Novel Optical Fibers for Distributed Sensor Applications

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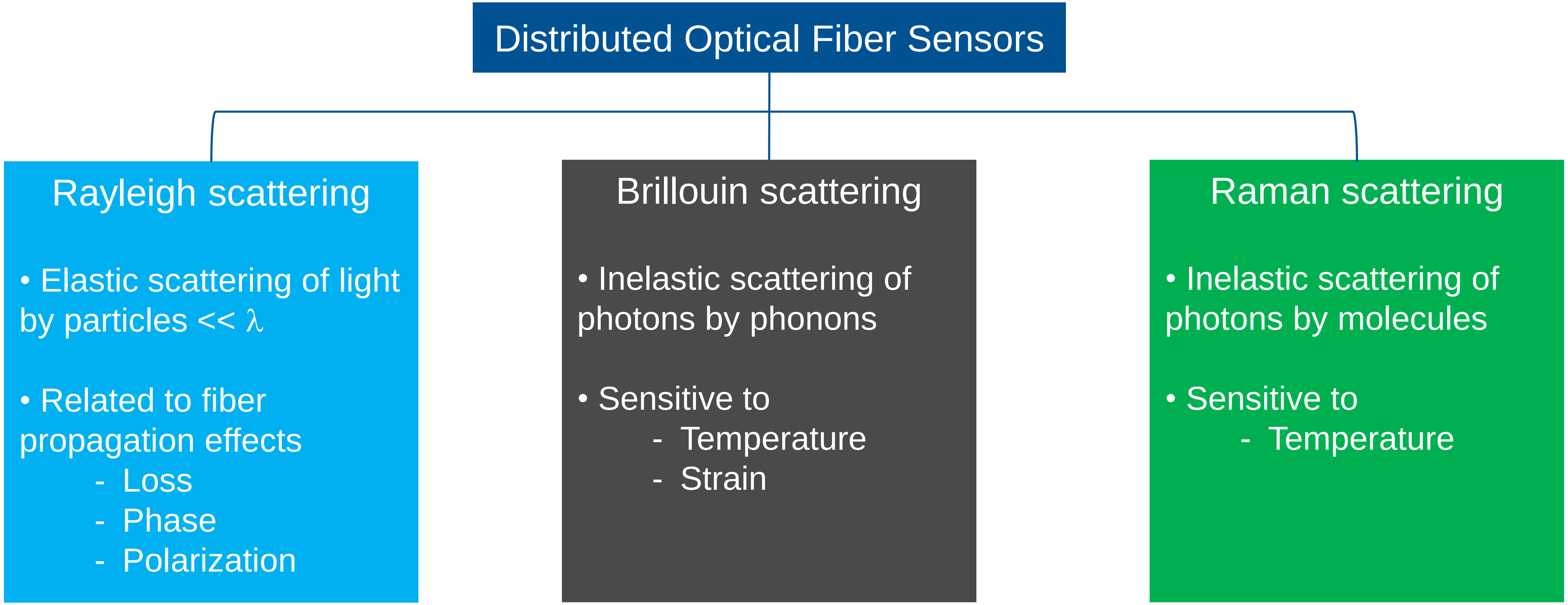
Acknowledgement: Jeffery S. Stone, Shenping Li

Distributed Optical Fiber Sensors



Distributed Optical Fiber Sensors

Rayleigh scattering

- Elastic scattering of light by particles << λ
- Related to fiber propagation effects
  - Loss
  - Phase
  - Polarization

Brillouin scattering

- Inelastic scattering of photons by phonons
- Sensitive to
  - Temperature
  - Strain

Raman scattering

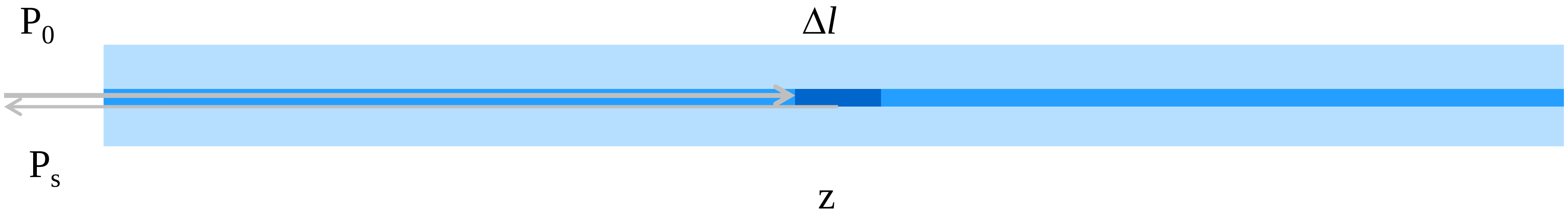
- Inelastic scattering of photons by molecules
- Sensitive to
  - Temperature

- Needs for improving sensitivity, spatial resolution, and sensing range and for measuring strain and temperature simultaneously

New Fiber Designs for Distributed Fiber Sensors

- Fiber with enhanced Rayleigh scattering
- Fiber with weak Bragg gratings
- Dual core fiber for separating temperature and strain
- Few mode fiber for Brillouin sensors
- Brillouin frequency managed fiber

Backscattered Light due to Rayleigh Scattering



- Power detected from Rayleigh scattering at location z

$$P_s = C\alpha_s \Delta l P_0 e^{-2(\alpha_s+\alpha_0)z}$$

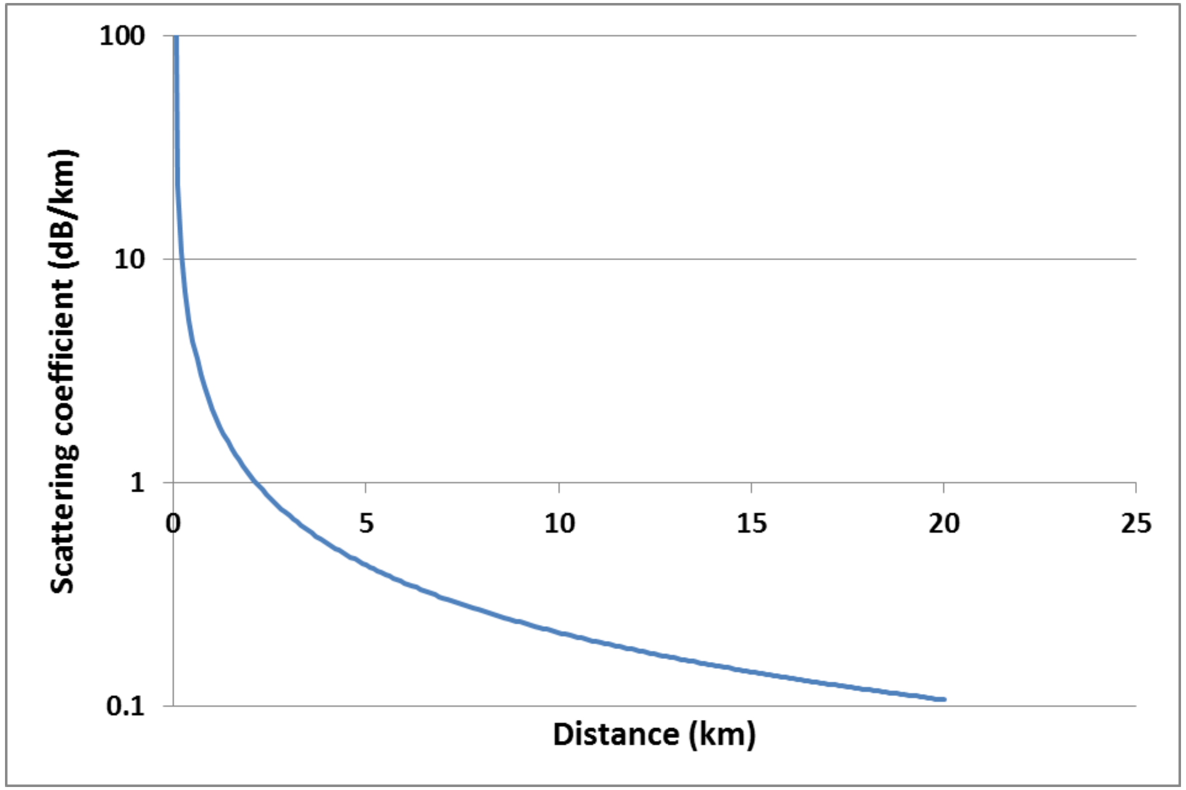
P_0: launch power at z=0

C: capture efficiency

α_s: Rayleigh scattering coefficient

α_0: loss coefficient due to other factors

Optimal Rayleigh Scattering Coefficient



- Maximal power is detected when $\alpha_s(in\, dB/km) = \frac{4.3}{2z}$
- Optimal Rayleigh scattering coefficient depends on sensing distance

Capture Efficiency

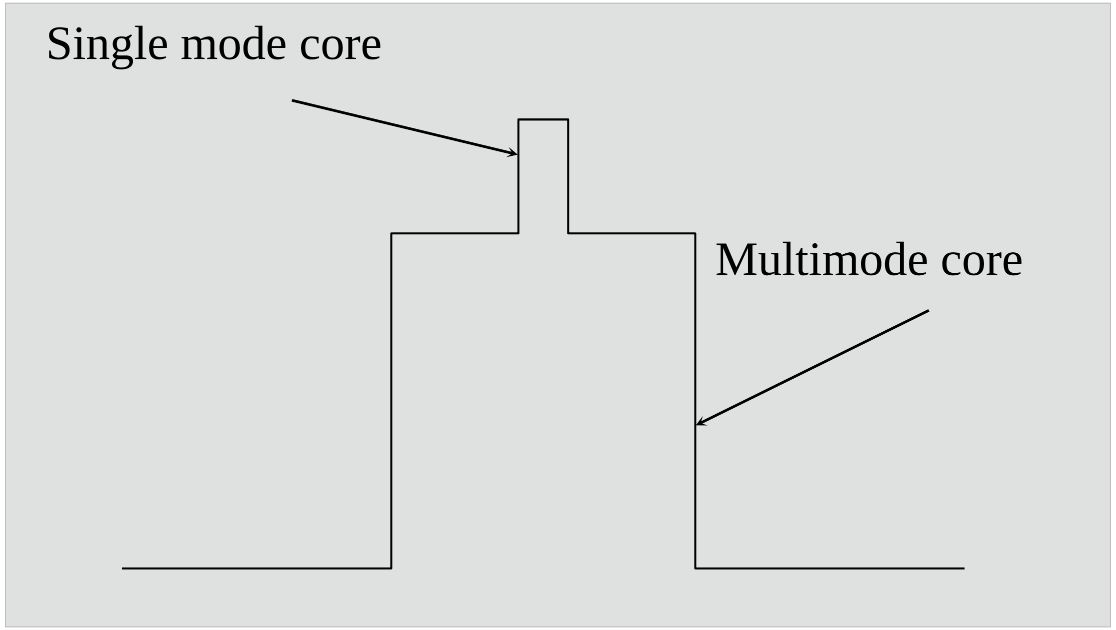
$$C = \kappa \frac{NA^2}{n_1^2}$$

NA: numerical aperture, n_1: refractive index of core

κ: a parameter depending on types of fiber core

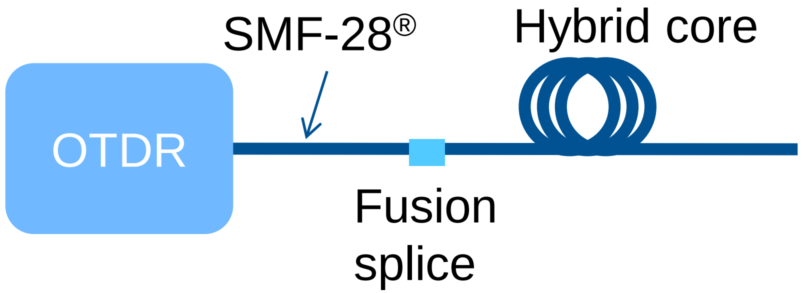
$$\kappa = \begin{cases} 0.38 & for\, step\ index\ profile \\ 0.25 & for\, parabolic\, index\ profile \end{cases}$$

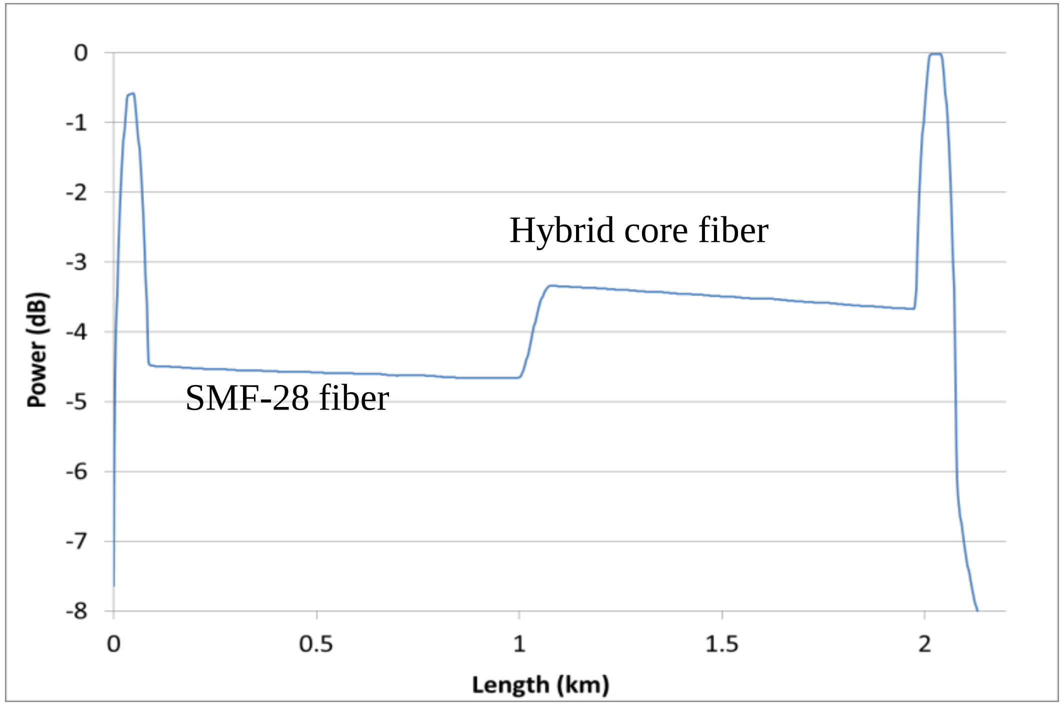
Hybrid Core Design



- A single mode core on top of a multimode core
- Higher Ge doping level increases the Rayleigh scattering coefficient
- High numerical aperture enables higher capture efficiency

Measured Rayleigh Backscattered Power





- Single mode core of 0.4% delta, multimode core of 0.85% delta
- Backscattered signal from the single mode core is about 1.3 dB higher than that from the SMF-28 fiber
- Backscattered power is expected be about 4 dB higher if the multimode core is used to capture the light

New Fiber Designs for Distributed Fiber Sensors

- Fiber with enhanced Rayleigh scattering
- Fiber with weak Bragg gratings
- Dual core fiber for separating temperature and strain
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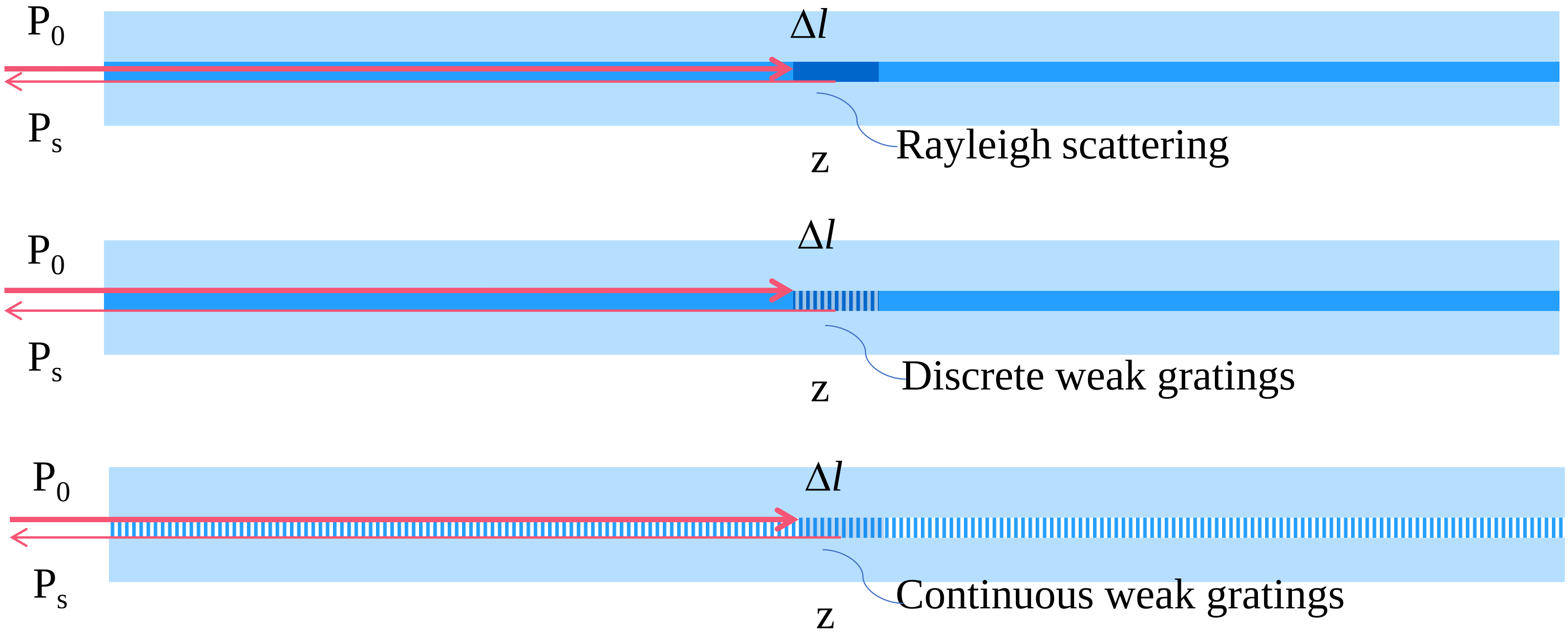
Optical fibers with weak gratings to enhance backscattering



- The capture efficacy is high, because the reflection by the grating is within the fiber core
- The attenuation increase is low because the scattered light is only in the backward direction

Methods for writing grating inside fiber

- Online grating writing during the fiber draw
  - Need to implement grating writing setup on the draw
  - Difficult for high-speed draw
- Offline grating writing after the fiber draw
  - For fibers with 250 μm diameter acrylate coating, the coating materials must be removed, and the fiber needs to be recoated after writing
  - Use a UV transparent coating, which is more expansive than UV curable coatings, and is difficult to apply with high draw speeds
  - We propose to use fibers with a Titania doped cladding layer
    - Can be drawn without coating for continuous grating writing offline
    - Fiber can be coated after grating writing to protect the fiber

Distributed weak Bragg gratings for sensing

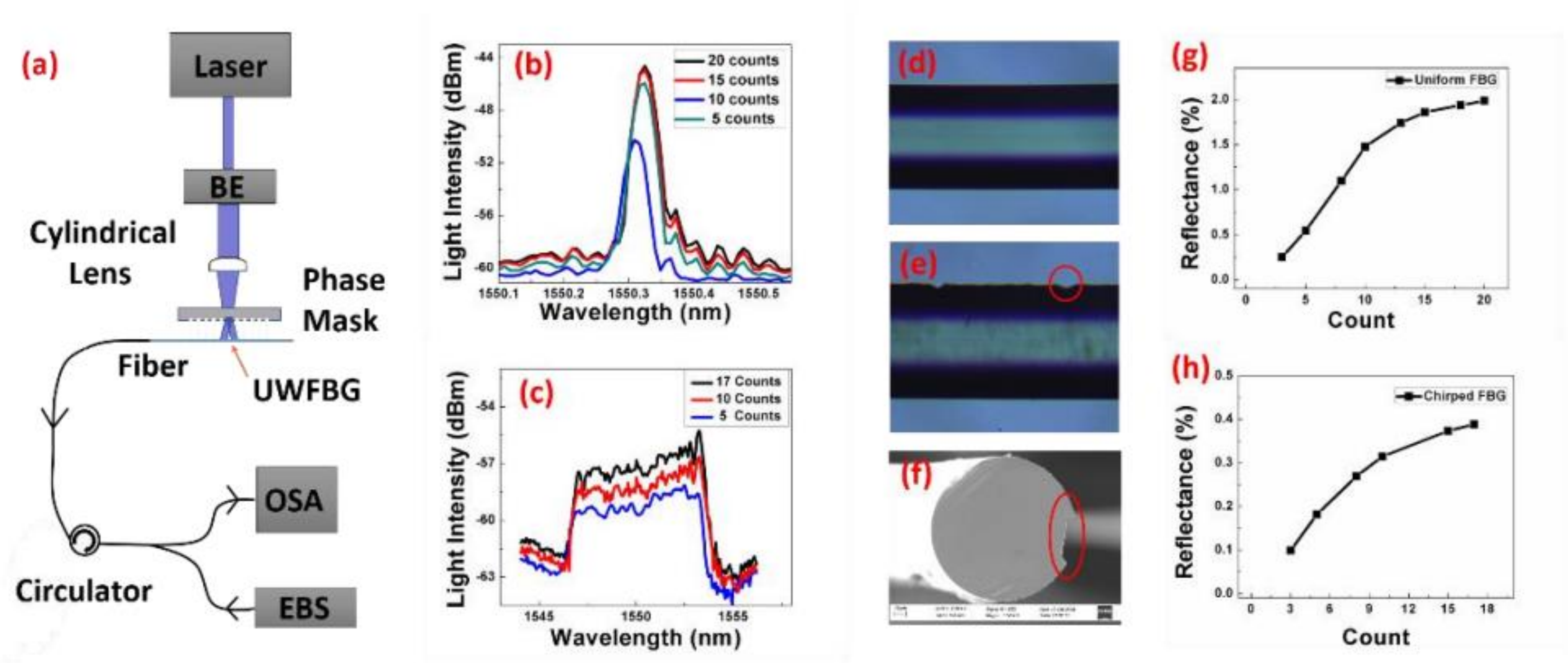


Fig. 1. (a) Fabrication setup; (b) Reflection spectra of uniform UWFBG after 5, 10, 15 and 20 counts of laser pulses; (c) Reflection spectra of chirped UWFBG after 5, 10 and 17 counts of laser pulses; Optical microscope images of fiber when intensity of incident radiation is at 180-mJ/cm^2 (d) and 220-mJ/cm^2 (e); (f) cross-sectional SEM image of the damaged fiber; FBG reflectance of (g) uniform FBG vs. pulse numbers; and (h) chirped FBG vs pulse numbers.

J. Wu, Z. Peng, M. Wang, R. Cao, M. J. Li, H. Wen, H. Liu, and K. P. Chen, Optical Sensors and Sensing Congress 2019, paper ETh1A.4.

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Dual Core Fiber for Strain and Temperature Separation

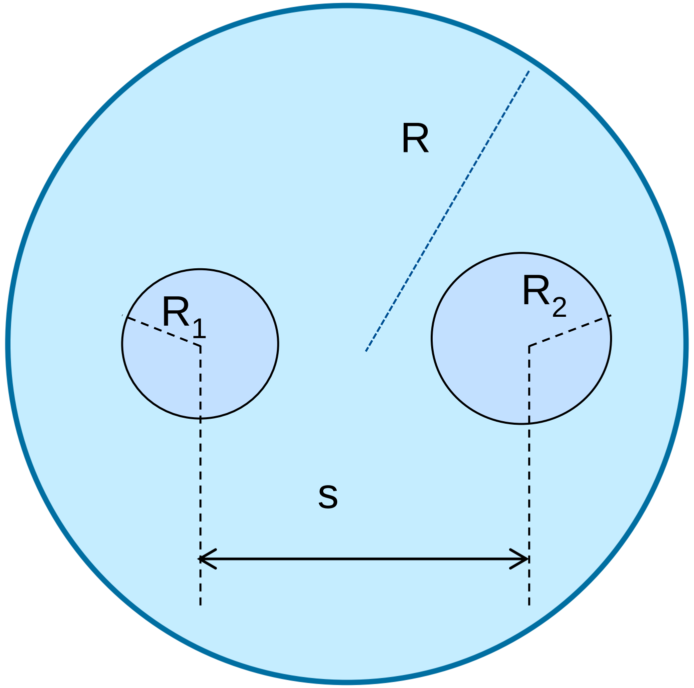
- Two cores have different temperature and stain coefficients

$$\Delta v_B^{c1} = K_\varepsilon^{c1}\Delta\varepsilon + K_T^{c1}\Delta T,$$

$$\Delta v_B^{c2} = K_\varepsilon^{c2}\Delta\varepsilon + K_T^{c2}\Delta T$$

- If $K_\varepsilon^{c1}K_T^{c2} \neq K_\varepsilon^{c2}K_T^{c1}$

  then a solution exists for $\Delta\varepsilon$ and ΔT



Dual Core Fiber Design Considerations

- Different temperature and strain coefficients for the two cores
  - Different dopants
  - Different dopant levels
- Large BFS difference between the two cores
  - Separate the two BFS peaks
- Low attenuation
  - Increasing sensing distance
- Large MFD
  - Reduce fiber nonlinear effects
  - Reduce splice loss

Dual Core Fiber Design

- Design procedure
  - Solve optical wave equations to get effective index n_{eff}

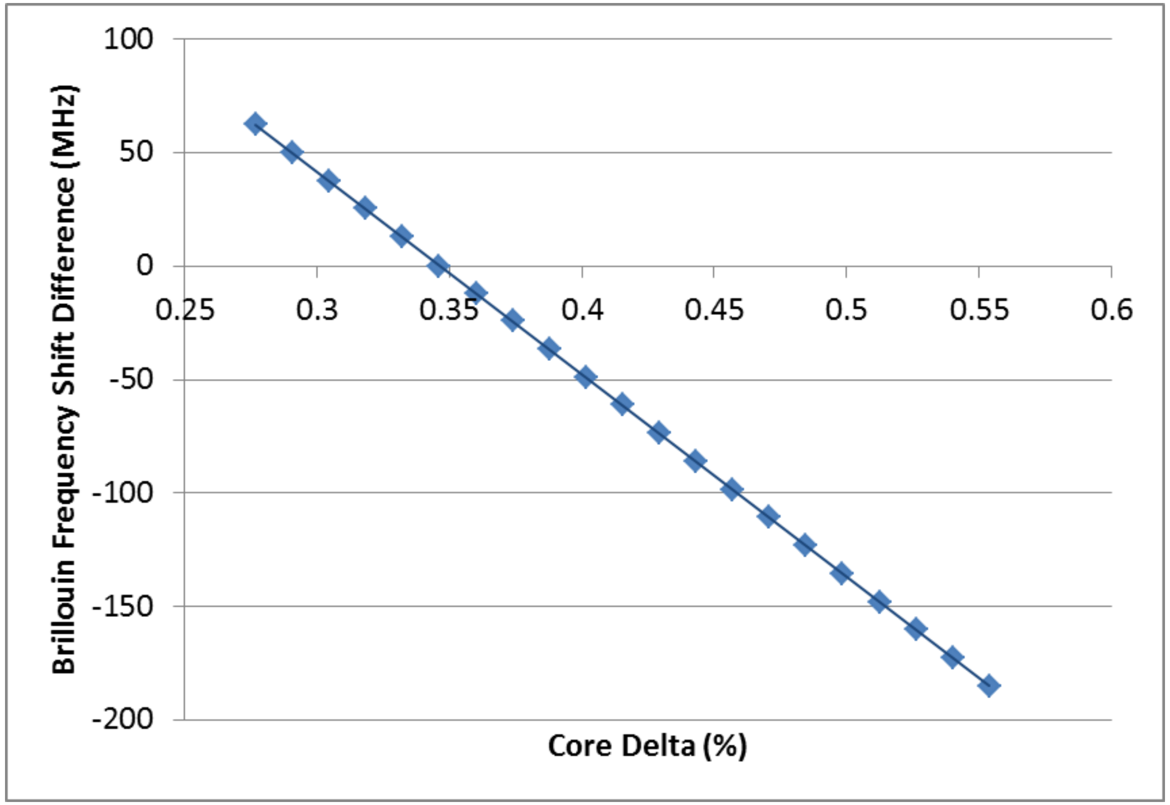
$$\nabla_t^2 \mathbf{E} + \left(\mu_0 \varepsilon_0 \varepsilon_r \omega^2 - \beta^2\right)\mathbf{E} = 0$$

  - Solve acoustic wave equation to get longitudinal velocity V_{Leff}

$$\nabla_t^2 \rho_u + \left(\frac{\Omega_u^2}{V_L^2} - \mathrm{B}_u^2\right)\rho_u = 0$$

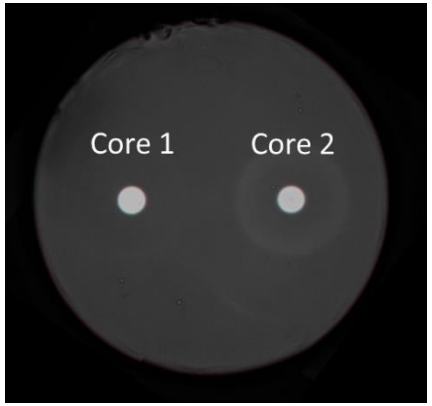
- Brillouin frequency shift

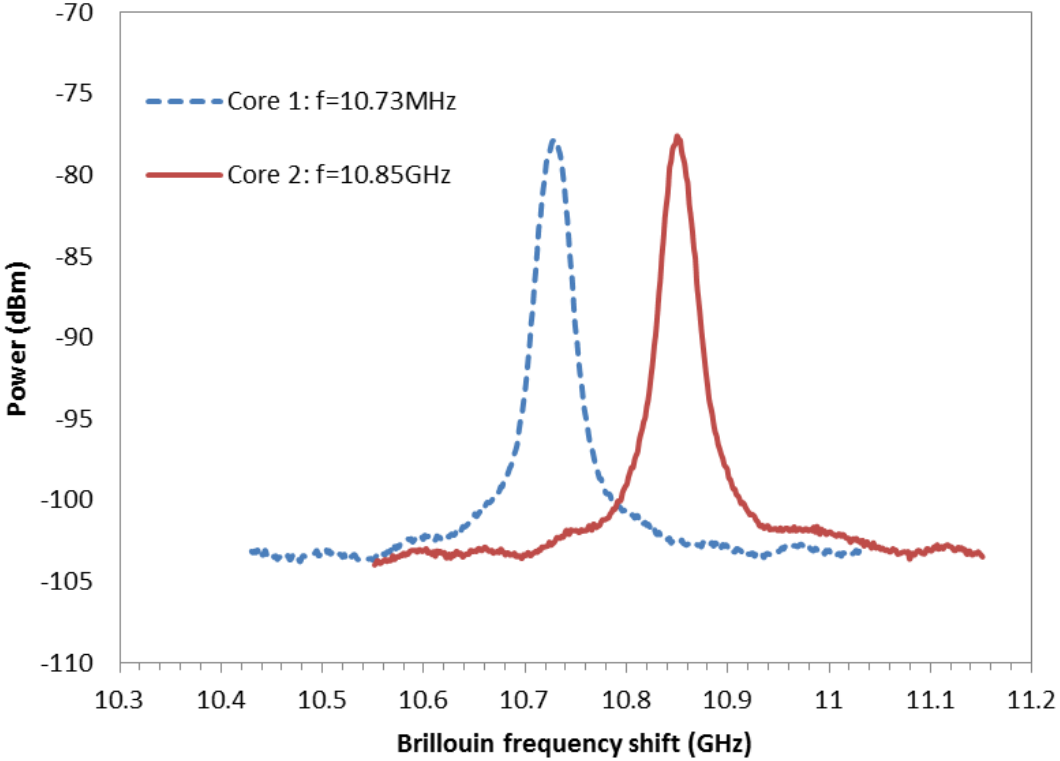
$$\nu_{B,i} = \frac{2 n_{eff,i} V_{Leff,i}}{\lambda} \qquad i = 1, 2$$



Dual Core Fiber Experimental Results

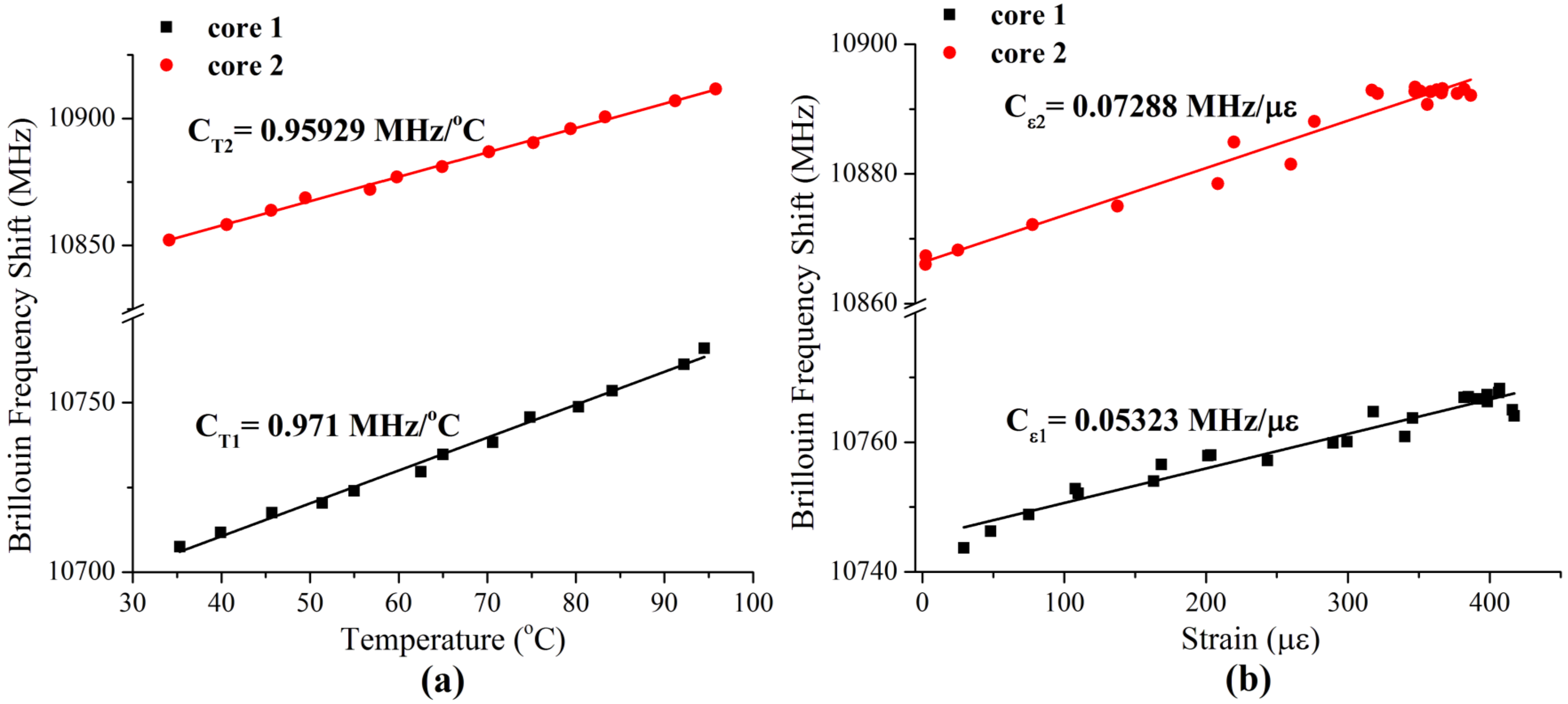
	Core 1	Core 2
Core spacing (µm)	54.5	
Optical core delta (%)	0.46	0.34
Core radius (µm)	4.25	4.4
Clad diameter (µm)	125	
Cutoff (nm)	1530	1320
MFD (µm) at 1550	9.3	10.4
MFD (µm) at 1310	8.1	9.3
Loss @1550 nm (dB/km)	0.23	0.29
Brillouin frequency shift (MHz)	10730	10850
Brillouin frequency shift (MHz)	120	





M. Li, S. Li, J. A. Derick, J. S. Stone, B. C. Chow, K. W. Bennett, and D. M. Sutherlin, in Asia Communications and Photonics Conference 2014, paper AW4I.3.

Measure Temperature and Strain Coefficients



- The two cores have different temperature and strain coefficients

Zaghloul, M.A.S.; Wang, M.; Milione, G.; Li, M.-J.; Li, S.; Huang, Y.-K.; Wang, T.; Chen, K.P. Sensors 2018, 18, 1176.

Simultaneous Temperature and Strain Measurements

Temperature [^oC] (Thermocouple)	Temperature [^oC] (Dual core fiber)	Strain [$\mu\epsilon$] (FE analysis)	Strain [$\mu\epsilon$] (Dual core fiber)
36.10	35.39	92.37	117.51
41.00	41.01	167.80	208.72
48.90	48.85	289.41	233.07
53.50	53.49	360.22	395.28
60.15	59.87	462.59	471.80
64.35	64.21	527.25	574.16
71.25	70.63	633.47	632.45
75.60	75.57	700.43	773.47
81.30	81.16	788.18	815.03

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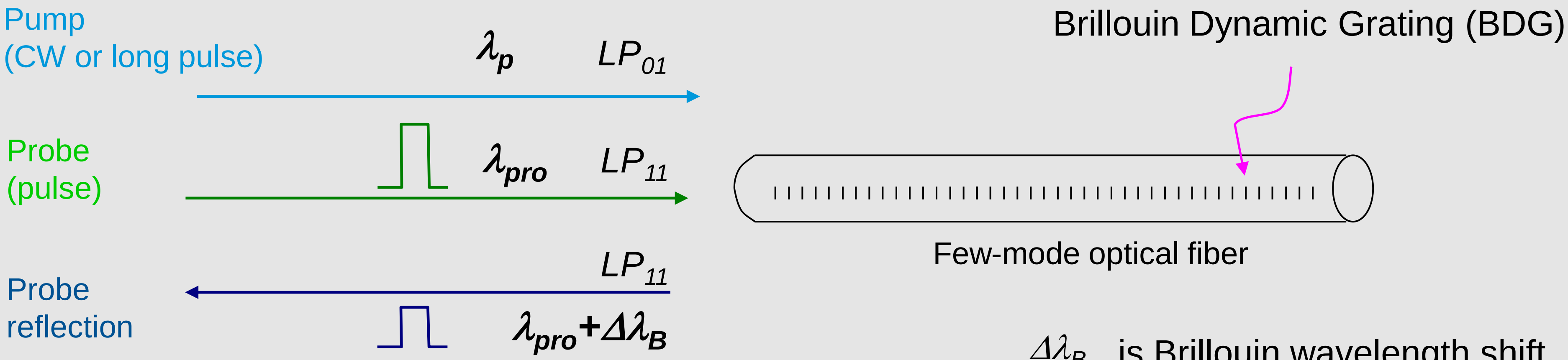
Principle of Few-mode Fiber Based BOTDR



$\Delta\lambda_B$ is Brillouin wavelength shift

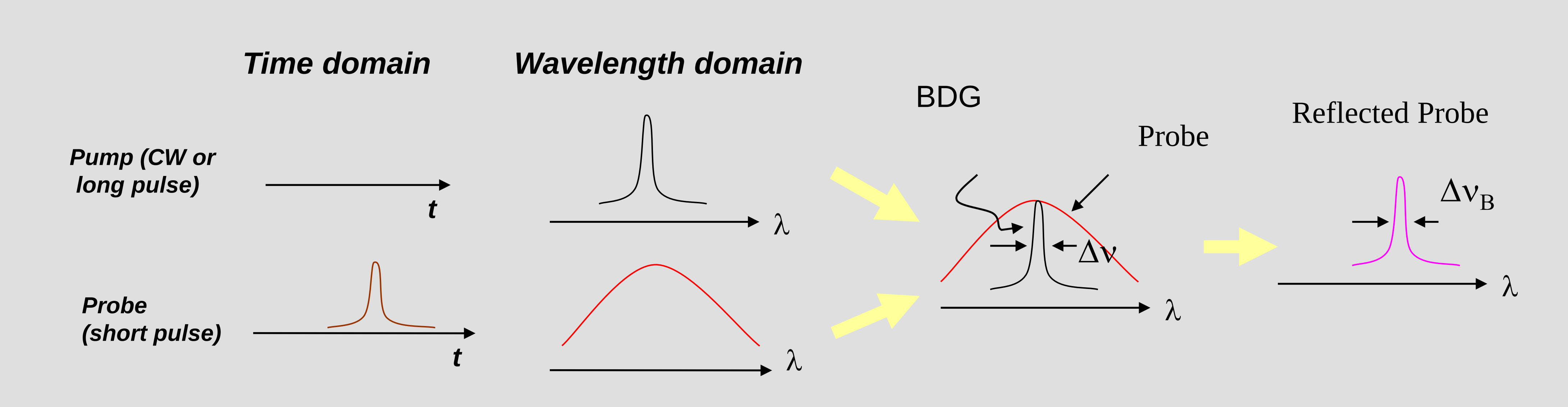
$$\lambda_{pro} - \lambda_p = \frac{n_{11} - n_{01}}{n_{01}} \lambda_p$$

n_{01}: effective index LP_{01} mode, n_{11} : effective index of LP_{11}

How to Achieve High-spatial-resolution and High Sensitivity Simultaneously?

- Spatial resolution: $\Delta L = c\tau/2n$, determined by pulse width of probe τ
- Temperature or strain sensitivity: $dT \propto \Delta\nu_B,\ d\varepsilon \propto \Delta\nu_B$

  determined by Brillouin spectral width $\Delta\nu_B$ of reflected probe



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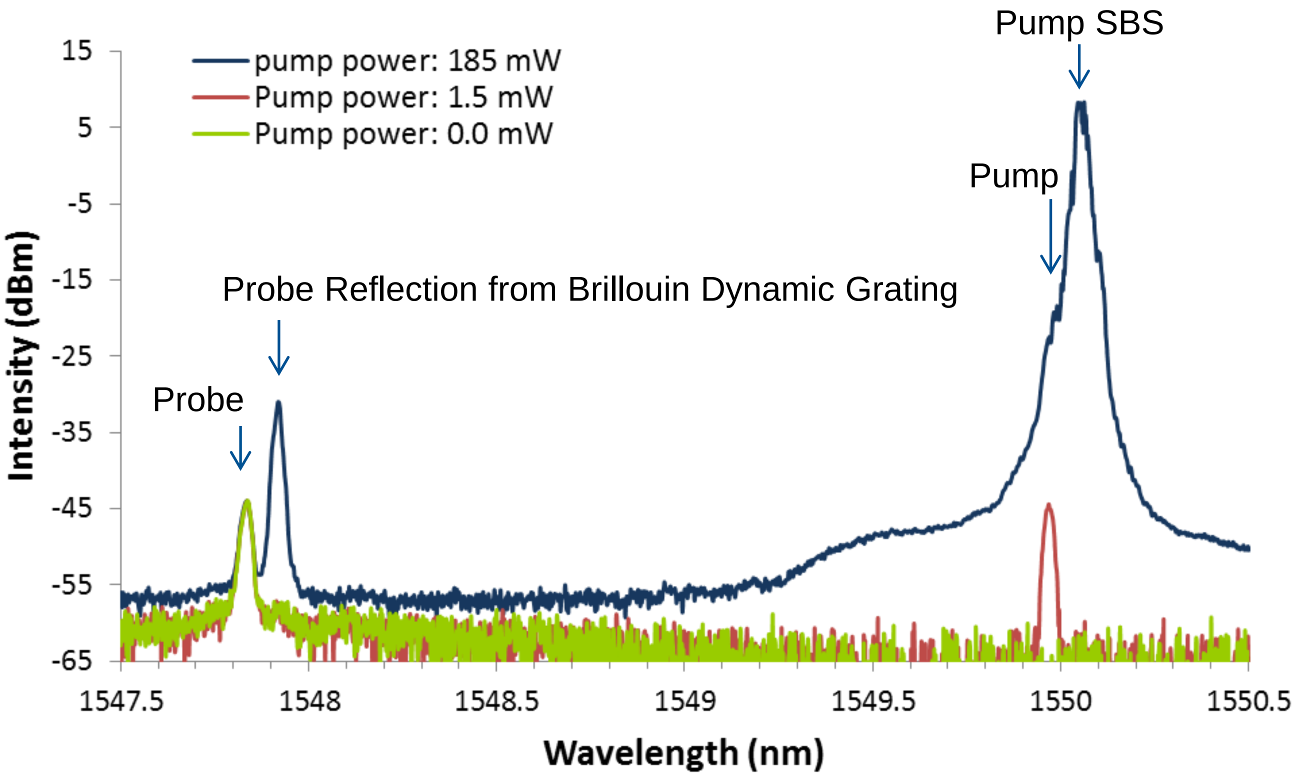
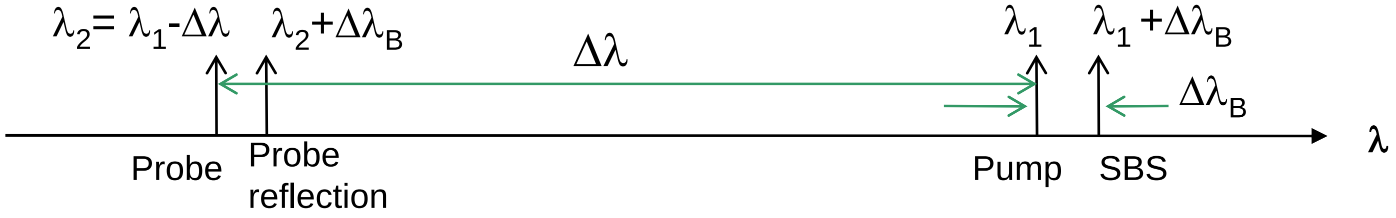
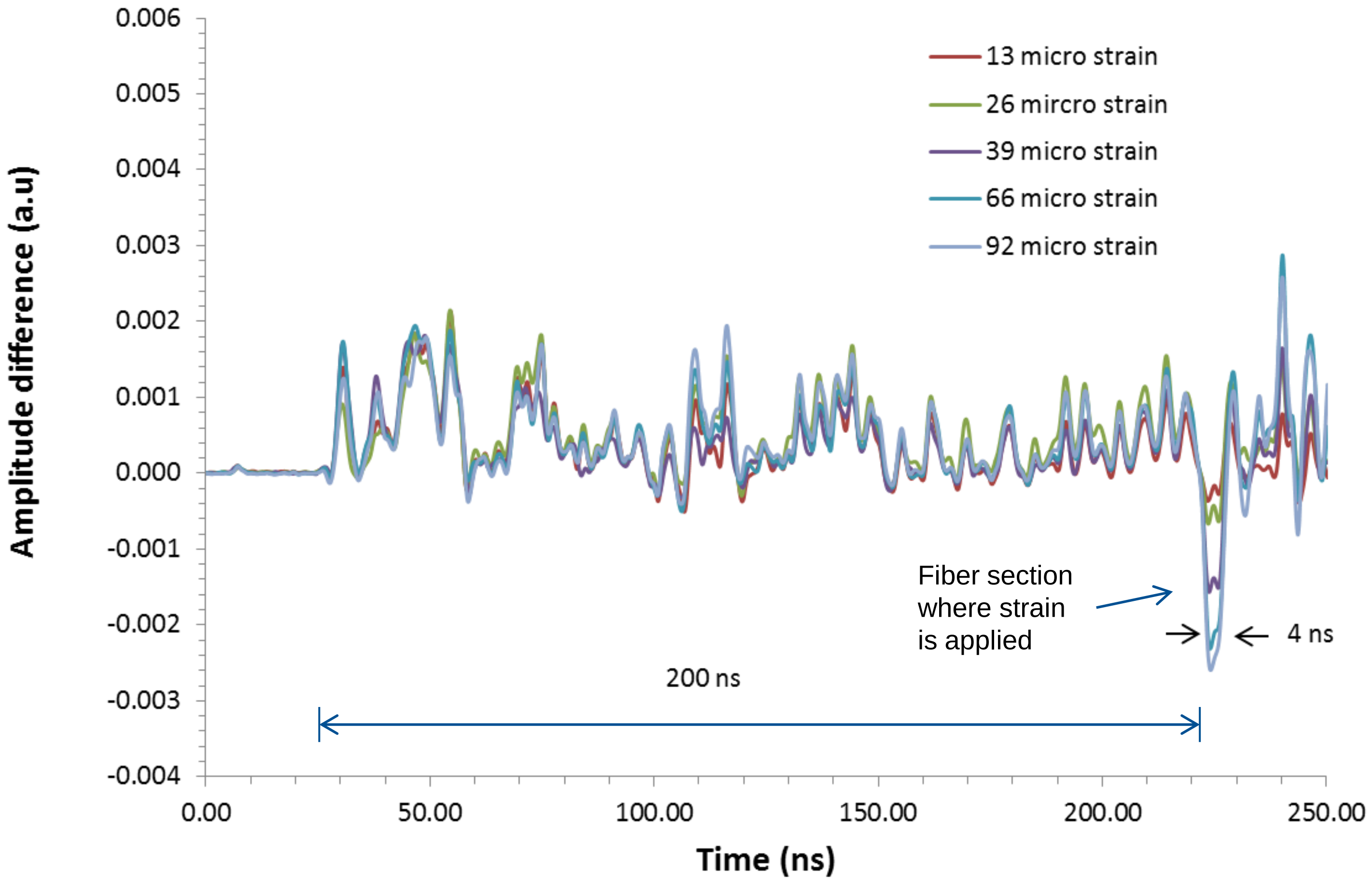
Optical Spectra of Back Scattered Light





Shenping Li, Ming-Jun Li, and Richard S. Vodhanel, Opt. Lett. 37, 4660-4662 (2012)

Strain Measurement with 0.4 m Spatial Resolution



Simultaneous Temperature and Strain Sensing

Brillouin frequency shift: $$\delta\nu_B = K_\nu^\varepsilon \delta\varepsilon + K_\nu^T \delta T$$

Phase matching wavelength separation: $$\delta(\Delta\lambda) = K_\lambda^\varepsilon \delta\varepsilon + K_\lambda^T \delta T$$

If $K_\lambda^\varepsilon K_\nu^T \neq K_\lambda^T K_\nu^\varepsilon$, simultaneous temperature and strain can be achieved.

Measured temperature and strain coefficients for one of our FMFs:

K_ν^ε = 0.0143 MHz/με, K_ν^T = *0.9005* MHz/^{0}C,
K_λ^ε = -0.00227 pm/με, K_λ^T = -0.01610 pm/^{0}C;

which results $$K_\lambda^\varepsilon K_\nu^T - K_\lambda^T K_\nu^\varepsilon = -0.00181 pm.MHz/\mu\varepsilon.^0C$$

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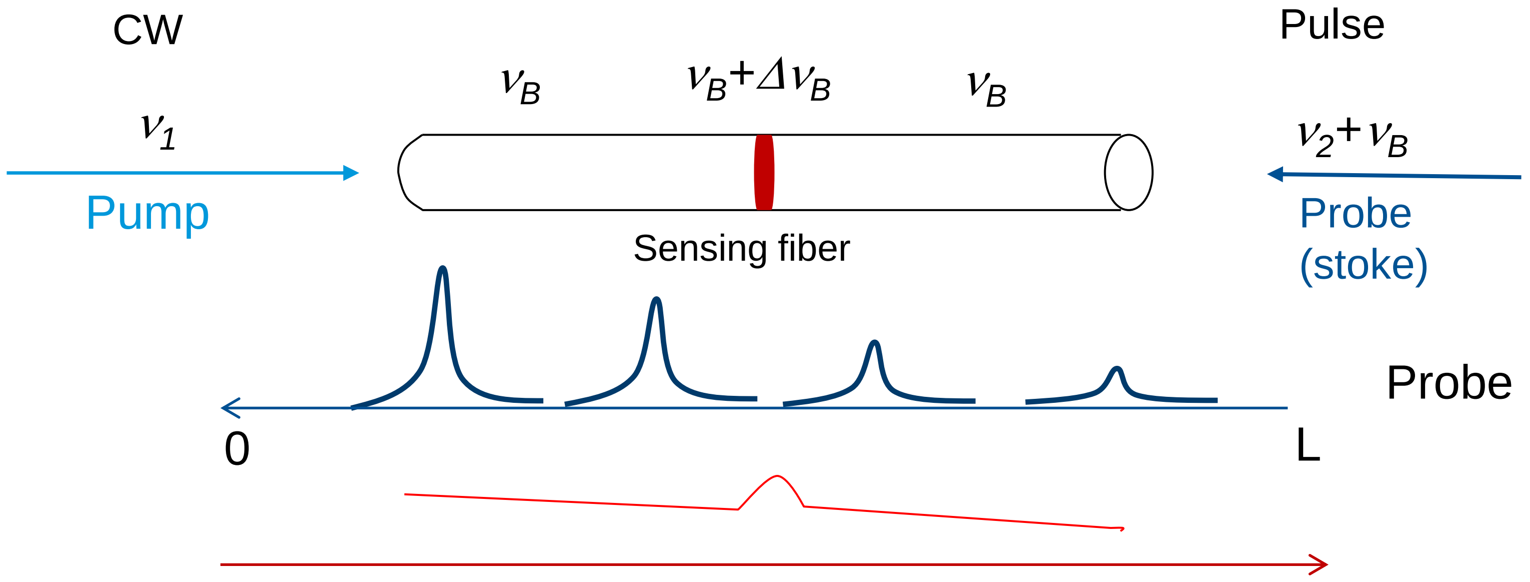
Sensing Range Limited by Nonlinear Effects

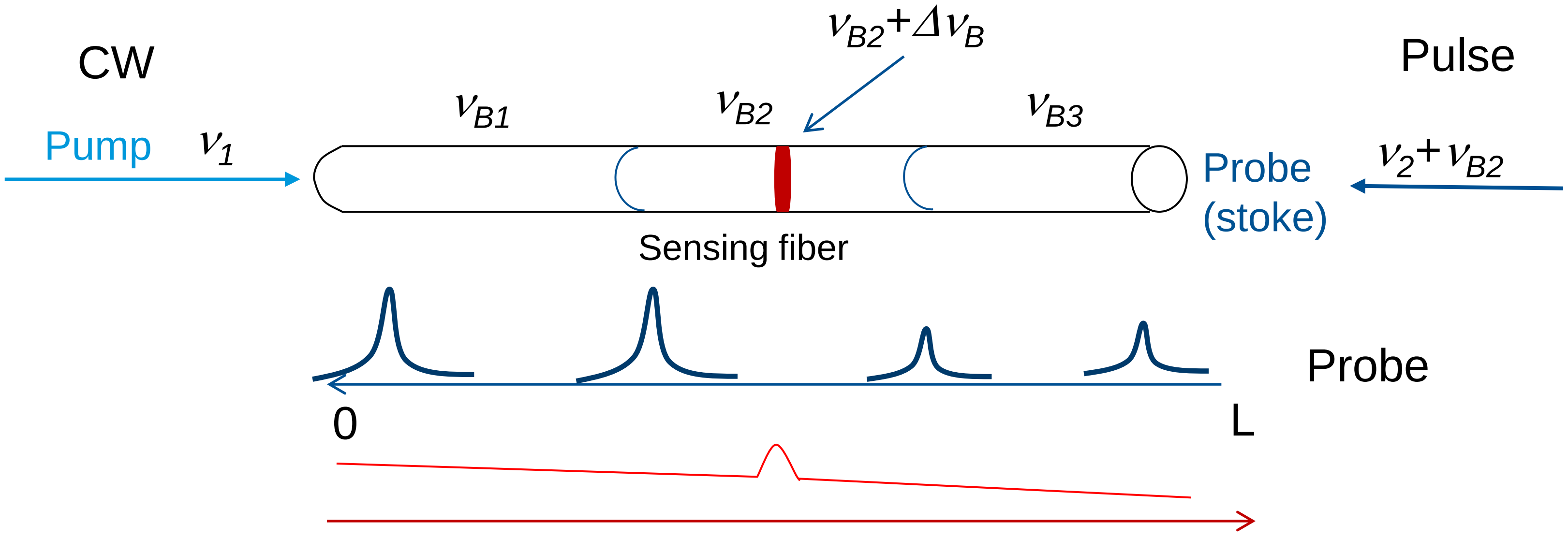


Excessive amplification + fiber nonlinear effects

➡ SNR degradation

➡ limited sensing range

Brillouin Frequency Shift Managed Fiber For BOTDA



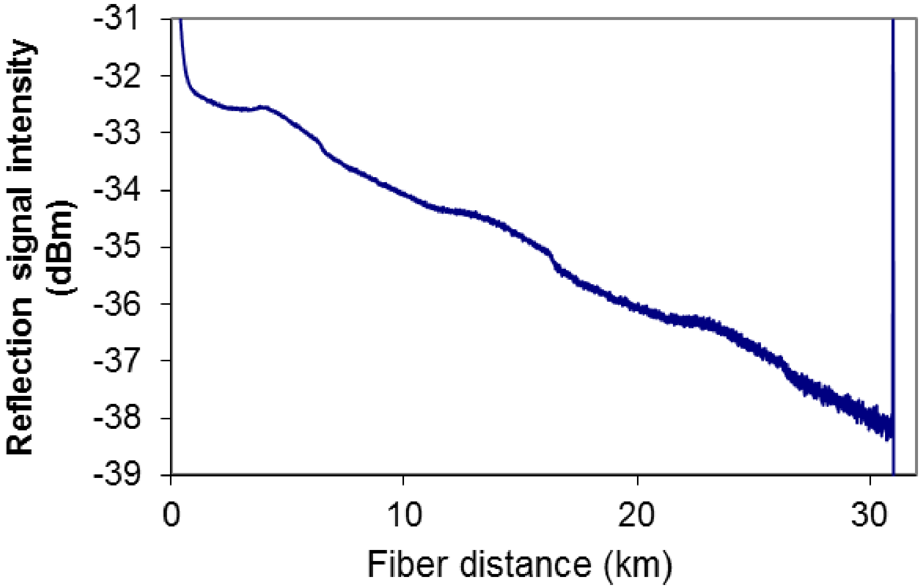
Reduced probe amplification

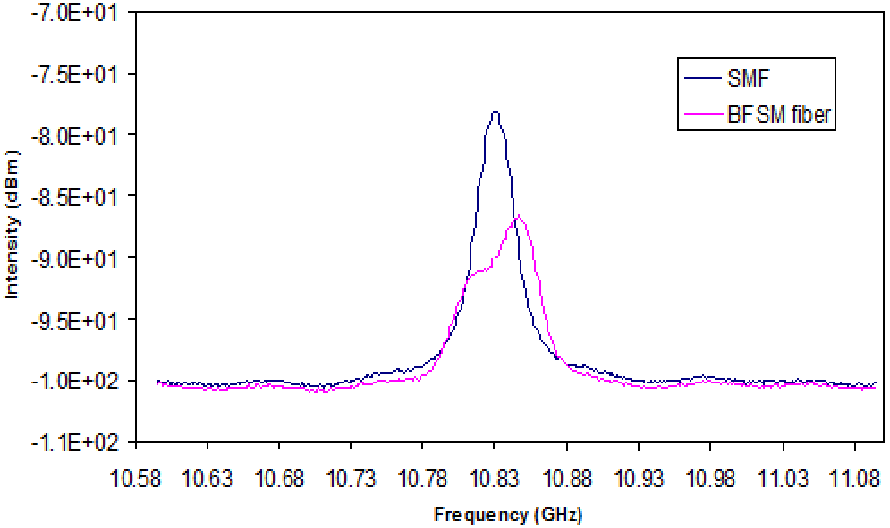
→ smaller fiber nonlinear effects

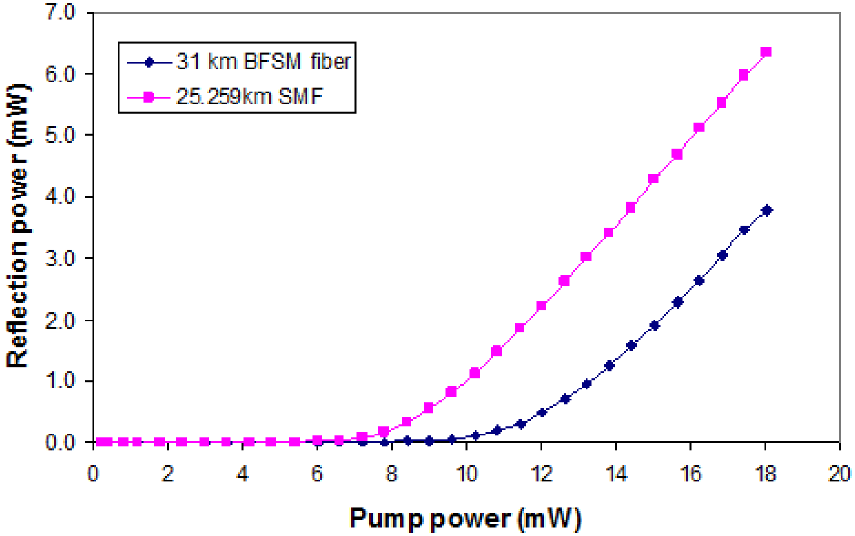
→ lower SNR degradation

→ longer sensing range

Experimental Results of Brillouin Frequency Shift Managed Fiber







- Period was about 5 km
- SBS threshold was increased by 2 dB
- Increase sensing range by 9 km

Summary

- Hybrid core fiber
  - Enhance Rayleigh scattering
  - Increase capture efficiency
- Fiber with weak gratings
  - Thin coated fiber allows continuous grating writing
  - Increase backscattered signal without increasing much the attenuation
- Dual core fiber
  - Separate temperature and strain effects
- Few mode fiber Brillouin dynamic grating
  - Increase resolution and sensitivity
  - Separate temperature and strain effects
- Brillouin frequency managed fiber
  - Longer sensing range

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