Mise en évidence de l'élasticité non linéaire de la silice dans des fibres optiques effilées

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Photon vs Phonon

Light is fast and sound is slow, but $\lambda = V/f$

- Optics

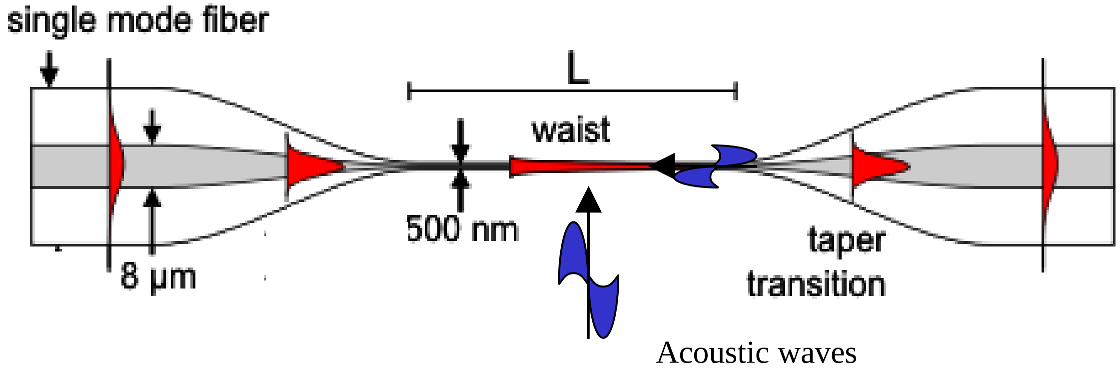
wavelength ~ 1 µm, velocity ~ 3 10^8 m/s frequency ~ 300 THz

- Acoustic phonons

frequency ~ 2 GHz, velocity ~ 5000 m/s wavelength ~ 1 µm

➔ Optical and elastic wavelength can be of the same order, in the µm range, despite the huge difference in frequency!

➔ We use **subwavelength diameter waveguide** to confine optical mode but we can also confine and alter acoustic wave.



Léon Brillouin

DIFFUSION DE LA LUMIÈRE ET DES RAYONS X

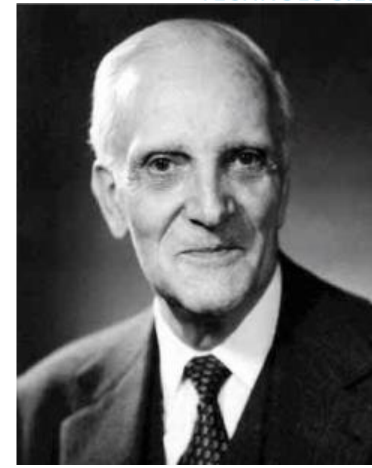
PAR

UN CORPS TRANSPARENT HOMOGÈNE

INFLUENCE DE L'AGITATION THERMIQUE

Par Léon BRILLOUIN

1. Un corps homogène subit, du fait de son agitation thermique, de perpétuelles fluctuations de densité. Ces fluctuations peuvent être mises en évidence par différents phénomènes. Un des principaux est la diffusion de la lumière. Lorsqu'un rayon lumineux traverse le corps, toutes les fluctuations de densité constituent pour lui une série d'obstacles qui dispersent, en toutes directions, de l'énergie lumineuse. Cette diffusion est en général à peine perceptible.


L. Brillouin (1889-1969)

Free Access : https://www.annphys.org/articles/anphys/abs/1922/17/contents/contents.html

Léon Brillouin « **Diffusion de la lumière et des rayons X par un corps transparent homogène-Influence de l'agitation thermique** »
Annales de physique, Vol 9., p88-122, 1922 – Thèse Paris 1920

Photon and Phonon in Brillouin scattering

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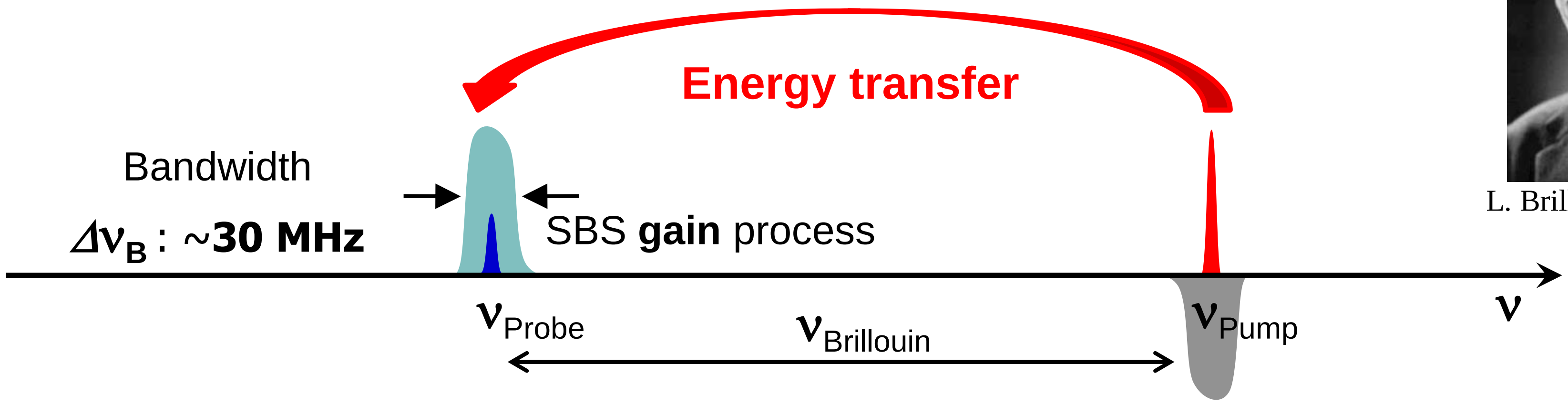
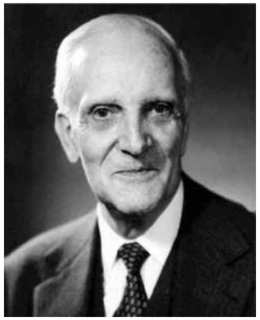
- Brillouin scattering

Under phase-matching conditions ($\nu_1=\nu_2+\nu_B$), where $\nu_B = \frac{2nV_a}{\lambda} \approx 11\,GHz$,

a **Bragg-type moving grating** is generated along the fiber core by **electrostriction**.

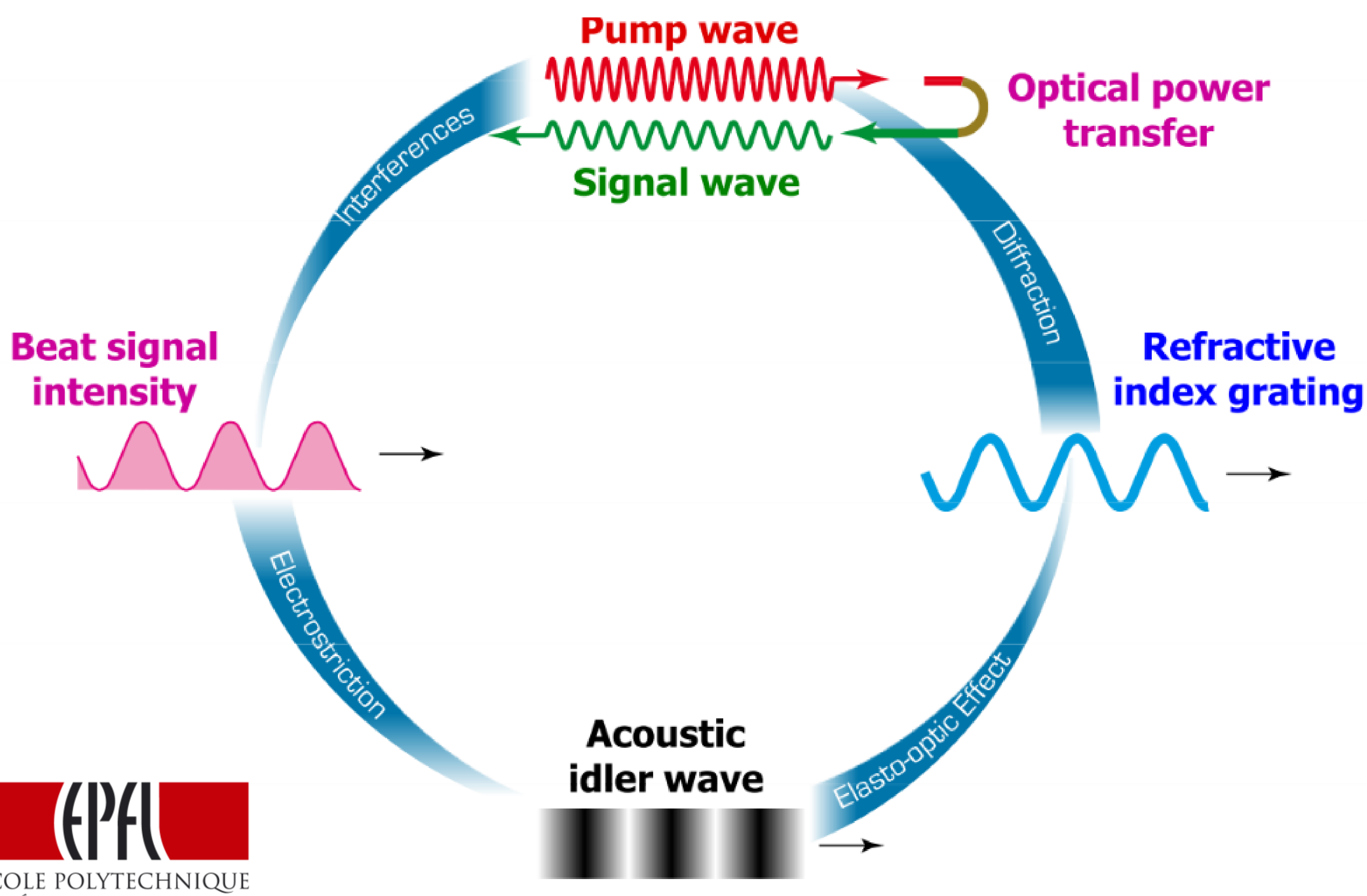




L. Brillouin (1889-1969)

- Sensing application — J-C. Beugnot *et al.*, Opt. Express, **19** (2011)
- Microwave photonic filter — D. Marpaung *et al.* Optica **2**, 76-83 (2015)
- Coherent laser — J. Li, H. Lee and K. J. Vahala, Nat. Comm. **4** (2013)

Brillouin scattering in optical fiber



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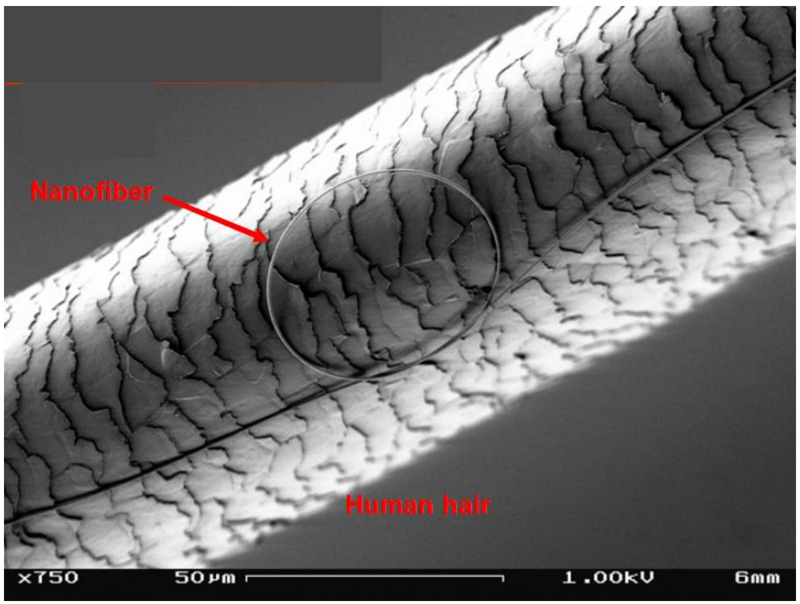
Nanofiber



Tong, Sumetsky Springer 2010

Applications in:

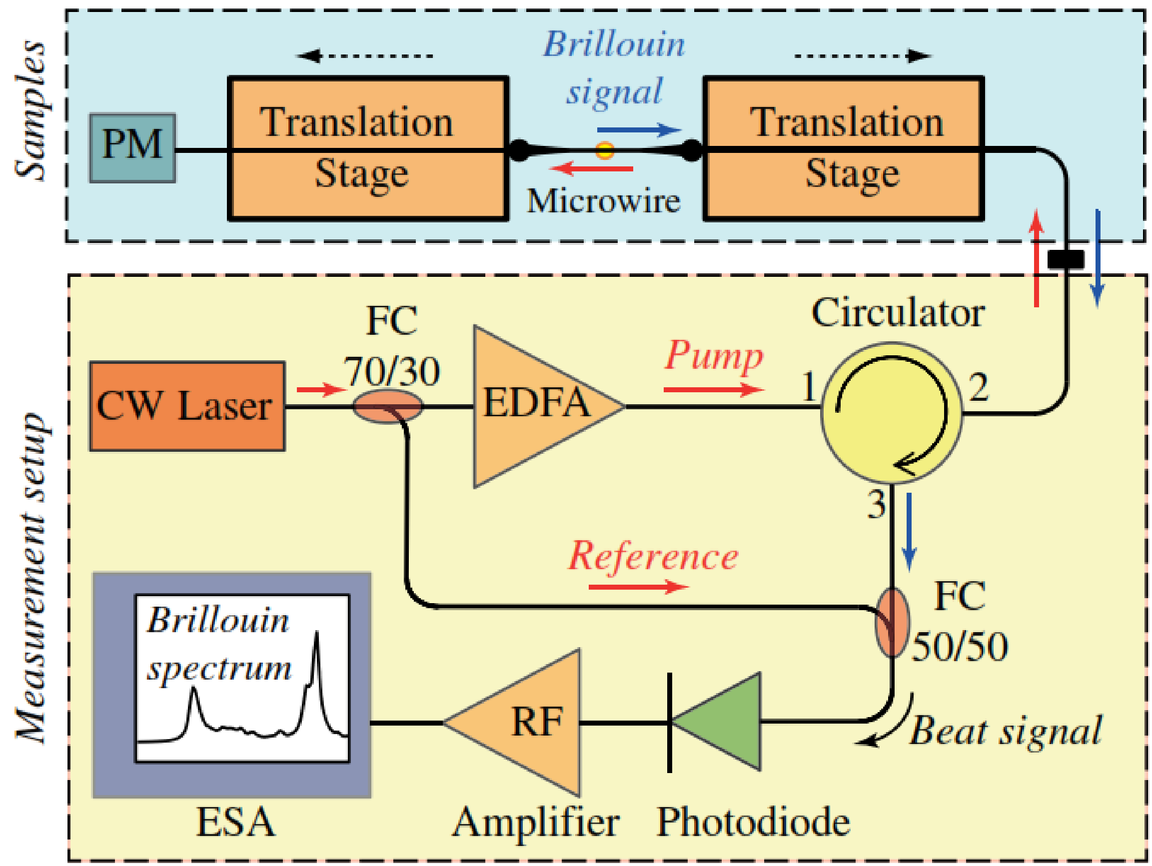
- Optical sensors
- Microcavities
- Light Emitting devices
- Quantum Optics
- Nonlinear Optics
- Optomechanics

…

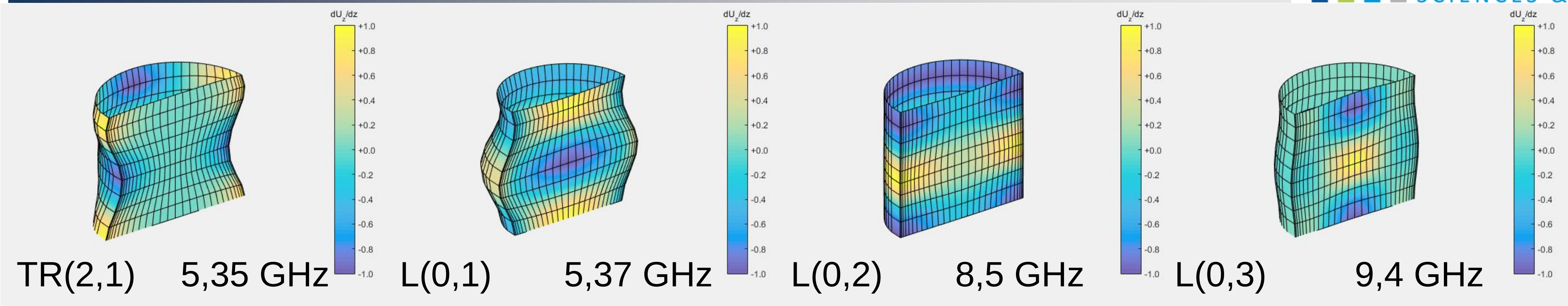
X. Wu and L. Tong,
Nanophotonics **2**, 407 (2013).

Experimental setup

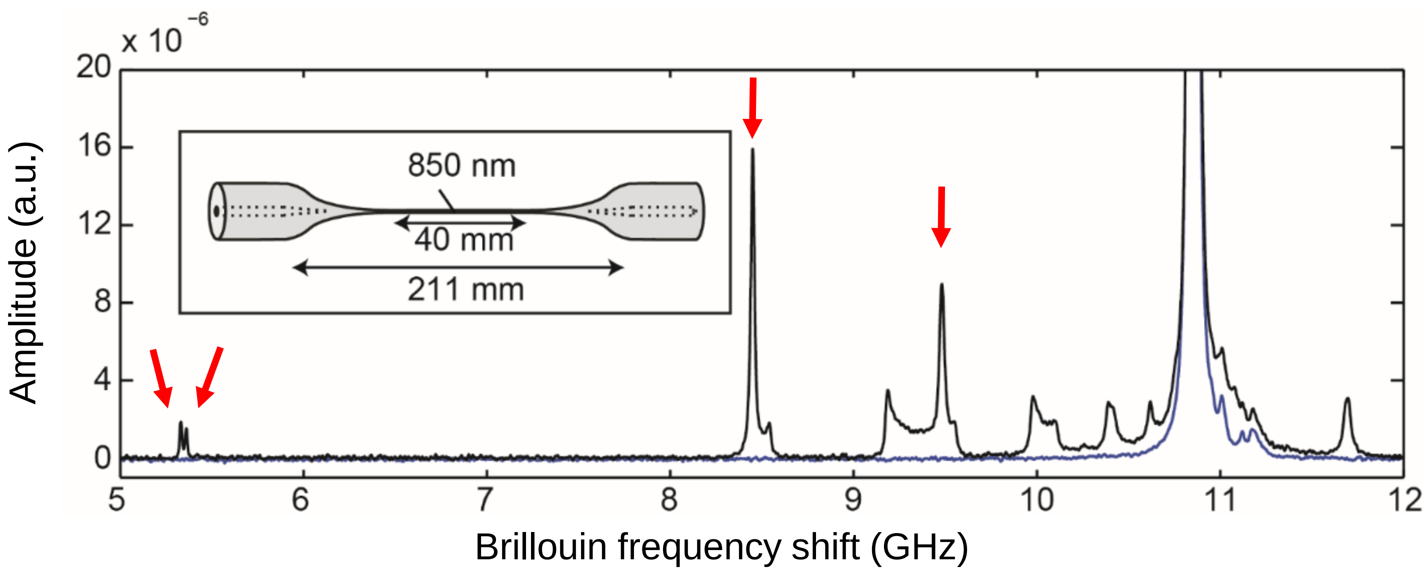
- ✓ All fiber system at 1550nm
- ✓ High coherent pump laser <100kHz
- ✓ In-situ, fast measurement <1s
- ✓ Non destructive method
- ✓ High spectral resolution



Brillouin spectrum

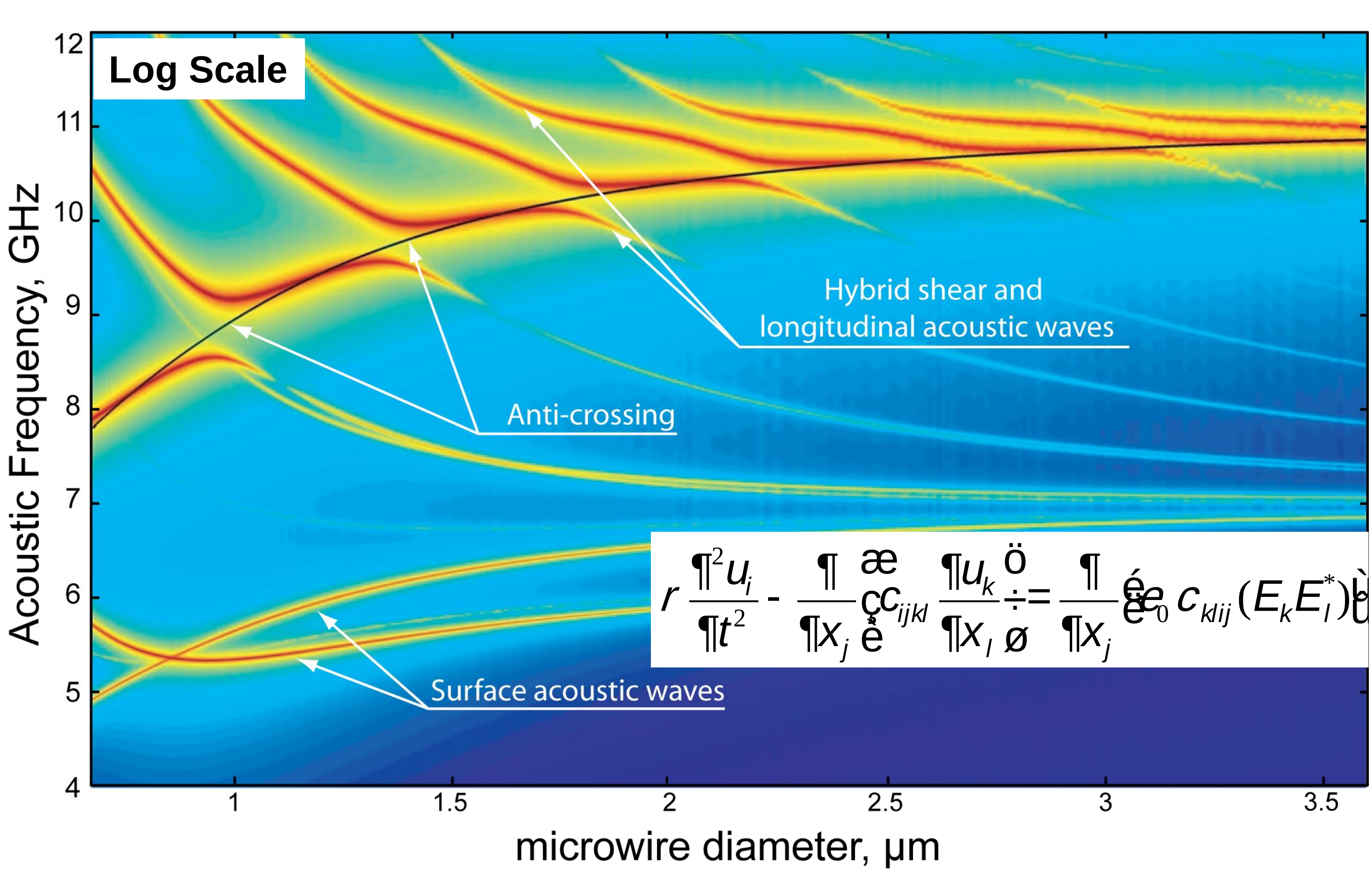


$$\nu_B = \frac{2n_{eff}}{\lambda} v$$ where *v* is the elastic velocity



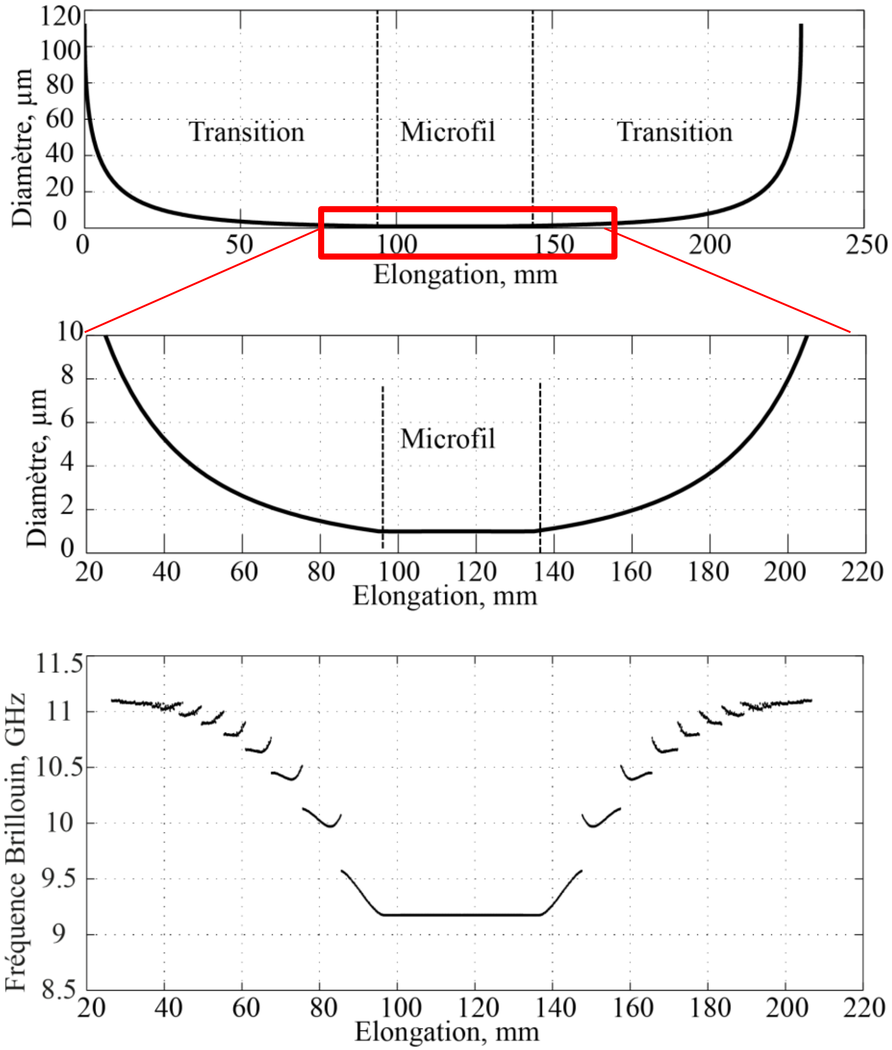
J.-C. Beugnot et al., *Nature Communications* **5**, 5242 (2014).

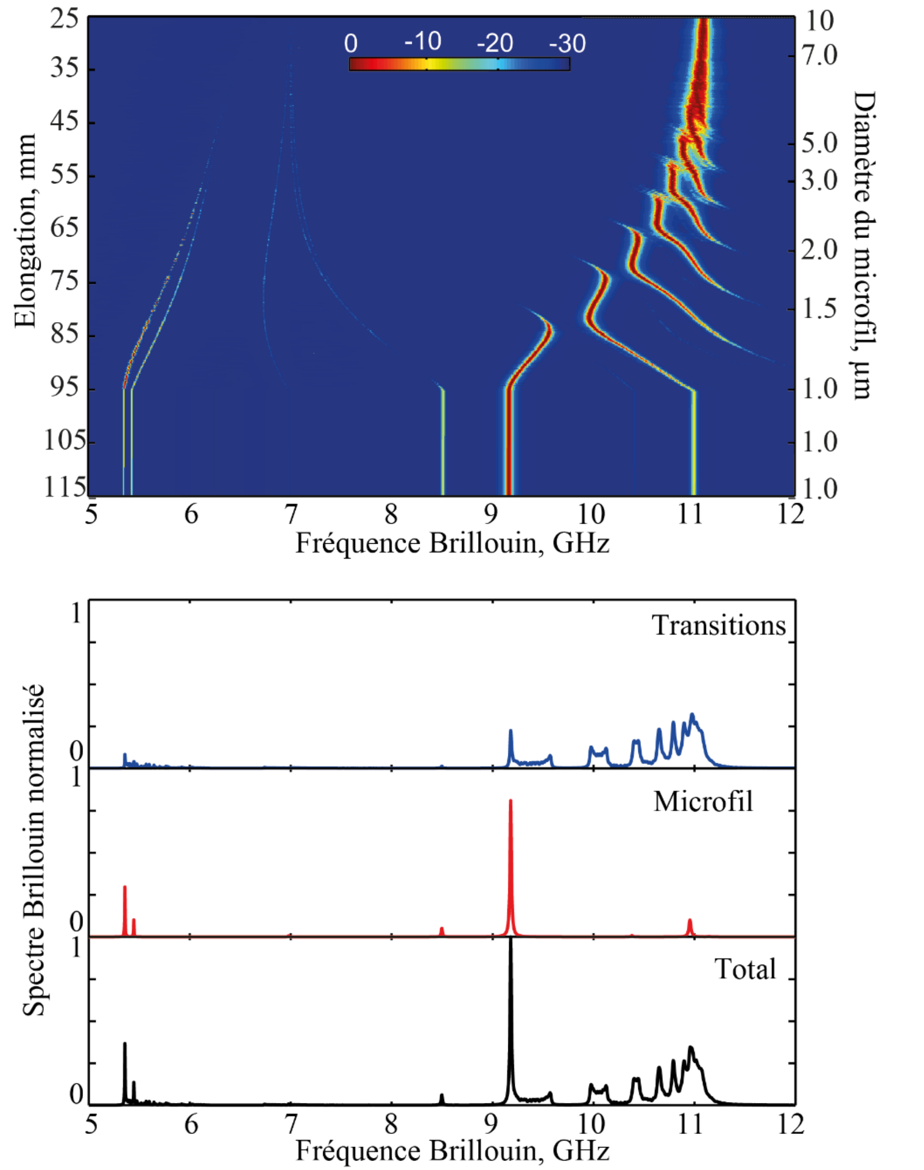
Numerical Brillouin scattering spectrum



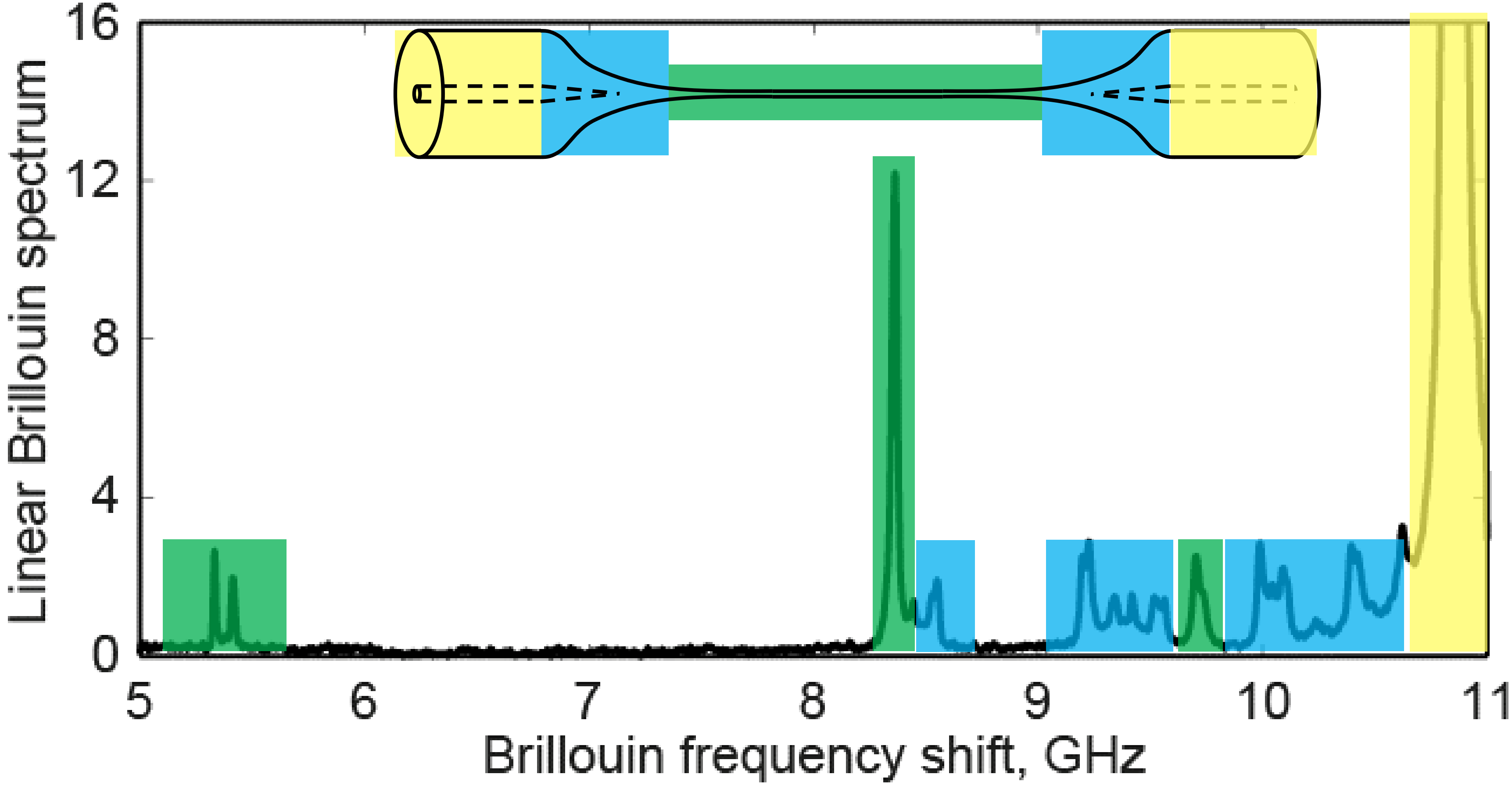
$$\rho \frac{\partial^2 u_i}{\partial t^2} - \frac{\partial}{\partial x_j}\left(c_{ijkl}\frac{\partial u_k}{\partial x_l}\right) = \frac{\partial}{\partial x_j}\left[\varepsilon_0 c_{klij}\left(E_k E_l^*\right)\right]$$

Theoretical Brillouin spectrum in tapered optical fiber



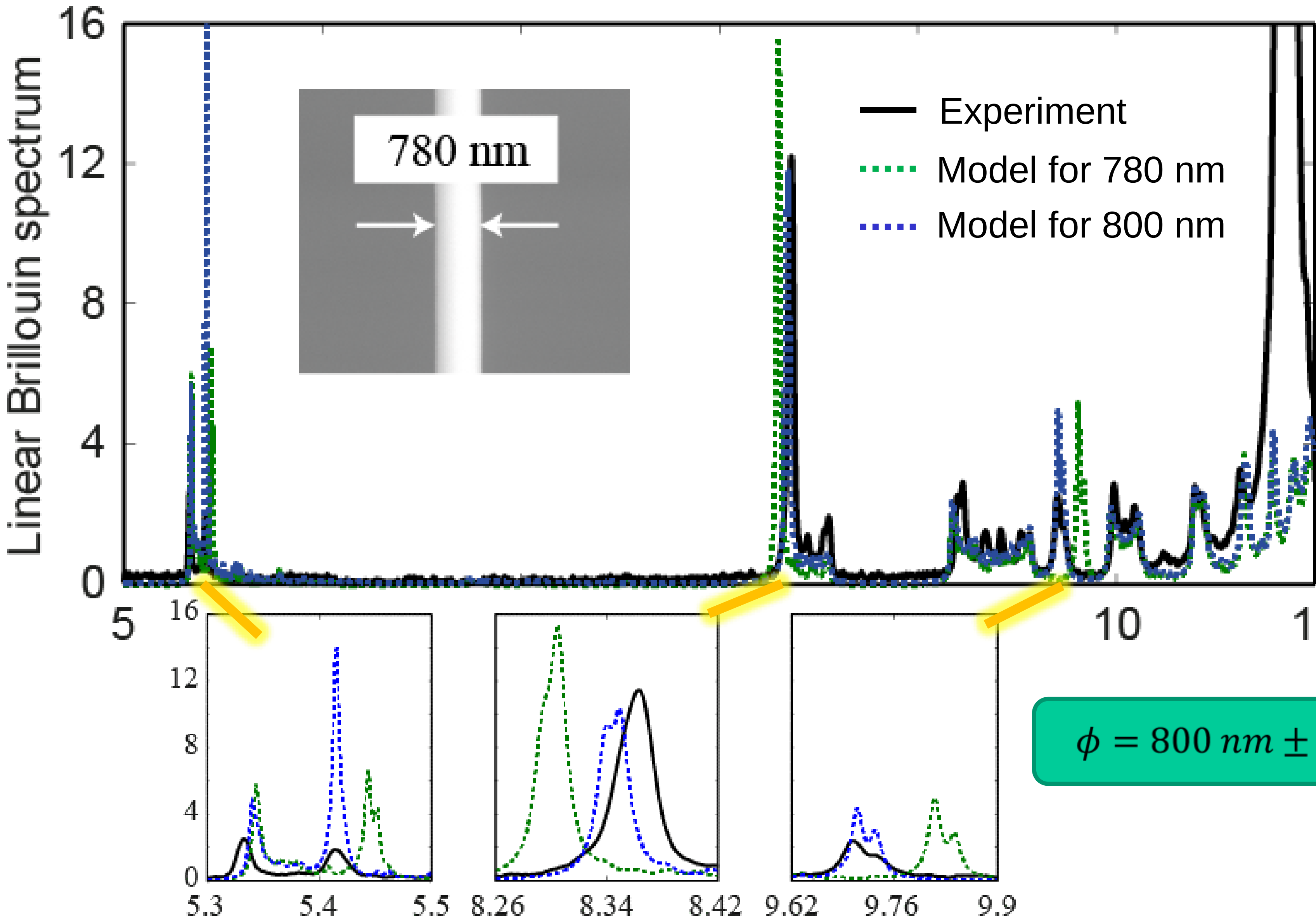


Metrology of optical tapered optical fiber



A. Godet *et al*., Optica, **10,** 1232 (2017)

Experiment VS numerical model



$$\phi = 800\,nm \pm 1\%$$

Strain effects on the Brillouin scattering spectrum

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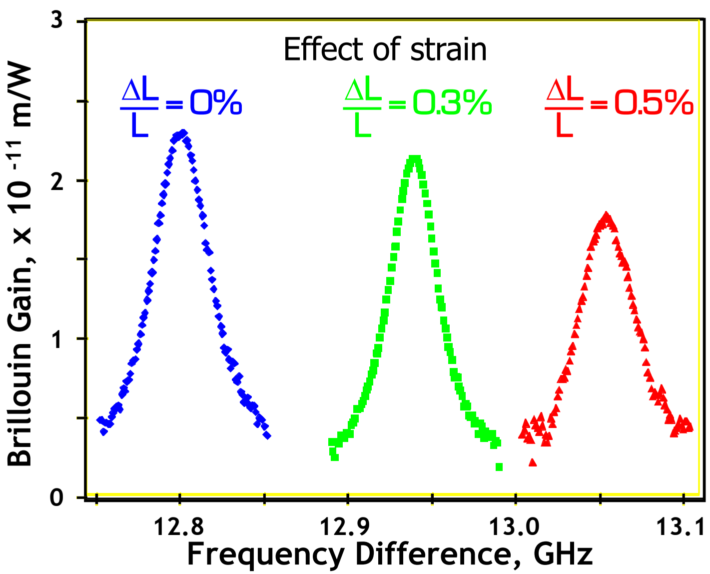
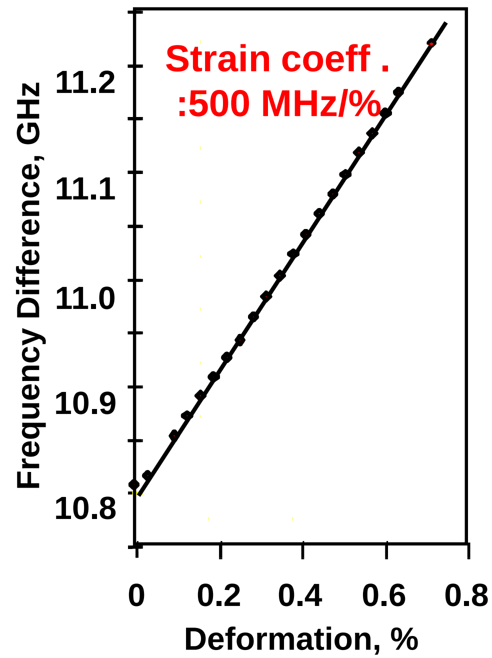
Deformation $\varepsilon = \Delta L / L$

➔ Density change $\Delta\rho$





$$\nu_B = \frac{2 n_{eff}}{\lambda} v$$

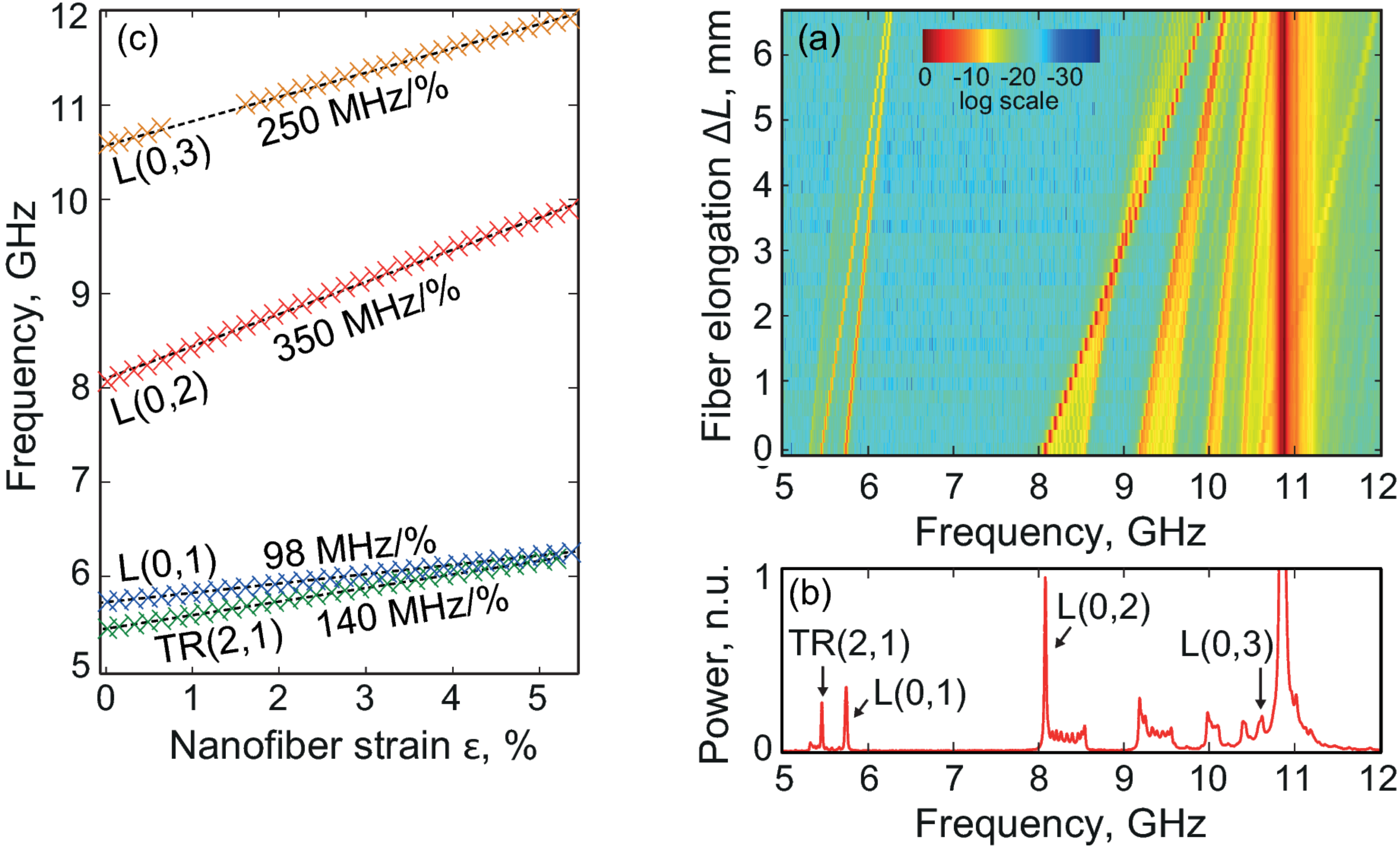
$$C_L = \left[\underbrace{\frac{1}{n_{eff}} \frac{\partial n_{eff}}{\partial \bar{\epsilon}_z}}_{-0{,}36} + \underbrace{\frac{1}{V_L} \frac{\partial V_L}{\partial \bar{\epsilon}_z}}_{4{,}58} \right] = 4{,}22$$

ν_B: Brillouin frequency

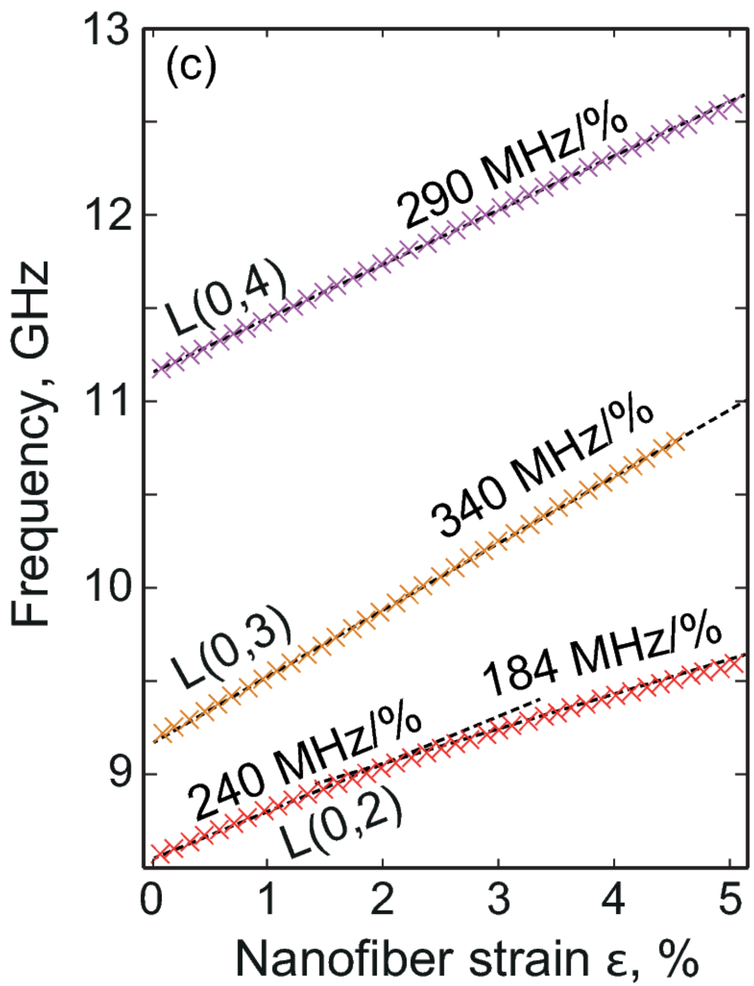
v = longitudinal velocity

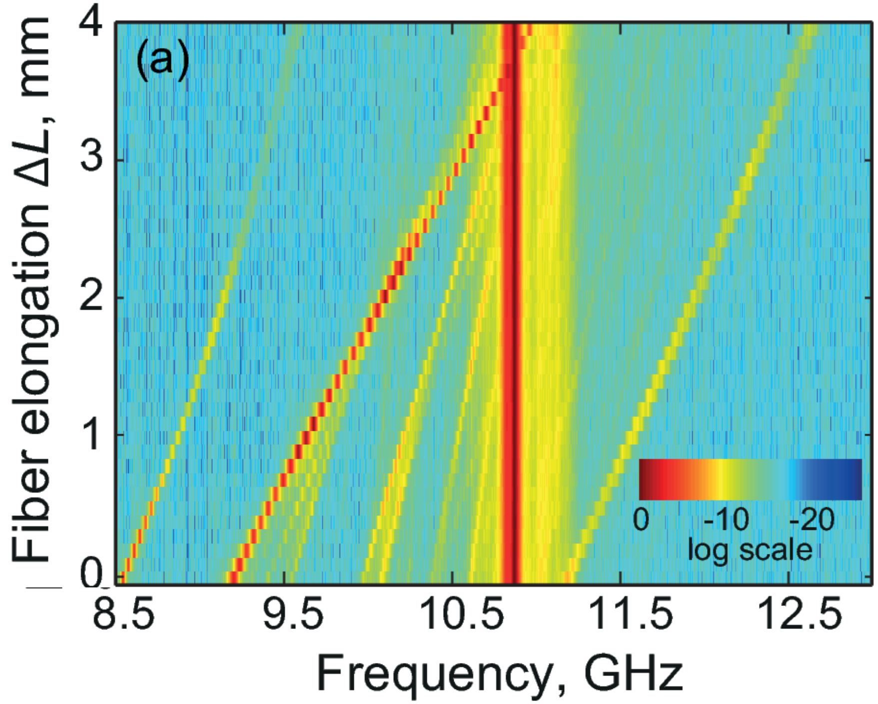
Horiguchi *et al.*, IEEE Phot. Technol. Lett., 1, 107 (1989),

Tensile strain measurement for 660 nm diameter nanofiber



Tensile strain measurement for 910 nm diameter nanofiber





910 diameter nanofiber Brillouin spectra feature nonlinear behavior with respect to tensile strain

Mechanics: Hooke law

Acoustic nonlinearity due to strong tensile strain

$$\sigma_i = C_{ij}\epsilon_j$$

For an isotropic medium like fused silica:

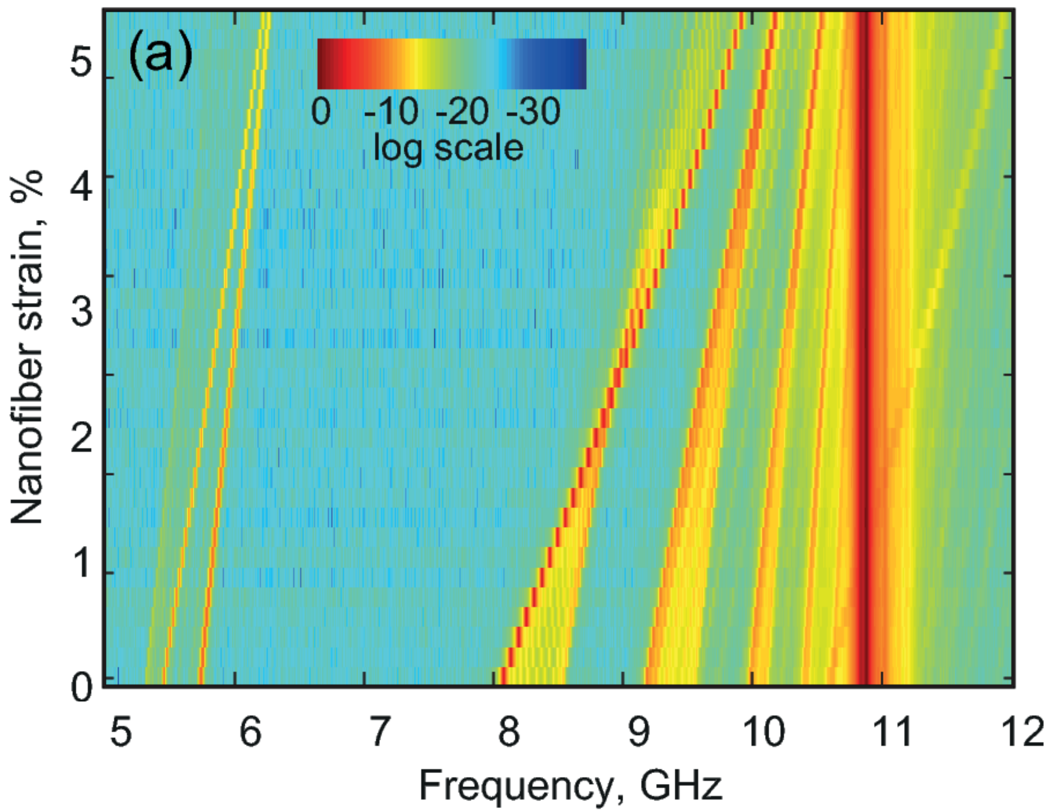
$$C_{ij} = \begin{pmatrix} \lambda+2\mu & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda+2\mu & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & \lambda+2\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu \end{pmatrix}$$

λ and μ are the Lamé constants for fused silica

The *effective* elastic constant features a transverse isotrope symmetry:

$$C_{ij}^{eff} = C_{ij} \circ \left\{ 1 + \begin{pmatrix} 3.05 & 3.4 & 15.05 & 0 & 0 & 0 \\ 3.4 & 3.05 & 15.05 & 0 & 0 & 0 \\ 15.05 & 15.05 & \mathbf{6.71} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.29 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.29 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.95 \end{pmatrix} \bar{\epsilon}_{zz} \right\}$$

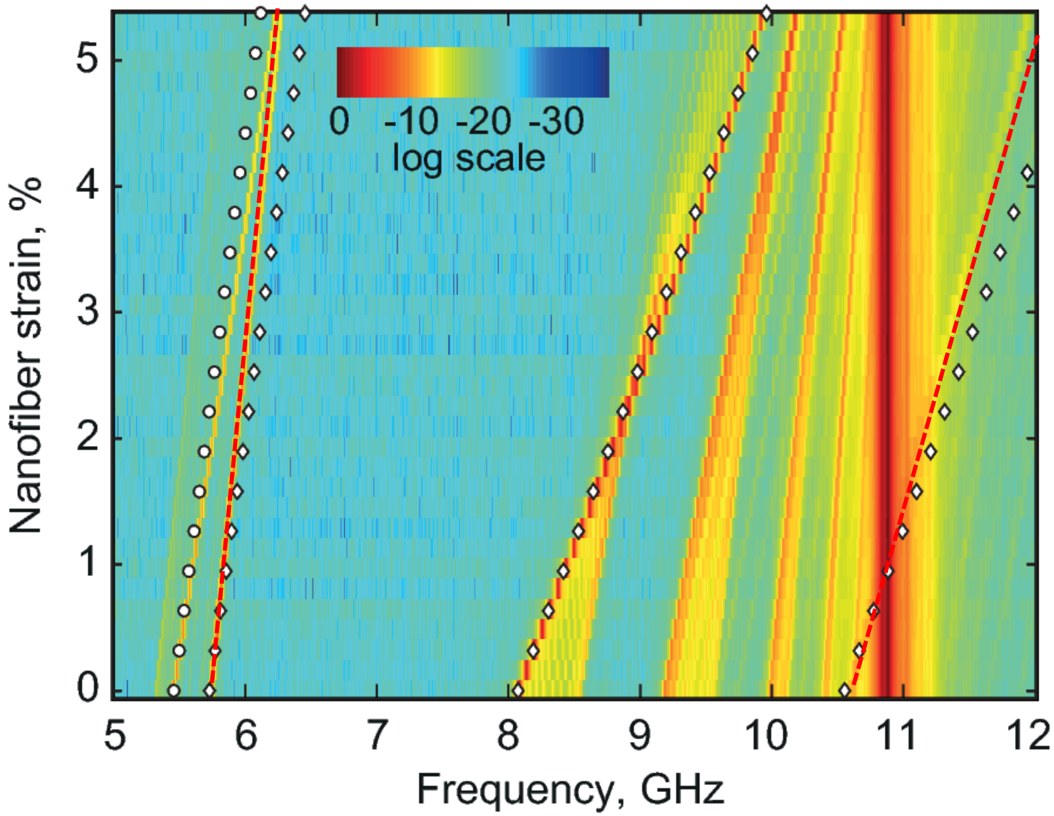
Brillouin model



➔ We have good agreement between Theory and Experiment

- Theory (white circle)
- Experience (false color)

Brillouin model



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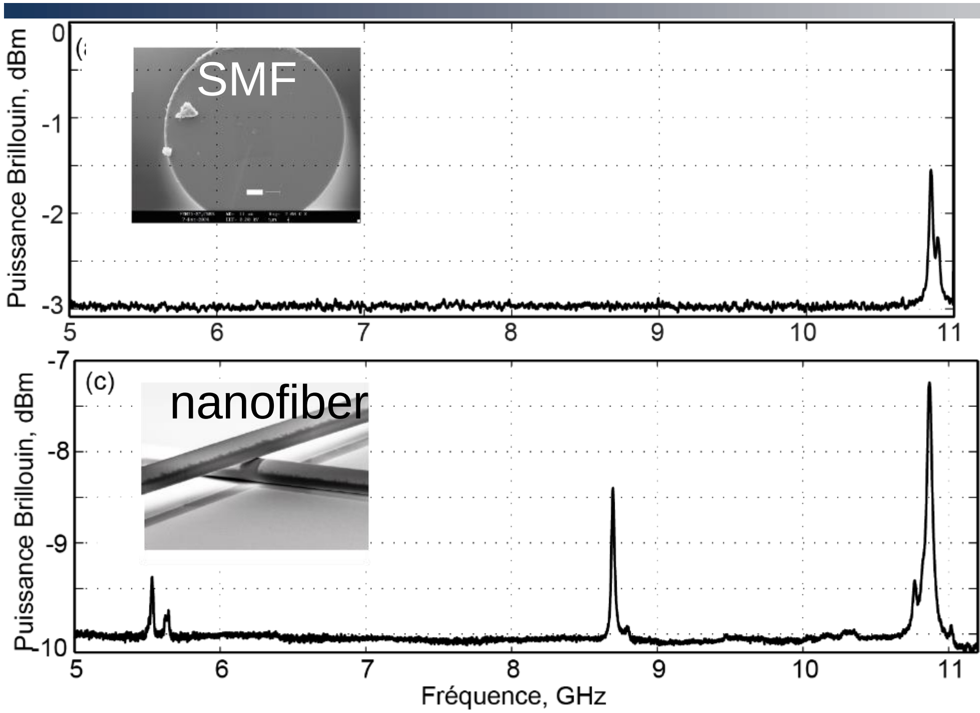
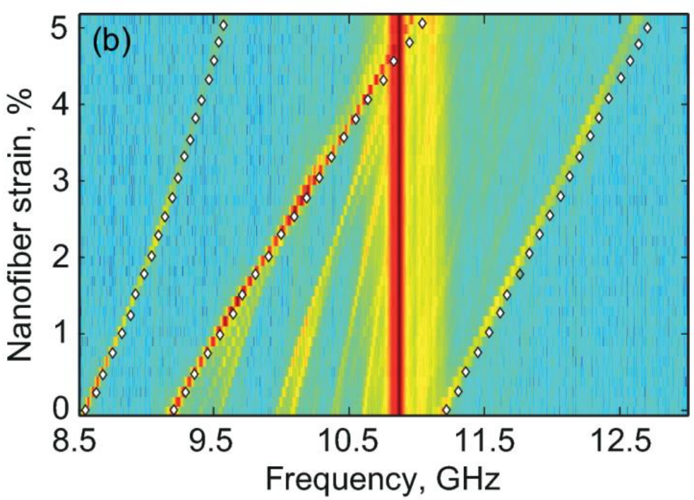
Conclusions





➔ Brillouin scattering is more rich in subwavelength diameter optical fiber

➔ Unlike single mode fibers, tensile strain dependence of Brillouin spectrum in nanofibers features

- **Nonlinear elasticity** of silica nanofibers
- **Induced material anisotropy**

➔ TOF offers favorable properties for manipulating light and sound at the nanoscale

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