

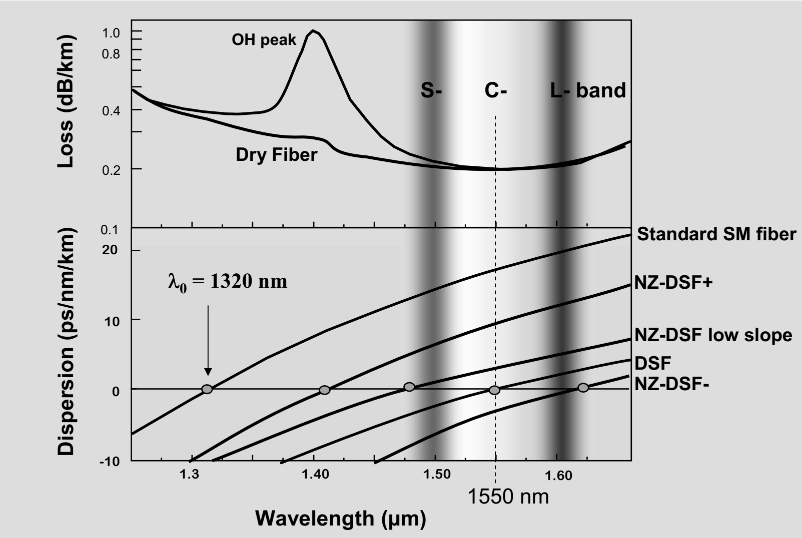


Limitations by FWM

5% Power penalty



S - ,C - and L - bands for DWDM



Raman amplification

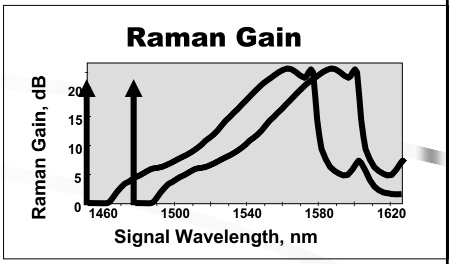
40 nm centered in any wavelength

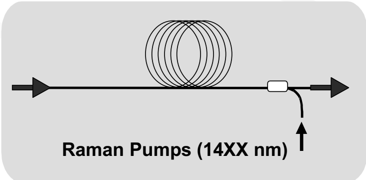
>90 nm combining pump lasers

Distributed gain:
fiber now has gain instead of loss

can use low power transmitter (mitigates nonlinearities)

Can be used for D = 0





Summary

- **Attenuation, Dispersion and PMD limits can be overcome with Optical Amplifiers, Dispersion Management and Compensation techniques**

- **Maximum capacity in practice: DWDM systems**
  > 10 Tb/s x Mm (in the lab)
  Limited by bandwidth of available amplifiers and nonlinearities

- **Capacity of fiber transmission is limited by nonlinear optical effects**
  - **Moderate and High dispersion fibers: XPM**
  - **Low dispersion fibers: FWM**

- **Nonlinearities can be reduced by**
  - **Large area fibers**
  - **Dispersion management strategies (D large, average D = 0)**
    Compensate also for dispersion slope
  - **Operate the system in |D| > 2 ps/nm/km region (L band, S band,…)**
  - **Distributed Raman Gain: loss-less fiber (no need to use high power)**

Where to get more information

- **G.P. Agrawal, *Fiber-Optic Communication Systems*, 3rd ed., Wiley, New York, 2002.**

- ***WDM Solutions*, PenWeell, free subscription: www.optoelectronics.world.com**

- **R. Ramaswami and K. N. Sivarajan, *Optical Networks*, 2nd ed., Morgan Kaufmann, San Francisco, 2002.**

- ***Optical Fiber Communications Conference* Proceedings (OFC), Optical Society of America, Washington, DC, (1973-2002).**

- ***Optical Fiber Telecommunications,* Vols. III-A, III-B, I.P. Kaminow and T. Koch, Eds. (1997); Vols. IV-A and IV-B, I.P. Kaminow and T. Li, Eds., (2002), Academic Press, San Diego.**

- **E. Desurvire, D. Bayart, B. Desthieux, S. Bigo, *Erbium-Doped Fiber Amplifiers: Device and System Developments*, Wiley, New York, 2002.**

- **E. Desurvire (Guest editor), C. R. Phyisique, *Dossier: Optical Telecommunications*, 4(1), 2003.**

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Fiber-Optic Parametric Devices

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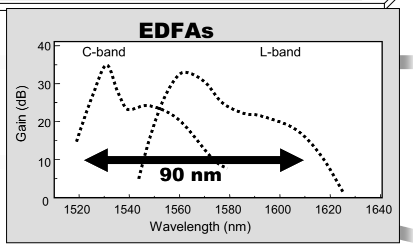
Optical Amplifiers for DWDM

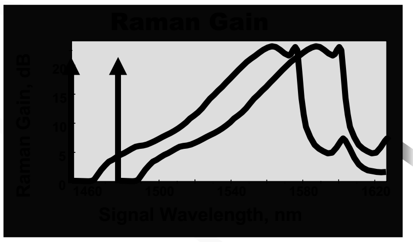
EDFA (1510-1620 nm) Erbium

TDFA (1440-1510 nm) Thulium

SOA (60 nm bandwidth)
Semiconductor Optical Amplifier

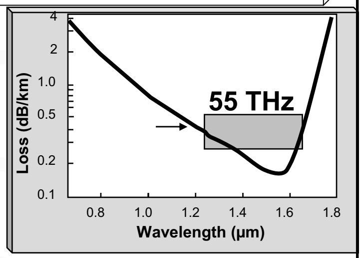
Raman Amplifiers (40 nm bandwidth; choice of spectral region)





Limited by Nature to ~ 100 nm
Physics: Quantum energy levels
Chemistry: Special materials

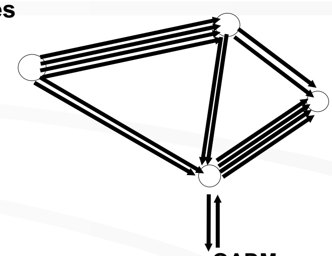
The ideal optical amplifier



- **Explore the full capacity of silica fibers (1250-1650 nm) with a single device**
  - ◎ 54.5 THz bandwidth
  - ◎ 1164 channels @ 40 Gb/s = 46.6 Tb/s
  - ◎ M x 46.6 = 140 Tb/s (M = 3) for M-ary format
- **400 nm bandwidth, flat gain spectrum, high output power**
- **Is it possible?**
- **Do we need it? Do we want it?**
- **If yes, probably the only option is the FOPA (Fiber-Optic Parametric Amplifier)**
- **But FOPDs can do much more than just amplify signals…**

WDM Networking

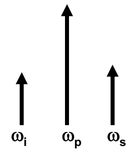
- **WDM networks need new functionalities**
  - Add and Drop Channels Optically
  - Wavelength Routing Assignment
  - Wavelength reuse
- **Wavelength Conversion**
- **Wavelength Exchangers**
- **FOPDs met the needs of WDM networking**



FOPAs

Fiber-Optic Parametric Amplifiers

- **Spectral region not limited by energy levels of the medium – can be optimized by engineering waveguide dispersion**
- **Large gain, flat gain spectrum, large bandwidth, low noise**
- **Based on ~ phase matched FWM**
- **Idler wave generated**
  - can be used as wavelength converter

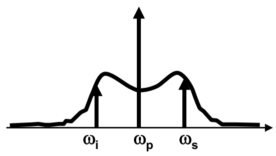


$\omega_i = 2\omega_p - \omega_s$

- **Typical pump power, fiber length, gain, bandwidth, noise figure:**
  - **P = 0.1 – 1 W,**
  - **L = 0.2 – 5 km,**
  - **G = 20 – 40 dB (up to 70 dB demonstrated)**
  - **$\Delta\lambda_{3dB}$ = 20 – 60 nm (100 nm demonstrated)**
  - **NF = 3.5 – 4.5 dB (0 dB in phase sensitive mode)**

Two Types of FOPA

Single pump or 1P-FOPA

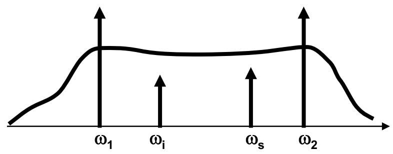


$\omega_\iota + \omega_s = 2\omega_p$

$\hat{P}_{NL}(\omega_s) = \frac{3}{4}\varepsilon_0\chi^{(3)}\hat{E}^2(\omega_p)\hat{E}^*(\omega_i)$

- Simpler

Double pump or 2P-FOPA



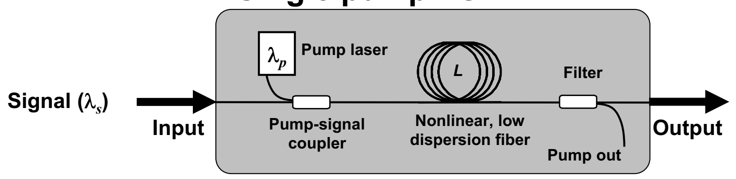
$\omega_i + \omega_s = \omega_1 + \omega_2$

$\hat{P}_{NL}(\omega_s) = \frac{3}{2}\varepsilon_0\chi^{(3)}\hat{E}(\omega_1)\hat{E}(\omega_2)\hat{E}^*(\omega_i)$

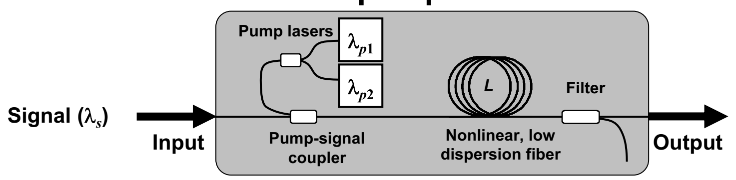
- Broader gain spectrum
- Flatter gain spectrum
- Narrow-band idler

FOPA Basic Components

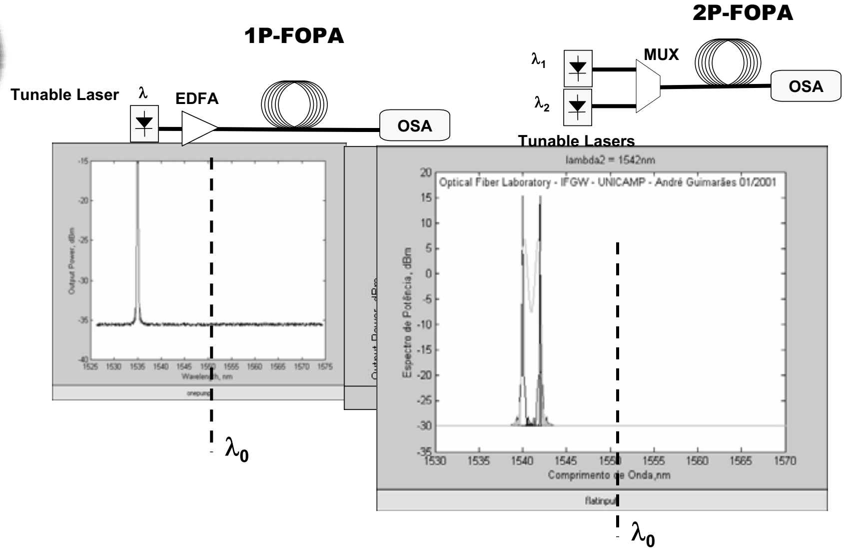
Single pump FOPA



Double pump FOPA



Gain spectrum



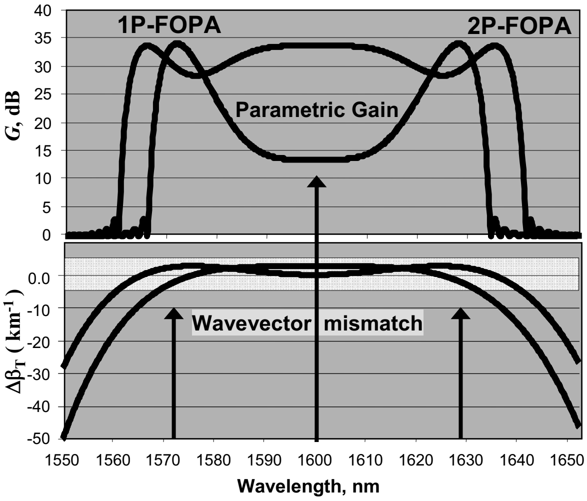
Gain and Phase Matching

- **Parametric processes depend critically on phase matching conditions**

S_{ZD} =	0.065	ps/nm^2/km
λ_{ZD} =	1600	nm
L =	2.0	km
α =	0.20	dB/km
γ =	2.4	W^{-1}/km

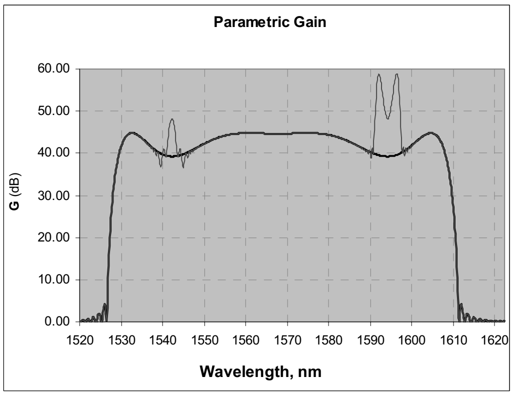
λ_1 =	1572	nm
λ_2 =	1628.625	nm
P_1 =	0.50	W
P_2 =	0.50	W

λ_1 =	1600	nm
P_1 =	1.0	W



Tuning the central pump wavelength of a 2P-FOPA

1568.2 nm



$\lambda_2 - \lambda_1$ = 52 nm, $P_1 = P_2$ = 2.2 W
λ_0 = 1568.2 nm, L = 0.95 km, α = 4.0 dB/km, (L_{eff} = 0.63 km)
γ = 2.1 W^{-1}/km, β_3 = 0.11 ps^3/km, β_4 = -5.5x10^{-4} ps^4/km

FOPD examples

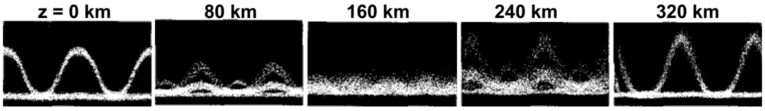
- 1550 nm to 500 nm (visible) wavelength conversion
  - 375 THz (1020 nm) translation!
  - 20 m PCF with γ = 70 W^{-1}/km, λ_{01} = 750 nm, and λ_{02} = 1260 nm

R. Jiang et. al., OFC 2006

- Conversion with phase conjugation (dispersion compensation)
  - 360 km transmission over standard (D = 16 ps/nm/km) fiber
  - 5 DWDM channels at 10 Gb/s
  - 2P-FOPA (HNLF, 1 km), orthogonal pumps, counter-phase modulation

FOPA*

z = 0 km | 80 km | 160 km | 240 km | 320 km

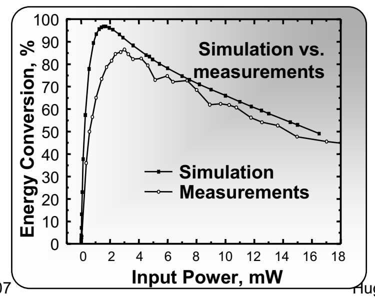


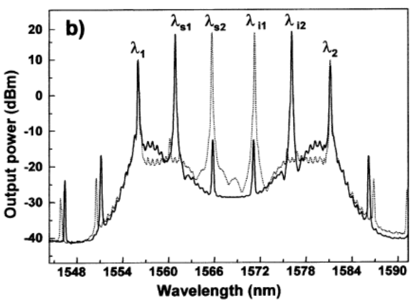
S. Radic et al., OFC 2003

Wavelength conversion

- FOPDs can convert wavelengths with gain
- Broadband, tunable
- Transparent to bit rate/protocol to > 1000 Gb/s
- L-C-S-… Band conversion
- Almost 100% energy conversion (pump to signal+idler)

J.M. Chavez Boggio et al., PTL 15, 1528 (2003)

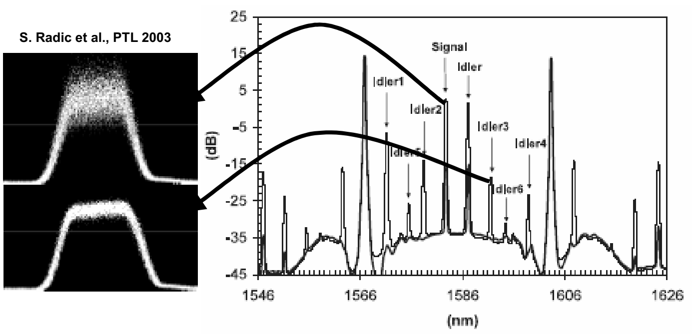




All-optical regenarion

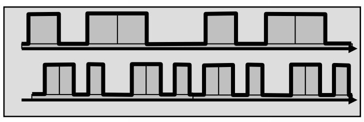
- High order idlers generated by cascaded FWM can reduce noise (fluctuations in levels “0” and “1”)

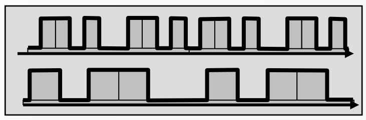
S. Radic et al., PTL 2003

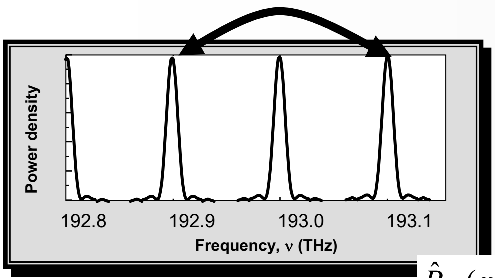


Wavelength Exchanger

Input **Output**







Simultaneous exchange of the modulation signals carried by two different channels

(without ADD or DROP devices)

$$\hat{P}_{NL}(\omega_s) = \tfrac{3}{2}\varepsilon_0\chi^{(3)}\hat{E}^*(\omega_1)\hat{E}(\omega_2)\hat{E}(\omega_i)$$

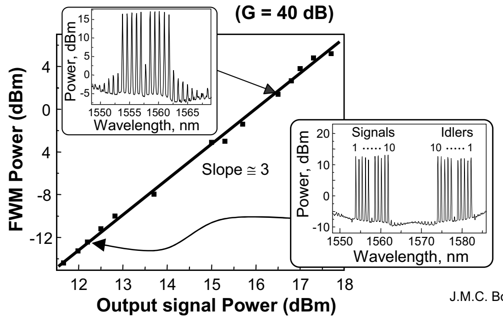
$$A_i = A_{i0}\underbrace{\cos(2\gamma PL)}_{\mathbf{0}} - iA_{s0}e^{i(\phi_{10}-\phi_{20})}\underbrace{\sin(2\gamma PL)}_{\mathbf{1}}$$

if $2\gamma PL = \pi/2$

K. Uesaka et al., IEEE-JSTQE 8, 560 (2002)

Spurious FWM under control

- Short fibers
- Uniform fibers
  - Up to 16 mW per channel (x10 channels) can be extracted from a 0.8 km DSF 2P-FOPA pumped at 4.4 W (22 dBm total signal output power)

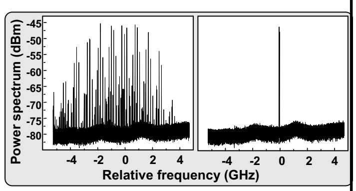


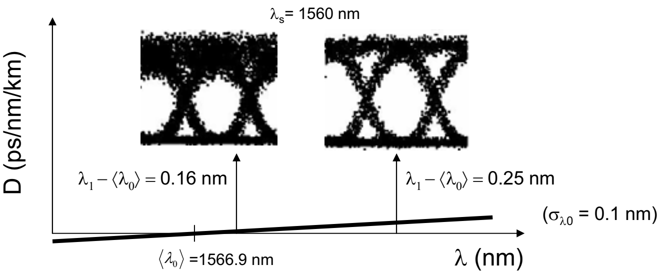
J.M.C. Boggio et. al., PTL 17, 1842-1844 (2005); Opt. Comm. 259, 94-103 (2006)
J.L. Blows Opt. Comm. 236,115 (2004).

Stimulated Brillouin Scattering

- Big problem
- Usually solved by broadening pump spectrum

  But this induces
  - gain fluctuations
  - idler broadening
  - Sensitiveness to $\lambda_0(z)$ fluctuations



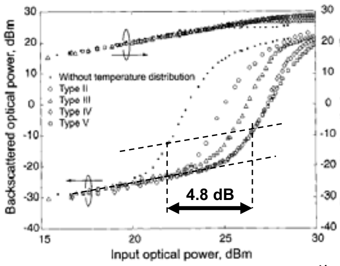


J.M. Chavez Boggio et al., Opt. Comm. 249, 451 (2005)

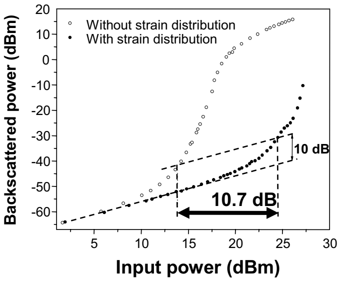
Mitigating SBS

- **Varying elastic properties along fiber length**
  - ➔ **Stain (or temperature) modifies the sound velocity, producing a shift in Brillouin frequency**
  - ➔ **A strain (or temperature) distribution along the length of the fiber (inhomogeneously) broadens the Brillouin spectrum, increasing the SBS threshold.**

J. Hansryd et al., JLT 19, 1691 (2001)



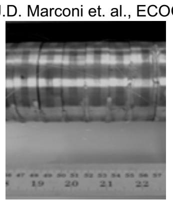
J.D. Marconi e al., ECOC'2005

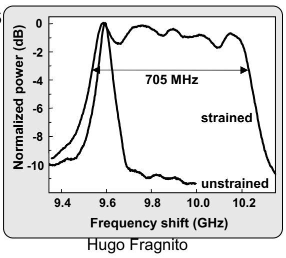


SBS: $\nu_B(z)$ and $\lambda_0(z)$

- **Brillouin frequency $\nu_B = 2\nu_{opt}V/c$**
  - **Sound velocity V =(stress/density)$^{1/2}$**
  - **Temperature** $d\nu_B/dT$ **= 1 MHz/K**
  - **Strain** $d\nu_B/dS$ **= 460 MHz/%**
- **Zero-dispersion wavelength also varies:**
  - **Temperature** $d\lambda_0/dT$ **= 0.03 nm/K**
  - **Strain** $d\lambda_0/dS$ **= 2 nm/%**
- **Can be used together to suppress SBS and control $\lambda_0(z)$**

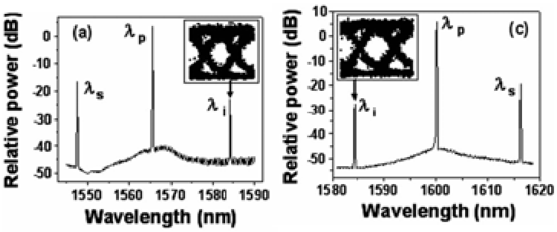
J.D. Marconi et. al., ECOC'2005





Example: Wavelength Converter

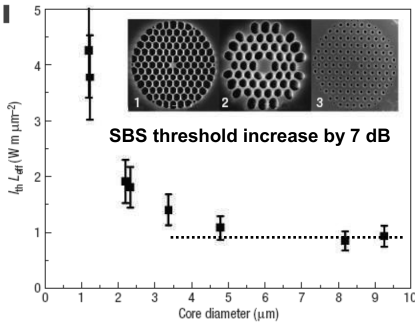
- Strain suppressed SBS
- 70 nm signal tuning range (1548 – 1618 nm)
- Narrow line idler (100 kHz pump width)

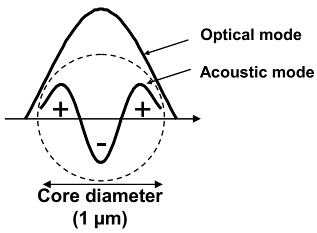


J.D. Marconi et al., ECOC'2005

Low SBS fibers

- Photonic Crystal Fibers
  - Acoustic and optical confinement
  - Strong interaction but low coupling between optic mode and acoustic modes





P. Dainese et al., Nature Phys. 2, 388, 2006

- Standard telecom-compatible fibers: 4 dB SBS threshold increase

M.V. Vaughin et al., JON 5, 40 (2006)

Review

- FOPAs for DWDM can be superior to Semiconductor, Erbium, and Raman amplifiers
  - in bandwidth
  - in gain flatness
  - in noise figure
- Parametric processes can be used in a variety of functions for optical networking (wavelength conversion/exchange) and signal processing (phase conjugation, power limiting, all optical switching, fast tunable filters…)
- Fibers for further progress: uniformity, tailored dispersion, highly nonlinear but low SBS
- As new fibers (photonic crystal or conventional) become available with optimized designs, FOPDs may revolutionize optical communications

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