Two-dimensional FEM Analysis of Brillouin Gain Spectra in Acoustic Guiding and Antiguiding Single Mode Optical Fibers

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Overview

- **Optical Fiber Sensors**
  - **Optical fiber properties**
  - **Distributed fiber sensors solutions**

- **Brillouin Scattering in optical fibers**

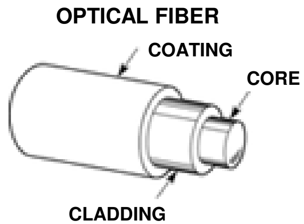
- **Brillouin Gain Spectrum computation using COMSOL Multiphysics**
  - **2D-FEM modeling**
  - **Validation of the model : example of GeO_2-doped core fiber**

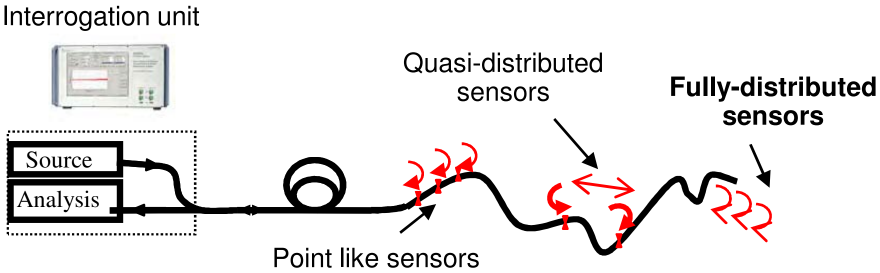
- **Analysis of acoustic anti-waveguides fibers**
  - **Example : Fluorine-doped cladding fibers**

- **Analysis of no-symmetrical geometry fibers**
  - **Example : Stress-induced polarization-maintaining fibers**

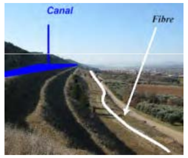
Optical fiber sensors

- **Optical fiber properties**





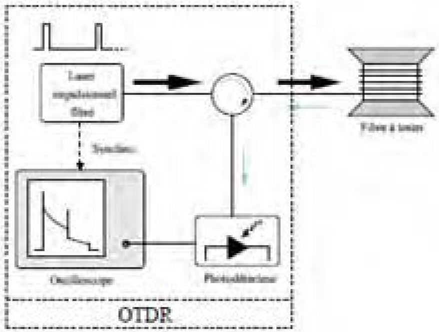
- **Application fields**

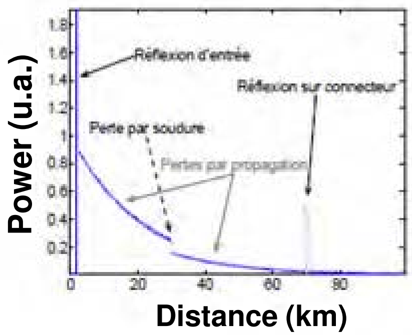


- Weakly intrusive
- Electro-magnetic immunity
- Fast information transfer/ rate

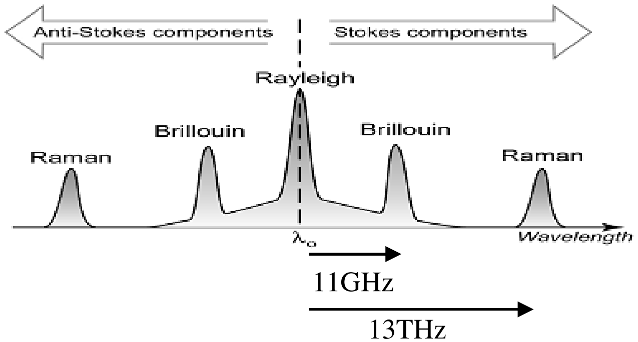
- **Distributed fiber sensors**

OTDR Principle





Back-scattered spectrum at λ_0 = 1550nm



Brillouin Scattering

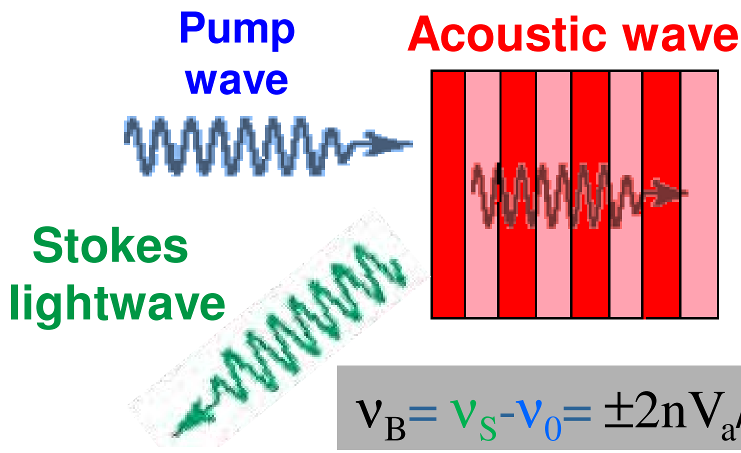
1) Acoustic Wave

Photo-elasticity ⇩

2) Propagating Bragg mirror

Diffraction ⇩

3) Backscattering wave

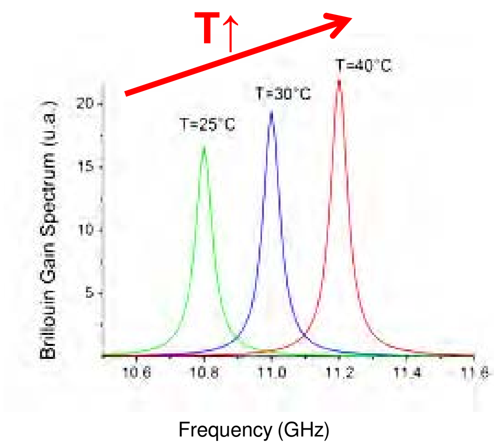


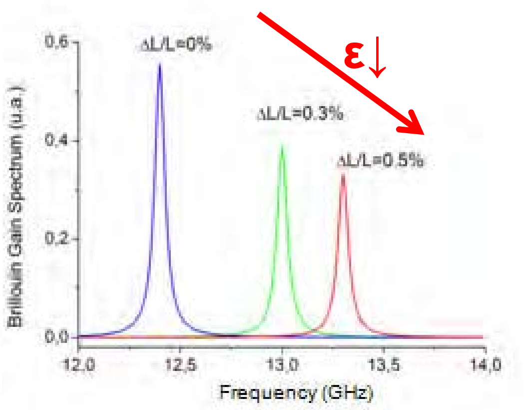
$$\nu_B = \nu_S - \nu_0 = \pm 2nV_a/\lambda_0$$

Dependences of the Brillouin shift ν_B

$$\nu_B = \frac{2n}{\lambda_0}\sqrt{\frac{E(1+\kappa)}{\rho(1+\kappa)(1-2\kappa)}}$$

$$\nu_B = \nu_0 + C_T \Delta T + C_\varepsilon \Delta\varepsilon$$



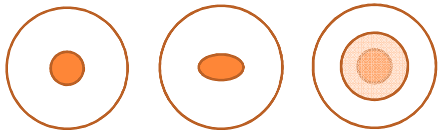


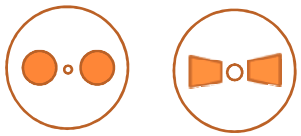
Brillouin Scattering

Brillouin Gain Spectrum is highly related to

- Doping composition:

Doping	*Refractive index variation* $\Delta n\%/wt.\%$	*Acoustic velocity variation* $\Delta V_l\%/wt.\%$
GeO_2	+0.056	-0.47
F	-0.31	-3.6
P_2O_5	+0.020	-0.31
TiO_2	+0.23	-0.59

- Geometry and doping profiles: 

- Frozen-in stress profiles: 

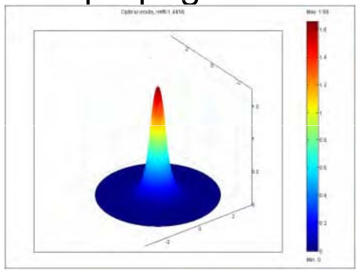
Need of a precise tool
to predict the Brillouin Gain Spectrum !

Brillouin Scattering

Optic

$$\Delta_t E + \frac{2\pi}{\lambda}(n^2 - n_{eff}^2)E = 0$$

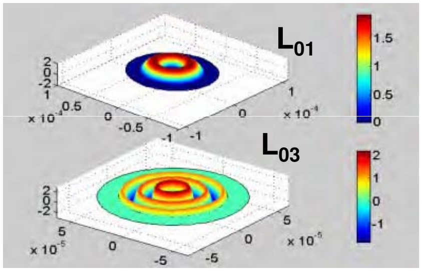
Monomode propagation : mode LP_{01}



Acoustic

$$\Delta_t u + \left(\frac{\Omega_m{}^2}{V_L{}^2} - \beta_{acoust}^2\right)u = 0$$

Solutions: L_{0m} modes



Acousto-optic overlap

$$I_m^{ao} = \frac{\left(\int |E|^2 u_{m^*} dxdy\right)^2}{\int |E|^4 dxdy . \int |u_m|^2 dxdy}$$

Brillouin Gain Spectrum

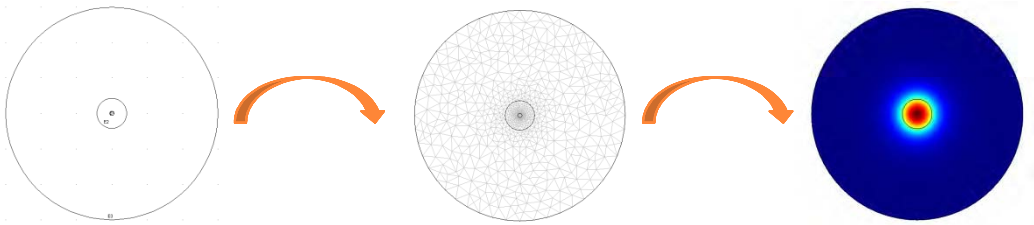
$$g(\nu) = \sum_m I_m^{ao} \frac{\left(\frac{\Gamma}{2}\right)^2}{\left(\frac{\Gamma}{2}\right)^2 + (\nu - \nu_m)^2}$$

Y. Koyamada, " *Lightwave Technol.*, **22**,631–639 (2004)
L. Tartara,*Optics Com.*, **282**, 2431-2436 (2009)

Simulation with COMSOL

- $V_L(x,y)$ and $n(x,y)$ vary on the cross-section with doping composition, frozen-in stress and geometry

- $E(x, y)$ and n_{eff} are calculated with PDE solver



Geometry Mesh Mode plot

- Bragg condition $\beta_{acoust} = 2 \times \beta_{opt} = \frac{4\pi n_{eff}}{\lambda}$ gives $u_m(x, y)$ and Ω_m

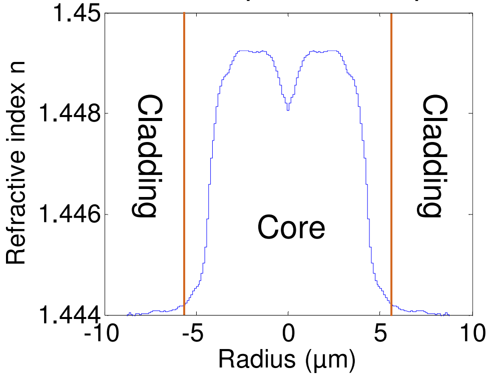
- The gain spectrum $g(\nu)$ is calculated taking into account overlap integrals of acoustic modes with the optical mode

Validation : *GeO_2-doped core fiber*

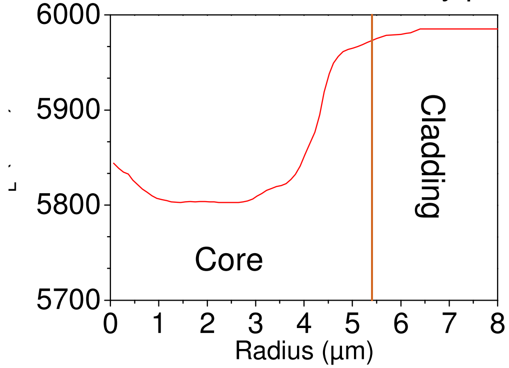
A $Ge0_2$-doped core fiber acts as an acoustic waveguide

- **Input data**

Measured Optical index profile

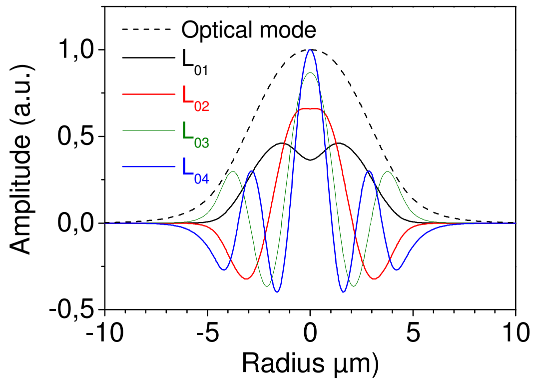


Calculated acoustic velocity profile

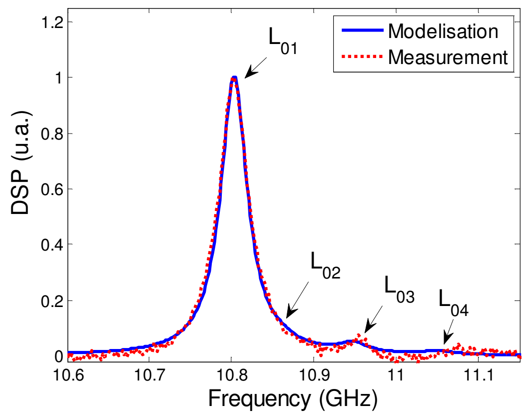


- **Modeling results**

Acoustic modes

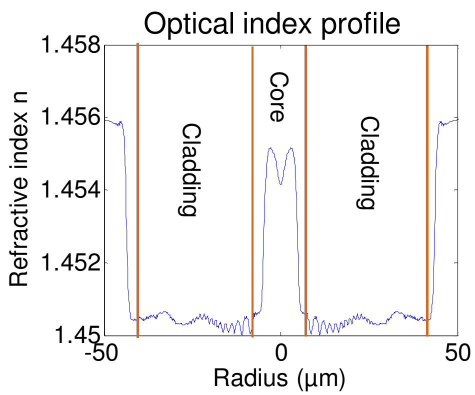


Brillouin spectrum



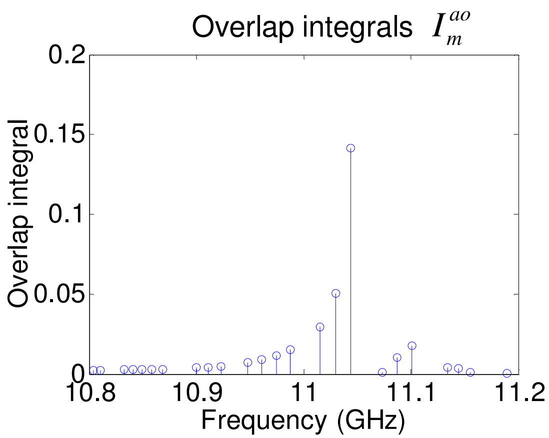
Acoustic anti-guiding fiber

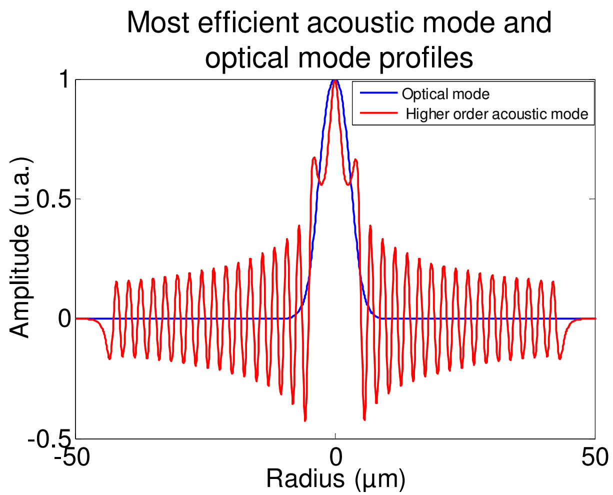
A Fluorine-doped cladding fiber

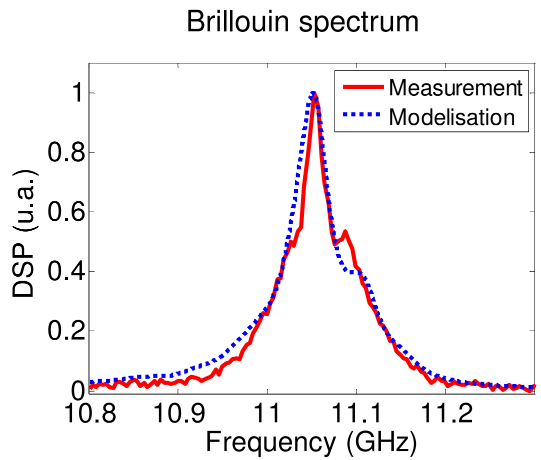


Applications

- Pure silica core *(very low attenuation transmission fibers)*
- High Stimulated Brillouin threshold *(high power fiber lasers)*
- High immunity to radiations *(optical sensors)*







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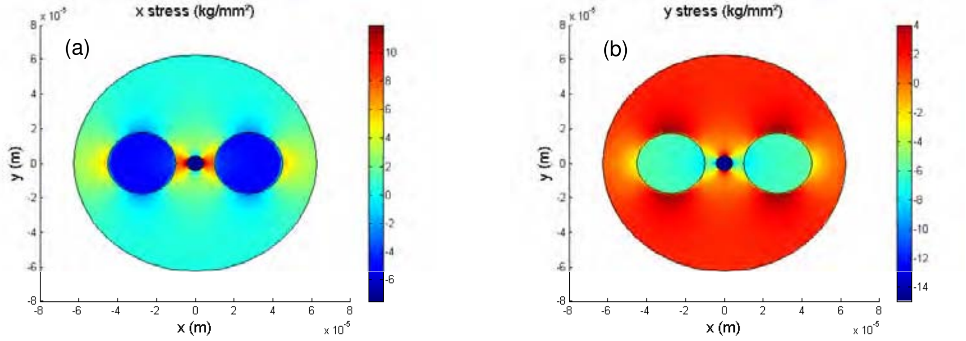
Polarization-maintaining fiber

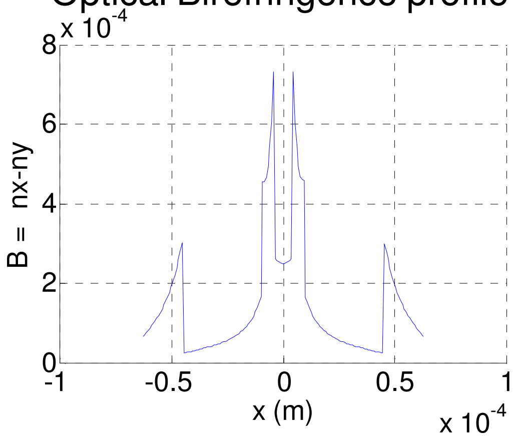
PANDA fiber : stress-induced birefringence

- **Frozen-in stress distributions**

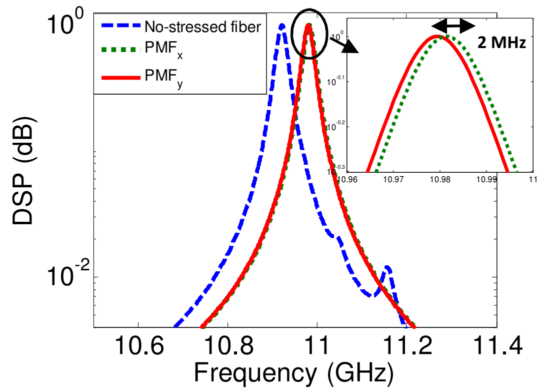


- **Modeling results**

Optical Birefringence profile



Brillouin spectra for polarization x and y compared to a no-stressed fiber



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Summary

- A 2D-FEM modal analysis to investigate the Brillouin spectrum in single-mode optical fibers: no problems of convergence
- Model to predict effectively the Brillouin spectrum in case of acoustic anti-waveguides
- Model adapted for more complicated geometries and stress-induced refractive index profiles and non-axis-symmetrical fibers
- Useful tool to design and analyze optical fibers for optical communications and Brillouin-based fiber sensors

Thank you for your attention!

Brillouin spectrum measurement
Self-heterodyne technique