ULTRALONG FIBER LASERS FOR OPTICAL FIBER SENSORS INTERROGATION

Manuel López-Amo

Special thanks to: Daniel Leandro, Mikel Bravo, Montserrat Fernández-Vallejo, Sergio Rota and Rosa Ana Pérez-Herrera

Zadar 13th April 2016

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  - Problems
- Experimental fiber sensor networks
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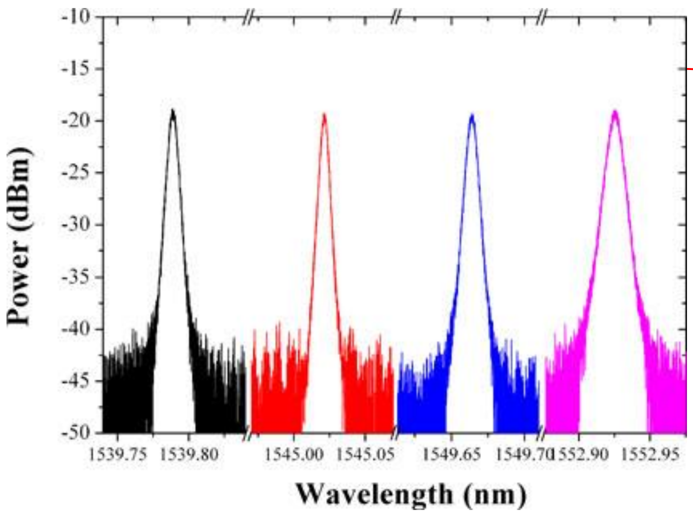
  - Lasing remote networks
- Conclusions

Optical communications group reseach lines:

1. Optical communications:
   - •Optical fiber lasers
     - •Er-doped
     - •Raman
     - •Random fiber lasers
   - •S.C. Lasers
   - •Integrated optics

Optical fiber sensors

3. Nano structured devices
4. Electronic applications



Fiber optic sensors

- Advantages:
  - Small size
  - Electomagnetic immunity
  - Intrinsically safe in hazardous environments
  - Chemically passive
  - Mechanically compatible with a host in operational environments
  - Can be used for distributed measurements
  - Can be accessed through optical fiber links for very long distances
  - Cabling is easier for a high number of sensors
  - Can be a part of the cavity of a fiber laser

- Drawbacks
  - Cost?

INTRODUCTION

CLASSICAL FIBER OPTIC SENSORS SYSTEMS:

Sensing element+ communication channel + light source and detection subsystem

FIBER OPTIC SENSOR NETWORKS:

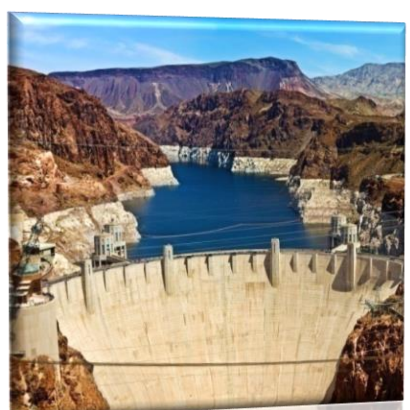
Two or more sensors that are located either directly inside the structures/locations to be monitored or very close to them

Presentation will be focused on point sensors. Distributed sensors are a good alternative

SUITABLE FOR:

They have found a growing niche in Avionics, Oil industry and in the field of Structural Health Monitoring (SHM) among others

Used for increasing the safety, longevity and reducing maintenance of the structures under analysis



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Amplified optical fiber sensor networks

- Main goal: to achieve multiplexing structures with **remote sensing** capability **or** able to gather a **high number of photonic sensors**, providing overall cost reductions where possible.

Current world records:

Number of sensors:

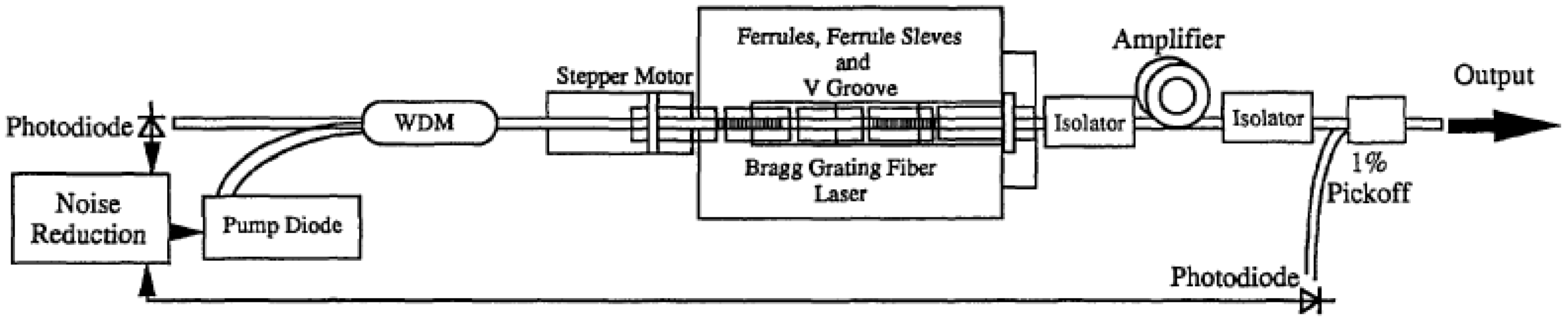
• **up to 256** interfeormetric sensors in: P.J. Nash and A. Strudley, in Proc. 20th Int. Conf. on Opt. Fiber Sensors, V. 7503, pp. T1-T4 (2009)

•**Up to 1000 weak FBGs** in: Y. Wang et al “A large serial time-division multiplexed fiber bragg grating sensor network” Journal of lightwave technology Vol. 30 n. 7 pp. 2751 - 2756 (2012)

Remote sensing: 4 FBGs at 250 km in: M. Fernandez-Vallejo, S. Rota-Rodrigo, M. Lopez-Amo, *Sensors,* V.11, pp. 8711-8720 (2011)

Why fiber lasers for sensing?

- Higher OSNR: Higher dynamic range, Higher resolution
- Mode-locked lasers for TDM multiplexing
- The laser mirrors can be the sensors: Integrated structure:
    - Sometimes tiny sensing structures
    - Sometimes ultralong multiplexing structures

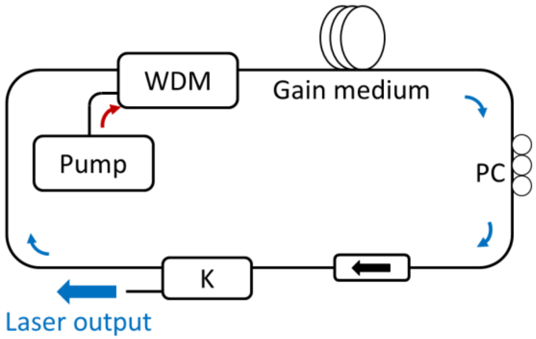


L= 2 cm, P_{pump}= 80 mW

G. A. Ball and W. W. Morey **"Compression-tuned single-frequency Bragg grating fiber laser"** Optics Letters Vol. 19, n. 23 pp.1979-1981 1994

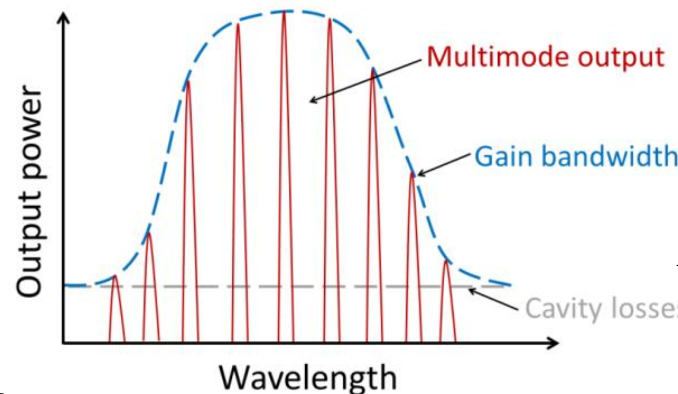
Optical fiber lasers main cavities for sensing

Ring cavity fiber laser



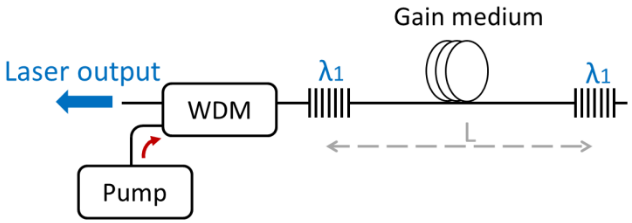
$$\Delta\lambda = \frac{\lambda^2}{n \cdot L}$$

Longitudinal modes



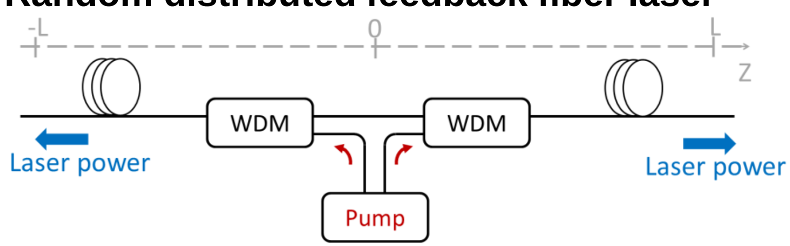
$$N = \frac{FWHM_{reflector}}{\Delta\lambda}$$

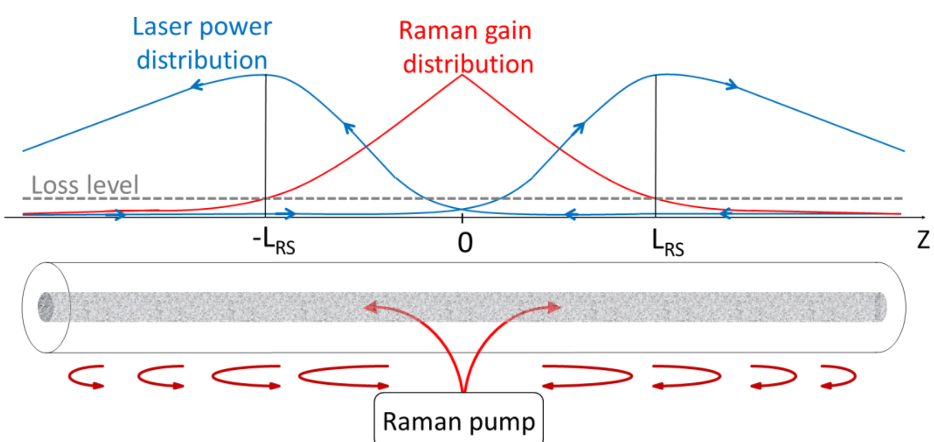
Linear cavity fiber laser (Fabry-Perot)



$$\Delta\lambda = \frac{\lambda^2}{n \cdot 2L}$$

Random distributed feedback fiber laser





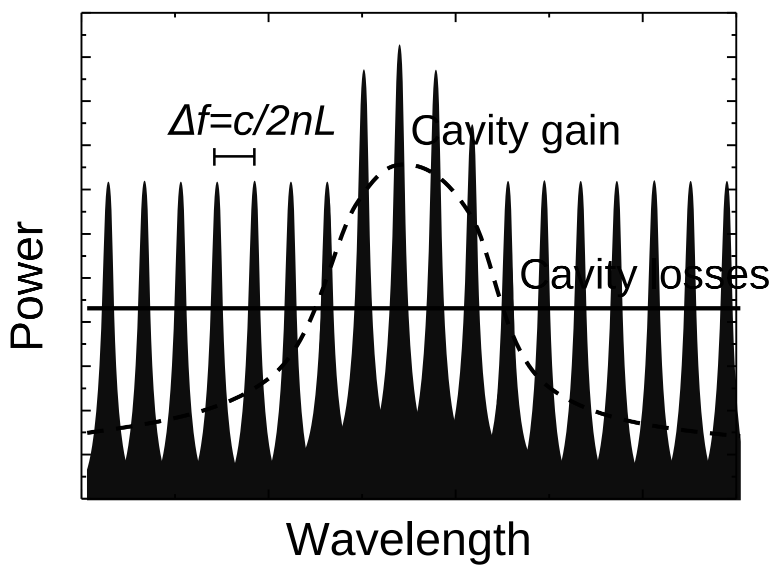
Rayleigh backscattering

Mirror-less-cavities

Infinite distributed cavities along the fiber → **No longitudinal modes**

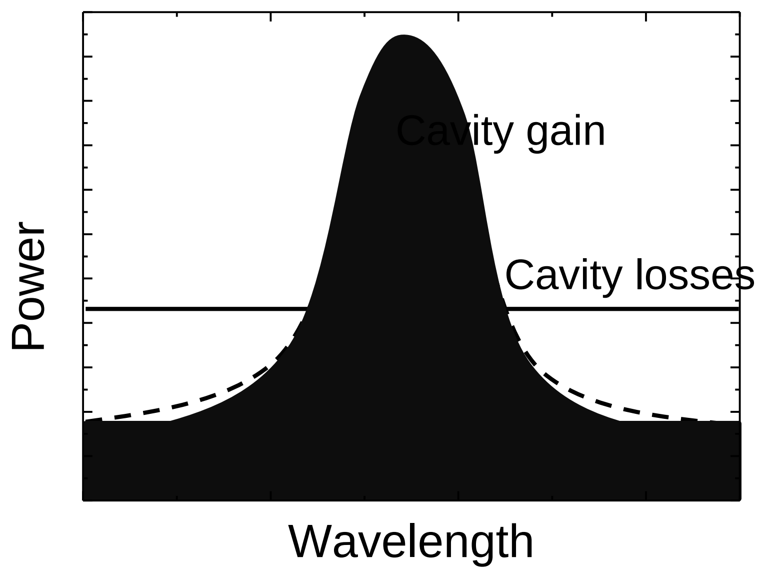
Classical vs Random fiber lasers I

Classical fiber laser



- **Cavity** length **fixed**. Longitudinal intermodal frequency *Δf=c/2nL*
- Wavelength variation of the peak due to **mode competition** and **mode hopping**
- **Limited resolution** if the peak wavelength is used for sensing applications

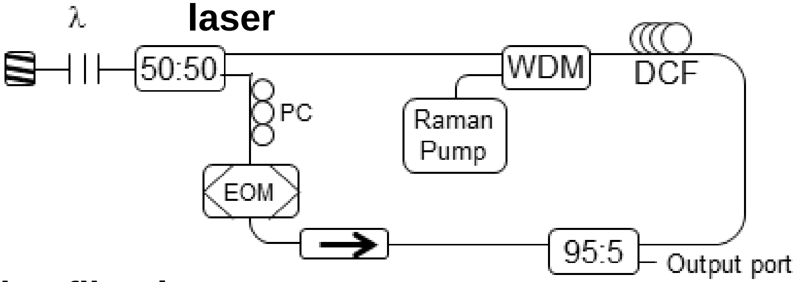
Random DFB fiber laser



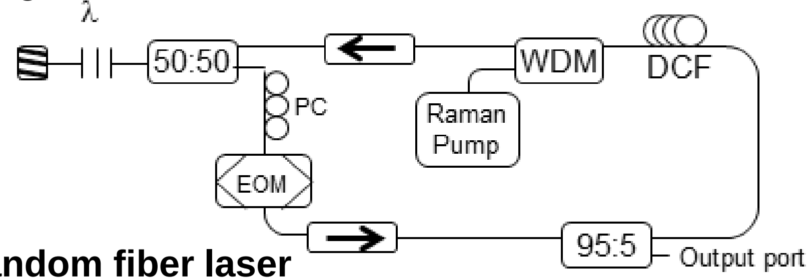
- **No fixed cavity**.
- Multitude lasing longitudinal modes degenerate in a **collective mode**
- **Absence** of mode competition and mode hopping

Lasers modulation study

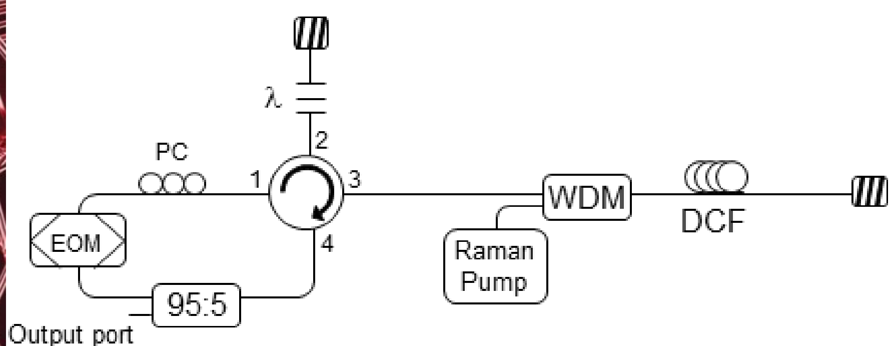
Hybrid ring-random fiber laser

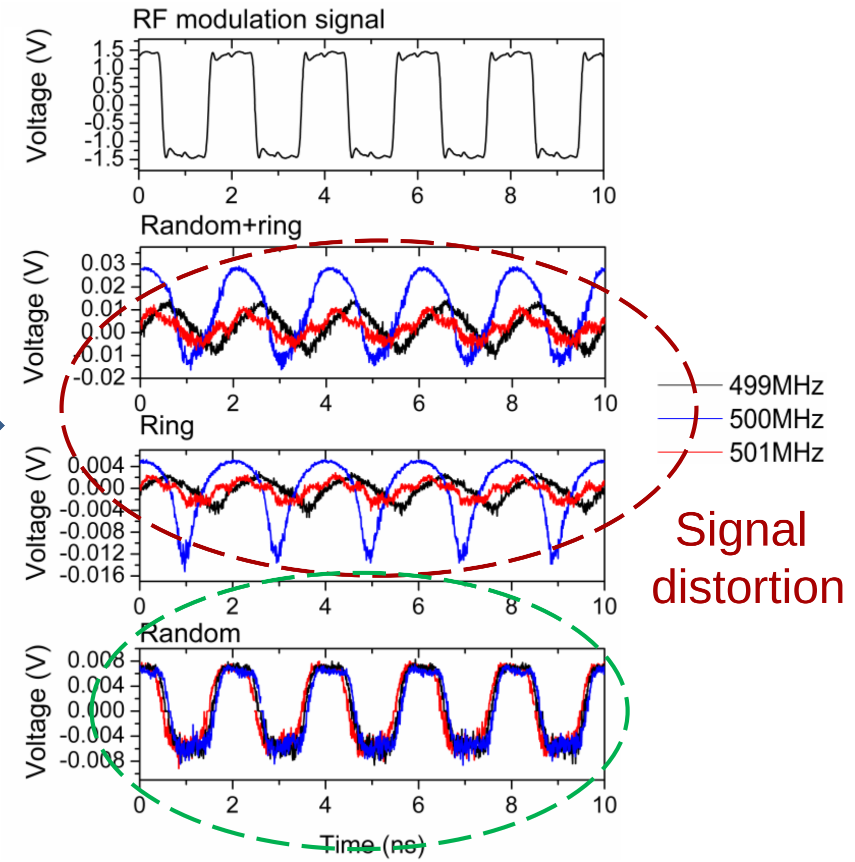


Ring fiber laser



Random fiber laser





Random DFB lasers adapt their cavities

NO signal distortion

M. Fernandez-Vallejo, S. Rota-Rodrigo and M. Lopez-Amo, "Comparative study of ring and random cavities for fiber lasers," *Appl. Opt.*, vol. 53, pp. 3501-3507, 2014.

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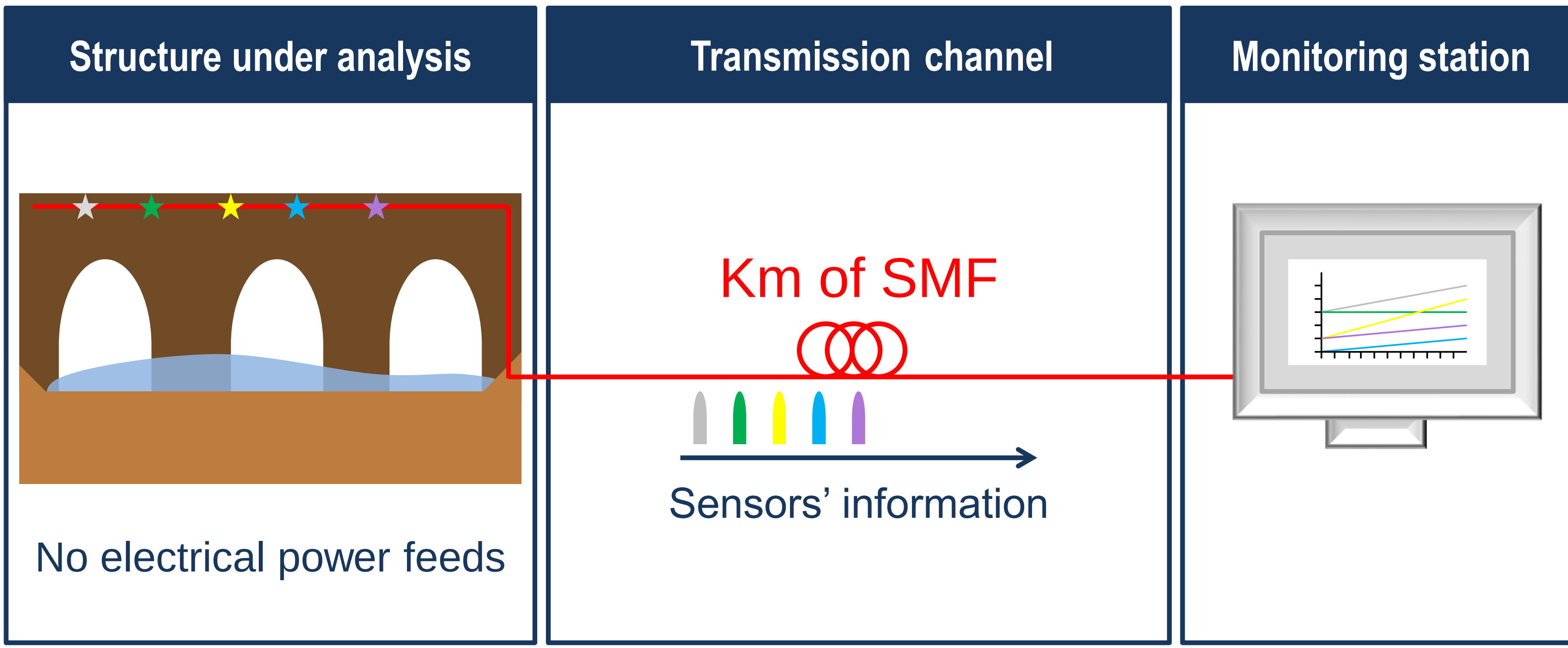
REMOTE SENSING CAPABILITY USING A FIBER OPTIC TRANSMISSION CHANNEL:

Continuous monitoring of structures from a central station located tens or hundreds of kilometers away from the field through the critical location of sensors, which send information to the central station, without the necessity of electrical power feeds in the remote locations



REMOTE SENSING CAPABILITY

Applications

- Structural health monitoring of large infrastructure
(oil or gas pipelines, ultralong bridges and tunnels, river banks and offshore platforms)

- Tsunami detection and warning before their arrival to the coast

- Geodynamical monitoring
(surveillance of volcanic and tectonic areas)

- Railway applications

LOSS

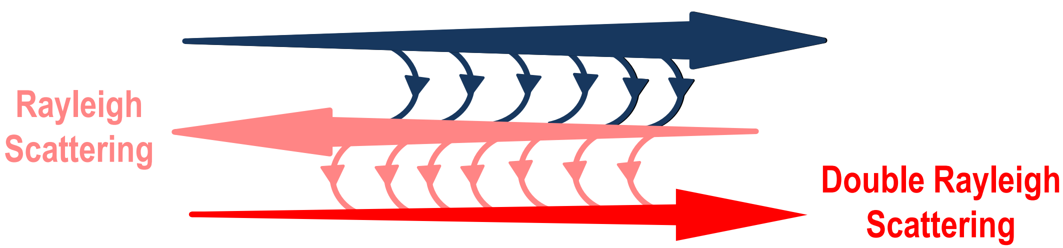
Solution: Optical amplification.Typically EDFAs or distributed Raman amplification

RAYLEIGH SCATTERING

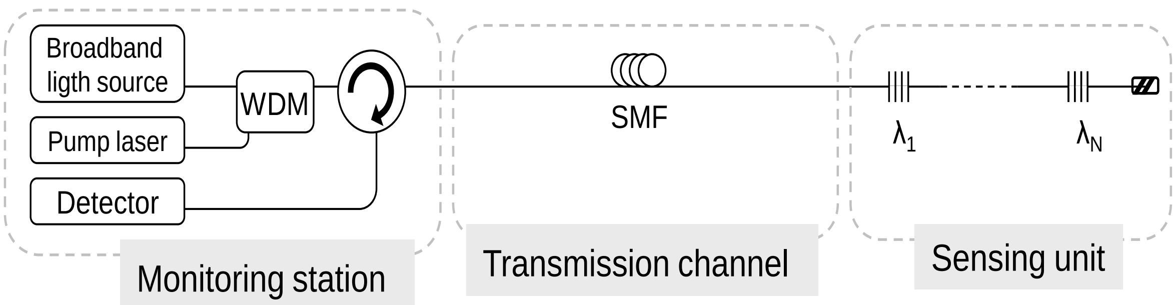
The highest liming factor for reaching further distances

The small reflections are amplified and accumulated over tens or hundreds of kilometers

It occupies the same spectral region as the signal → difficult to distinguish



Conventional sensing systems: < 25 km because of Rayleigh scattering



How to design a remote sensors network?

Aspects to be considered:

- Type of sensors: FBGs, intensity, interferometric, polarimetric…..
- Network topology: serial (bus), star, ring, mesh and tree
- Inclusion or not of optical amplification: active or passive networks
- Interrogation system
- Other issues: the complexity and maintenance
- **Cost**

•If optical amplification is needed, **Multiwavelength fiber lasers** may be a good option:

Erbium-doped fiber lasers
Raman fiber lasers
} as light sources or as sensors systems themselves

•Fiber optic networks offer flexibility to reach an optimum network for any application

State of the art:

CLASSIFICATION

- **Unamplified remote networks**: fiber networks without optical amplification
  Few reported systems over 50 km
  Two main drawbacks: limited number of sensors (poor S/N)
  difficult power equalization between channels
- **Amplified remote networks**: fiber networks with optical amplification
  Two main motivations:
  To increase the number of sensors multiplexed while ensuring good signal quality
  To increment the length of the system
  Raman or Erbium doped fiber amplification are the most employed for point sensors

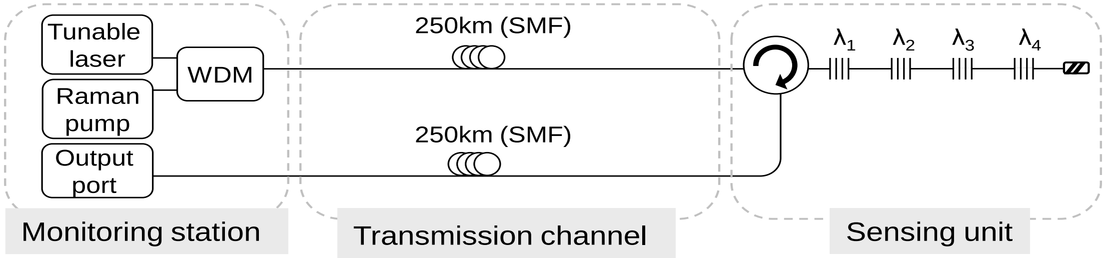
  Distributed sensing: Only for strain and temperature measurements
- **Lasing remote networks**: fiber networks based on multiwavelength fiber lasers
  To enhance the performance of sensing systems
  They offer a much improved SNR than the non-lasing ones

- **250 km system, by Fernandez-Vallejo *et. al. [2011]***

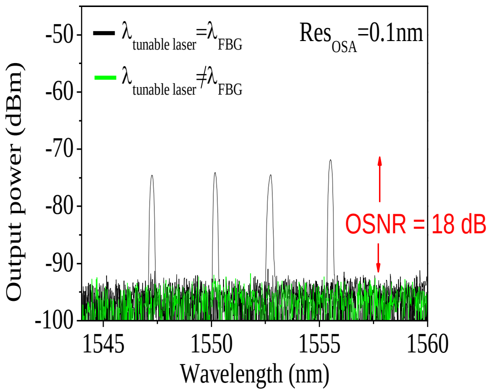
Transmission channel with two identical paths:
1º is to launch the amplified signal
2º is to guide the reflected signal

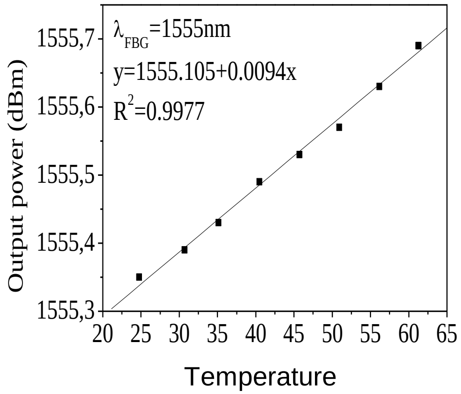
Addresses the double Rayleigh scattering
Not an economic problem in real applications

Mode operation: The simplest: to interrogate the FBGs the tunable laser makes a wavelength sweep



Results: $P_{raman\ pump}$=1.3W





M. Fernandez-Vallejo, S.Rota-Rodrigo and M. Lopez-Amo. Sensors 11, 8711 (2011).

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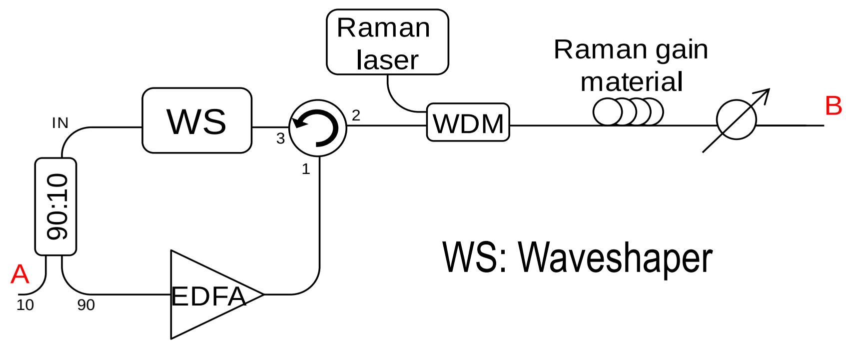
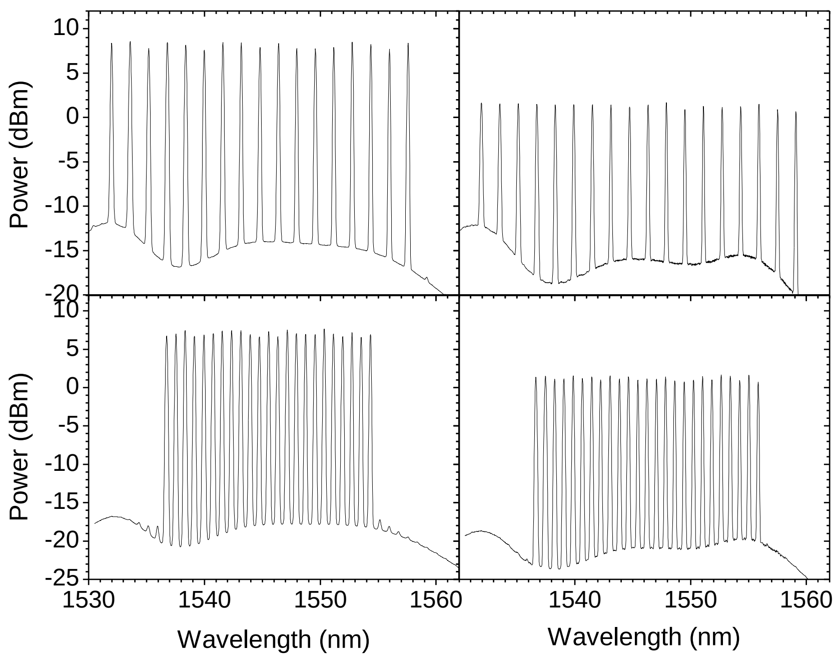
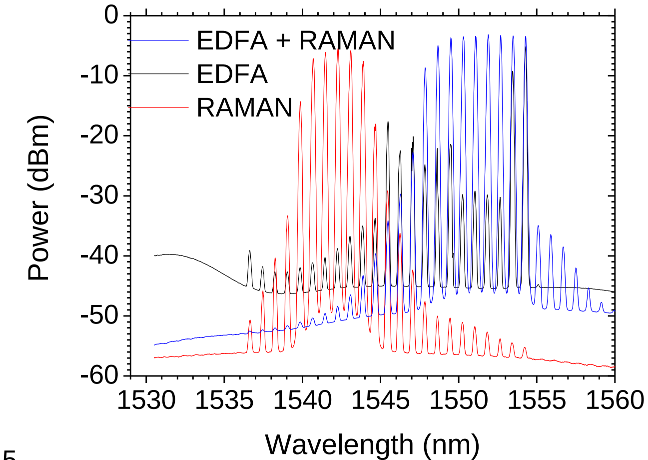
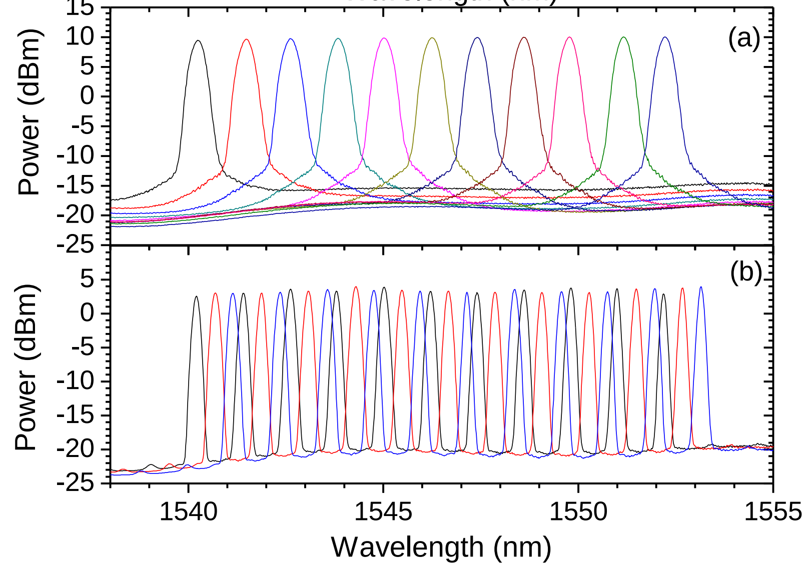
EXPERIMENTAL FIBER SENSOR NETWORKS
Switchable random laser for remote sensing





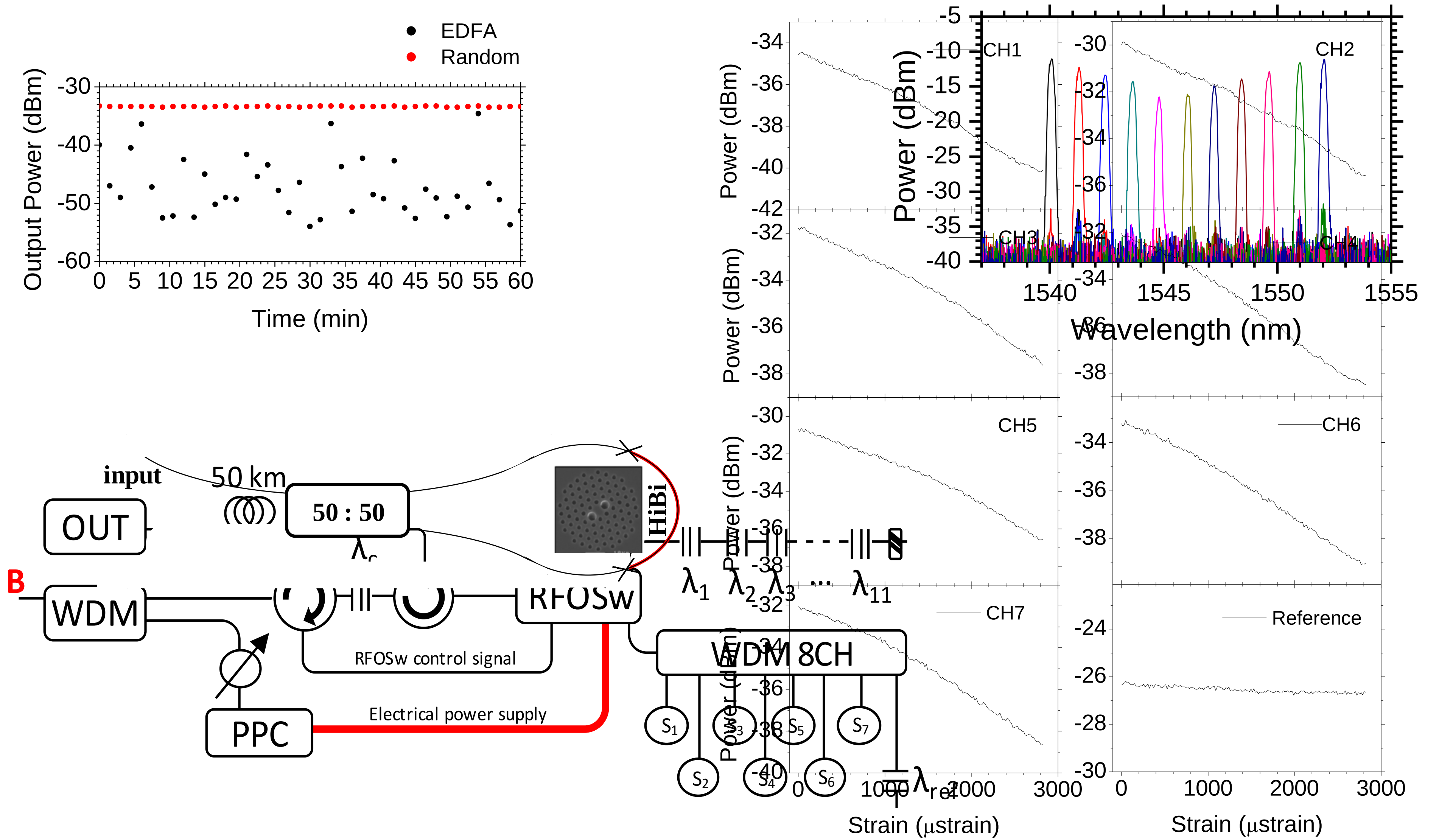
Maximum number of emission lines for the 200 and 100 GHz ITU grid measured for the DCF (a and c) and the SMF (b and d).





MWFL configuration for single discrete wavelength sweep (a) and discrete multi-wavelength sweep (b).

Switchable random laser for remote sensing II



M. Bravo et al. Fully-Switchable Multi-Wavelength Fiber Lasers Based on Random Distributed Feed-Back for Sensors Interrogation
J. of Lightwave Tech. V.33 n.12 pp .2598 - 2604 (2015)

- **155 km system, by D. Leandro *et. al. [2011]***

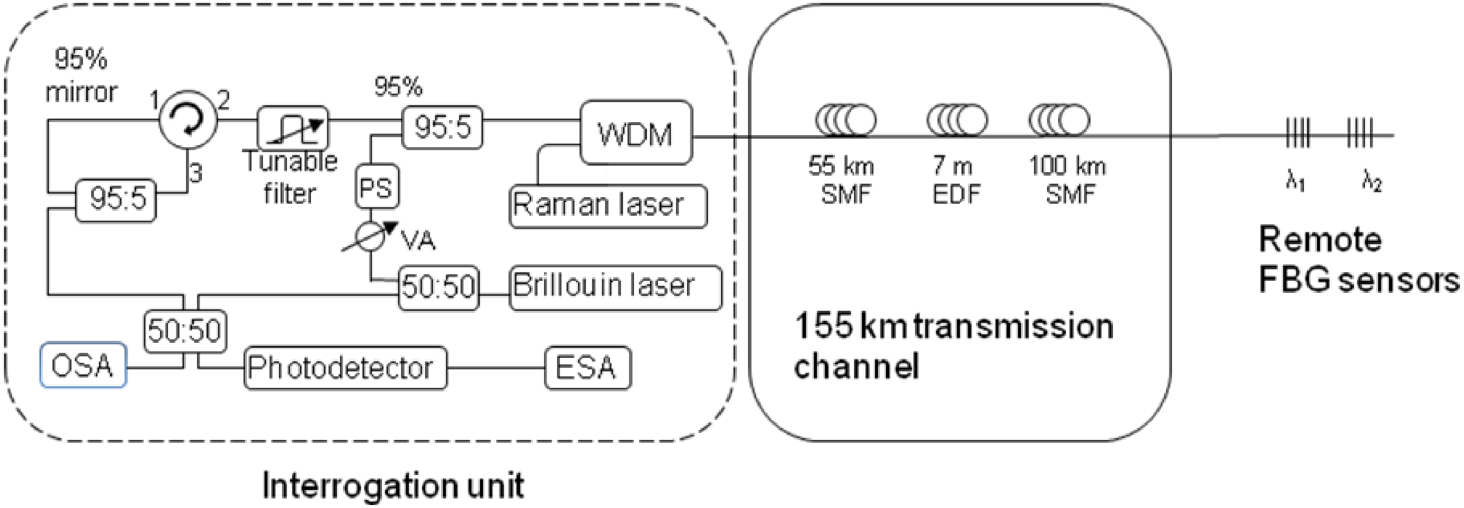
Hybrid Brillouin-Raman laser

SIGNAL DETECTION SYSTEM: heterodyne process

↳ ADVANTAGE: **Avoid Rayleigh noise problems**

Rayleigh noise is relegated to low frequencies (around DC)

Signal is transferred to noise-free (RF) frequencies around the Brillouin frequency shift in the fiber

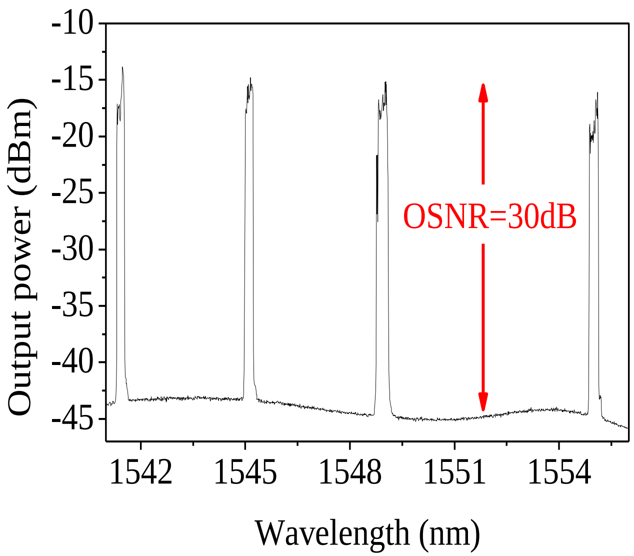


Daniel Leandro et al, Remote (155 km) Fiber Bragg Grating Interrogation Technique Combining Raman, Brillouin, and Erbium Gain in a Fiber Laser IEEE photonics technology letters, vol. 23, no. 10, May 15, 2011

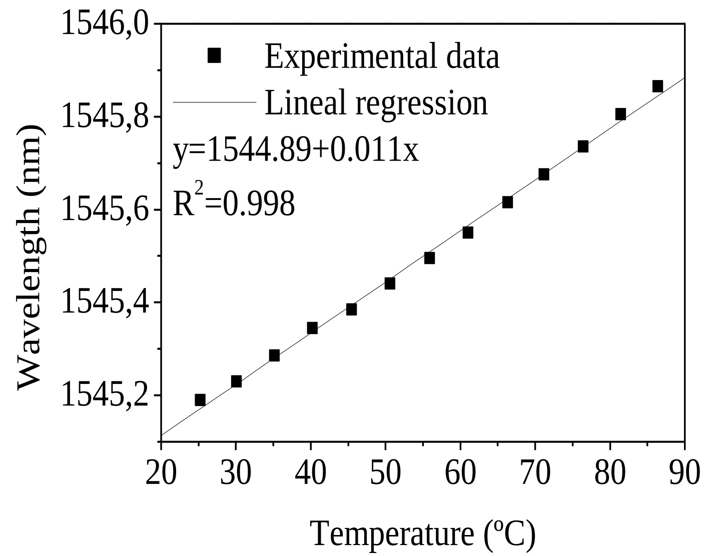
- **100 km system, by Fernandez-Vallejo *et. al. [2011]***

RESULTS: P_{pump_Raman}=0.8W and $P_{pump\_Brillouin}$=1.35mW

FBGs as sensing elements



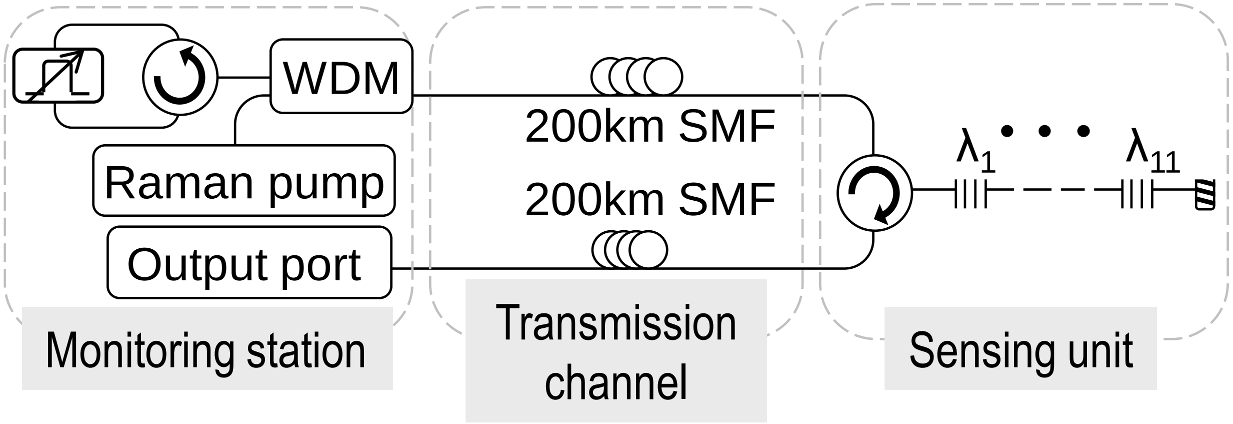
FBGs as sensors:
Sensitivity = 11 pm/ºC



- **155 km system, by D. Leandro *et. al. [2011]*** P_{pump_Raman}=0.6W, $P_{pump\_Brillouin}$=2 mW, OSNR=10 dB

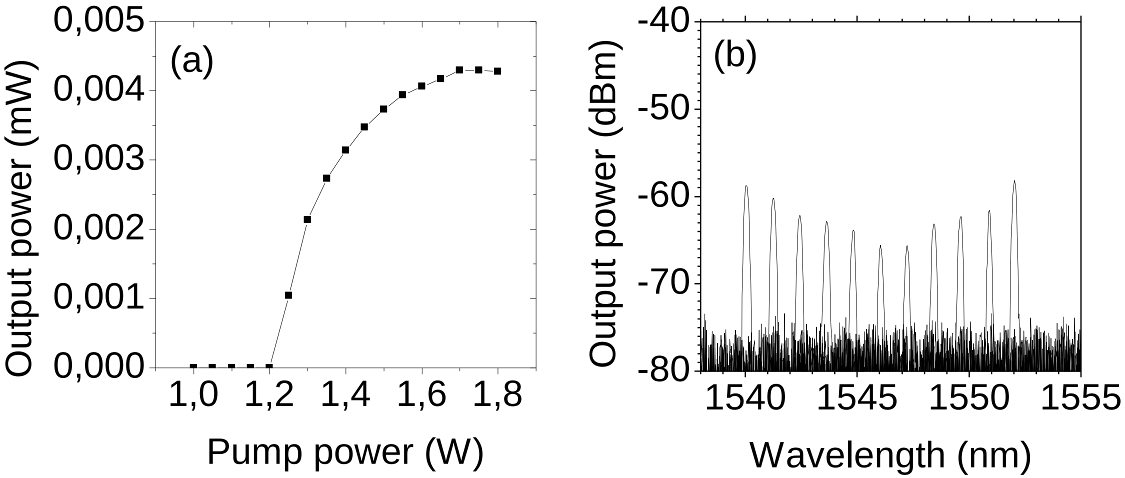
M. Fernandez-Vallejo et al. "Fiber Bragg Grating interrogation technique for remote sensing (100km) using a hybrid Brillouin-Raman fiber laser," (OFS-21), Proceedings of the SPIE,7753, art. no. 77537I, Ottawa (Canada), 2011.

- **200km random fiber laser, by Fernández-Vallejo *et. al. [2013]***



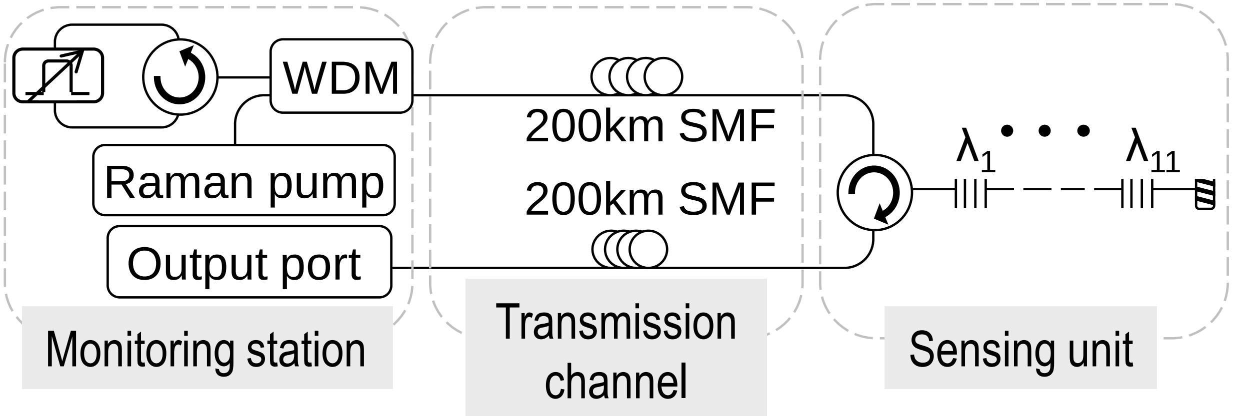
$P_{pump\ Raman}$=1.5 W

11 FBG sensors.
OSNR= From 17 to 10 dB



M. Fernández- Vallejo et al. Ultra-Long Laser Systems for Remote Fiber Bragg Gratings Arrays Interrogation IEEE Photonics Technology Letters, V. 25 (14), 1362-1364 **(2013)**

- **200km random fiber laser, by Fernández-Vallejo *et. al. [2013]***



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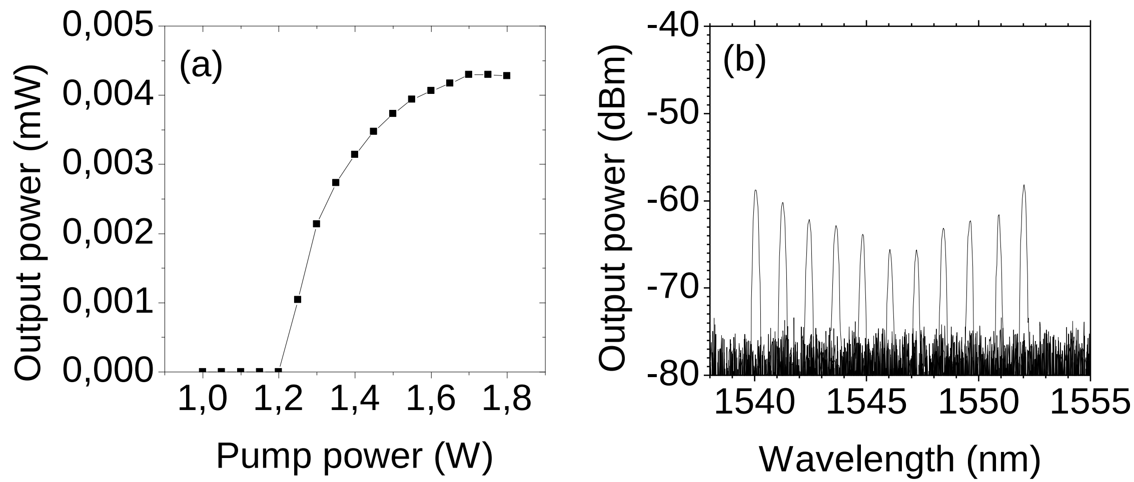
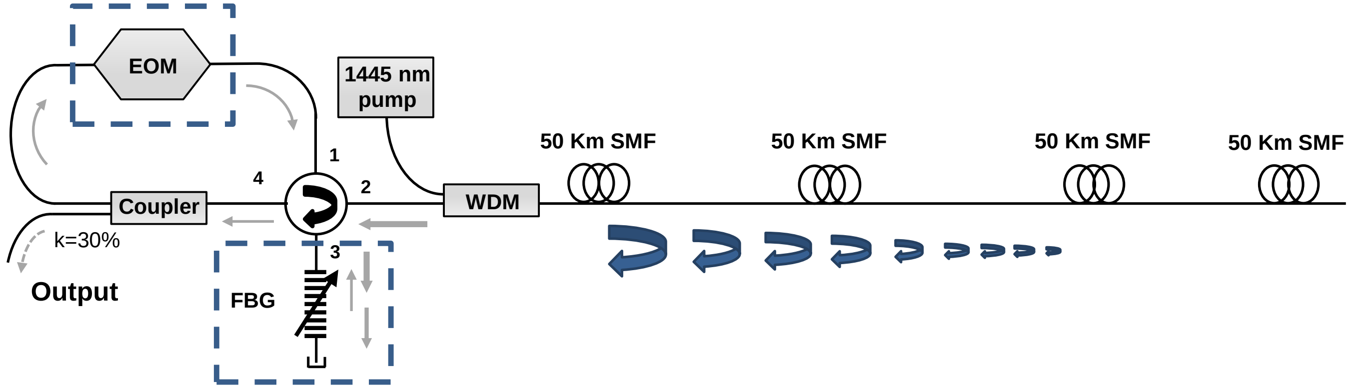


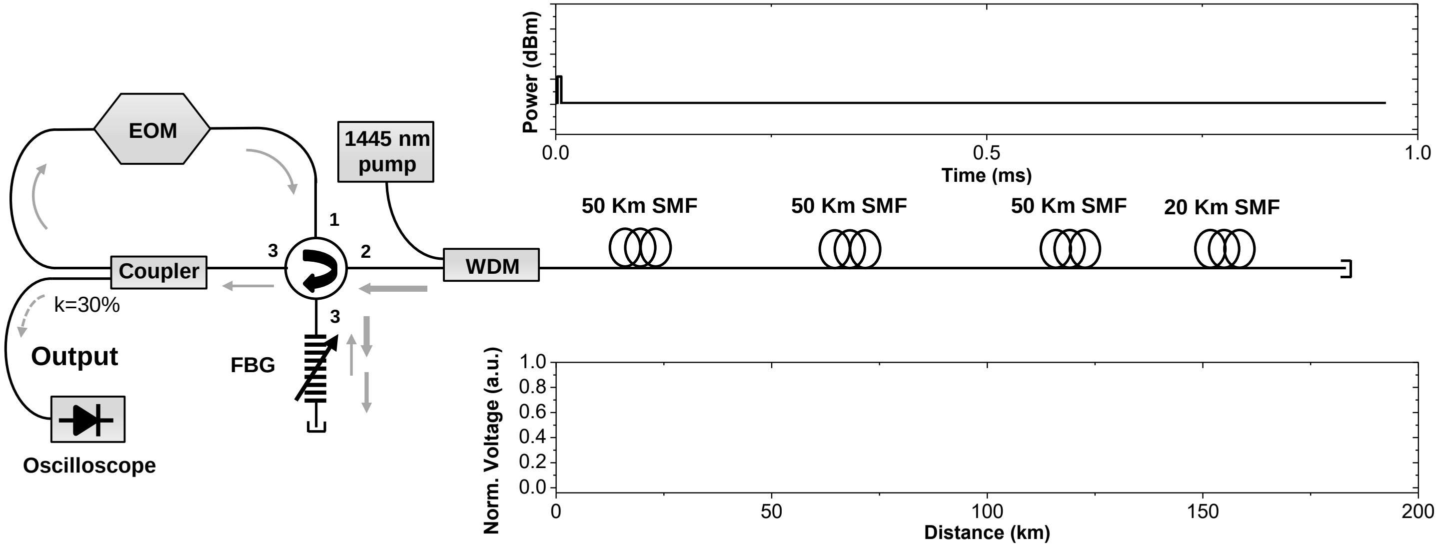
M. Fernández- Vallejo et al. Ultra-Long Laser Systems for Remote Fiber Bragg Gratings Arrays Interrogation IEEE photonics Tech letters 25 (14), 1362-1364(2013)

Our latest ultralong lasing network

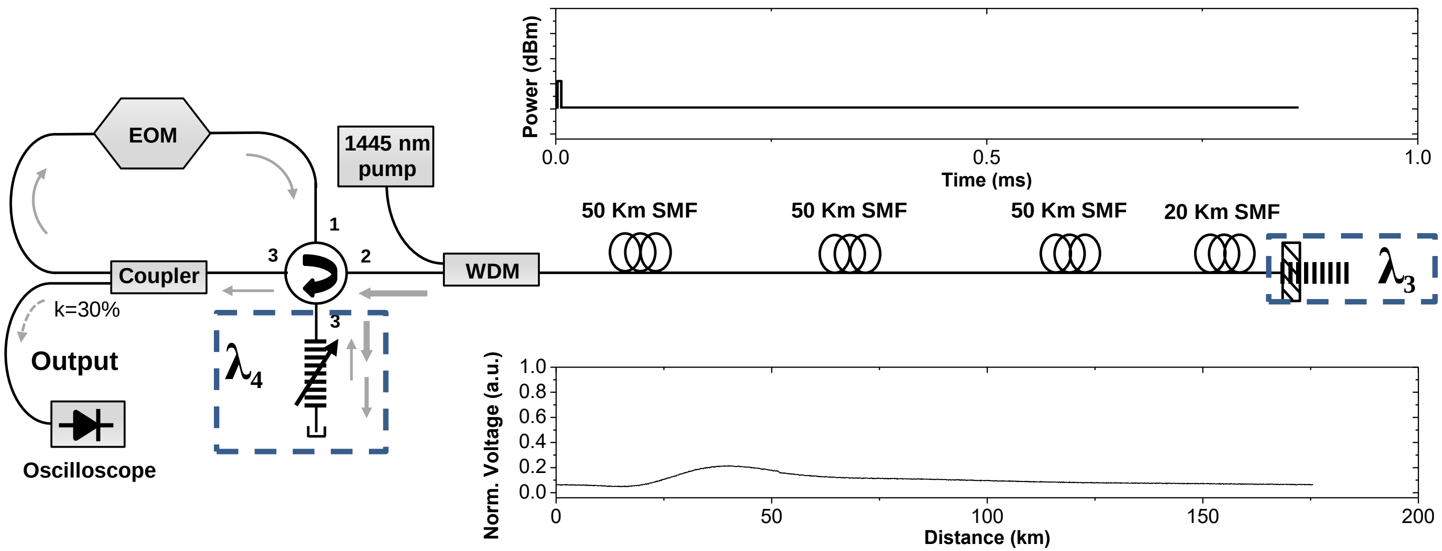


- Random DFB laser
- Equivalent single-arm configuration
- Tunable laser: Wavelength selected by a tunable FBG
- Amplitude-modulated
  - Pulse train (rectangular).
  - Pulse duration 8.3 μs
  - Repetition rate 450 Hz

D. Leandro et al. Time and wavelength division multiplexing scheme for ultra-long sensing based on a cavity-modulated rand[…] fiber laser OFS 24 Curitiba (Brasil) October 2015



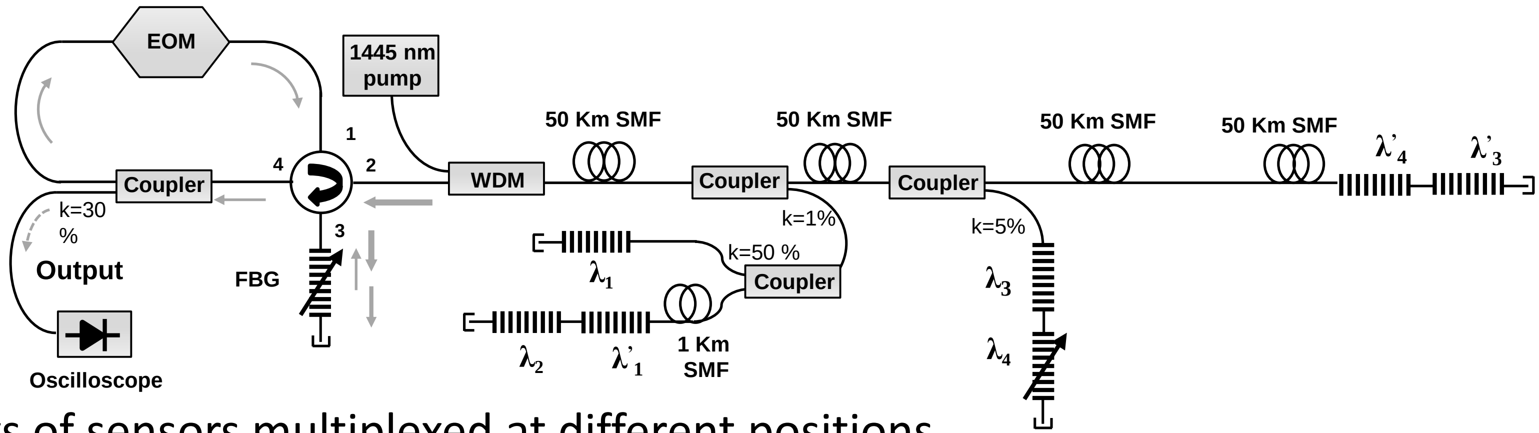
- Optical time-domain reflectometry in a lasing cavity:
  - Reflections along the fiber are detected



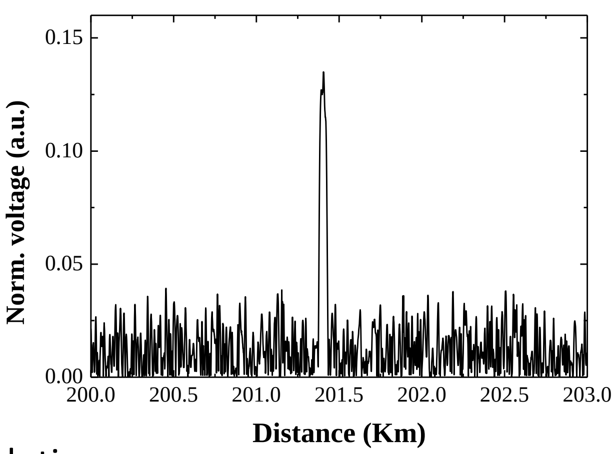
- Optical time-domain reflectometry in a lasing cavity:
  - Reflections along the fiber are detected
- Additional wavelength division multiplexing:
  - Tunable FBG → Wavelength sweep
  - One OTDR trace per wavelength step
  - A reflection appears when λ (laser) = λ (sensor FBG)

Results

200 km



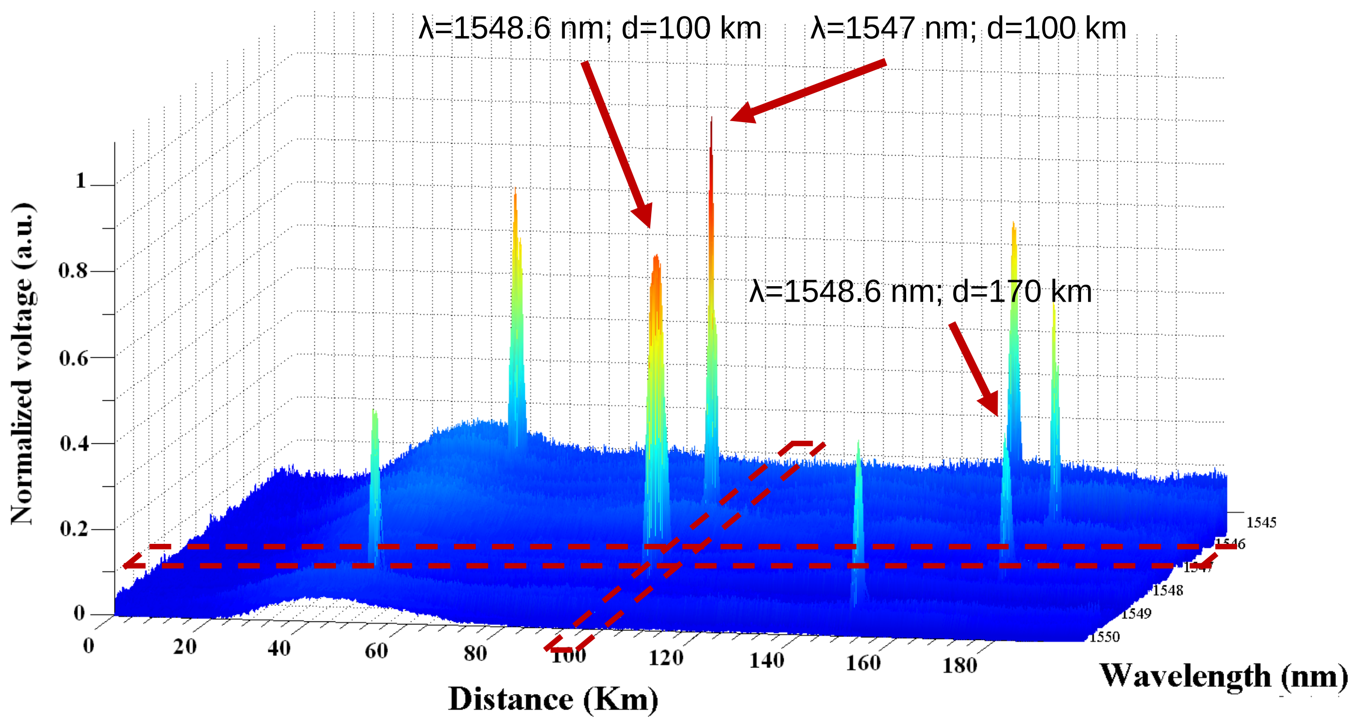
- Arrays of sensors multiplexed at different positions
  - Optical couplers inserted at km = 50, 100, 150
  - Pairs of FBGs located at km = 100, 150 and 170 or 200
  - Another coupler with 3 FBGs placed at km 50
  - λ_1=1545.6 nm, λ_2= 1550 nm, λ_3= 1547 nm,
  - λ_4= 1548.6 nm and λ_5= 1545.1 nm



- FBGs can be measured 201.4 km away: 85m spatial resolution
- Coupling factors k_n chosen to keep the laser in random operation

D. Leandro et al Time and wavelength division multiplexing scheme for ultra-long sensing based on a cavity-modulated random DFB fiber laser proceedings of OFS 2015 (Brasil)

- Every FBG sensor can be identified:
  - FBGs located at the same position are wavelength-multiplexed
  - FBGs with the same λ are time-multiplexed



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OPTICAL LASING NETWORKS FOR SENSING

- **Growing research topic**
- **Fiber lasers provide a higher quality of measurements**
- **Promising application in remote sensing**
- **Recent configurations using Random cavity distributed lasers**

Ultralong fiber lasers for optical fiber sensors

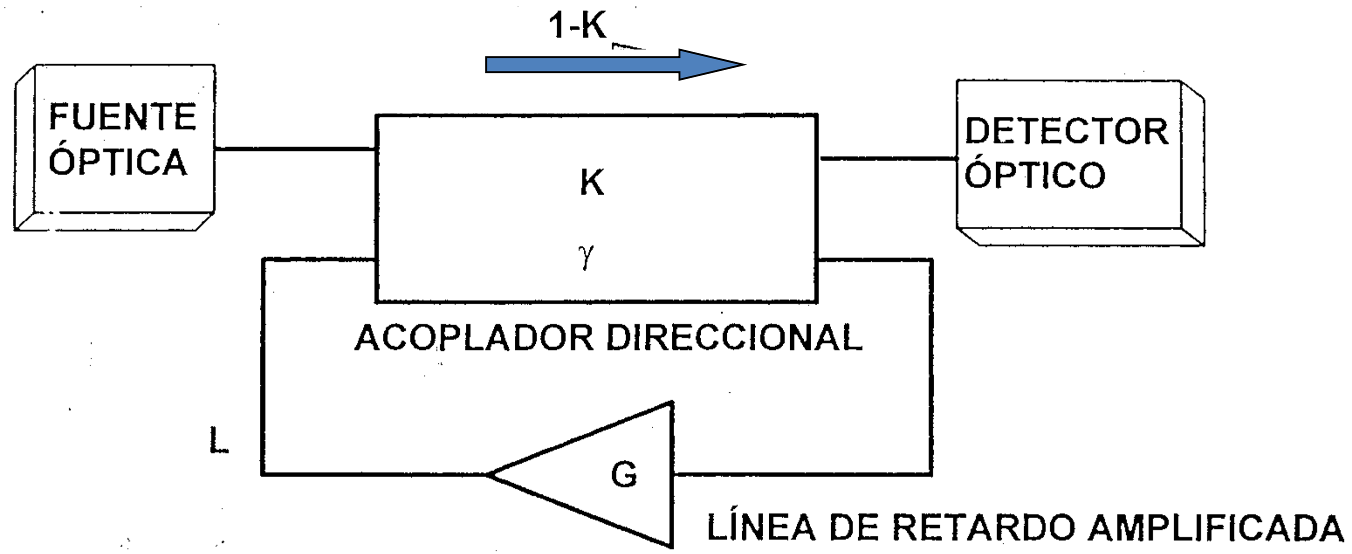
THANK YOU FOR YOUR ATTENTION

Manuel López-Amo

Zadar 13^{3h} April 2016

Universidad Pública de Navarra

a) Anillo simple con amplificación (1991)



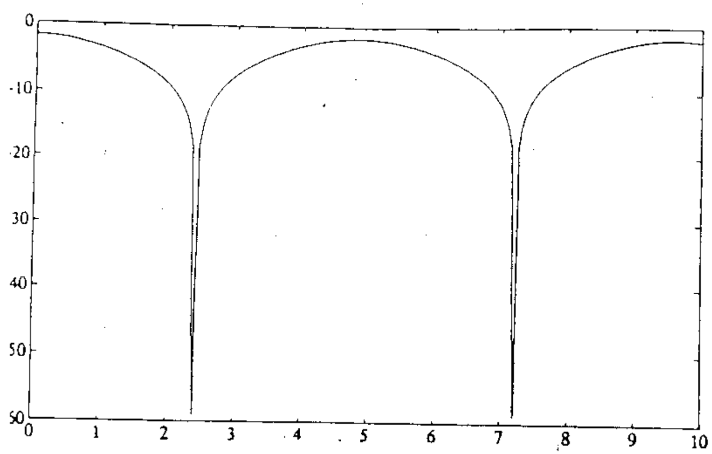
- LA FUNCIÓN DE TRANSFERENCIA PRESENTA:
  - UN POLO EN : $Z_p=G^*/(1-K)$
  - UN CERO EN : $Z_c=G^*(1-K)/(2K-1)$
- LA RESPUESTA EN FRECUENCIAS ES PERIÓDICA Y PRESENTA:
  - MÁXIMOS EN LAS FRECUENCIAS $f = mc/(nL)$
  - MÍNIMOS EN LAS FRECUENCIAS $f = (2m+1)c/(2nL)$

Respuesta en frecuencias eléctricas del anillo simple con amplificación

M.C.Vázquez, B.Vizoso, M.López-Amo, M.A.Muriel. **"Single and double amplified recirculating delay lines as fibre-optic filters"** Electronics Letters V.28 n.11 pp.1017-1019 Mayo1992.

SE CUMPLE LA CONDICIÓN DEL CERO

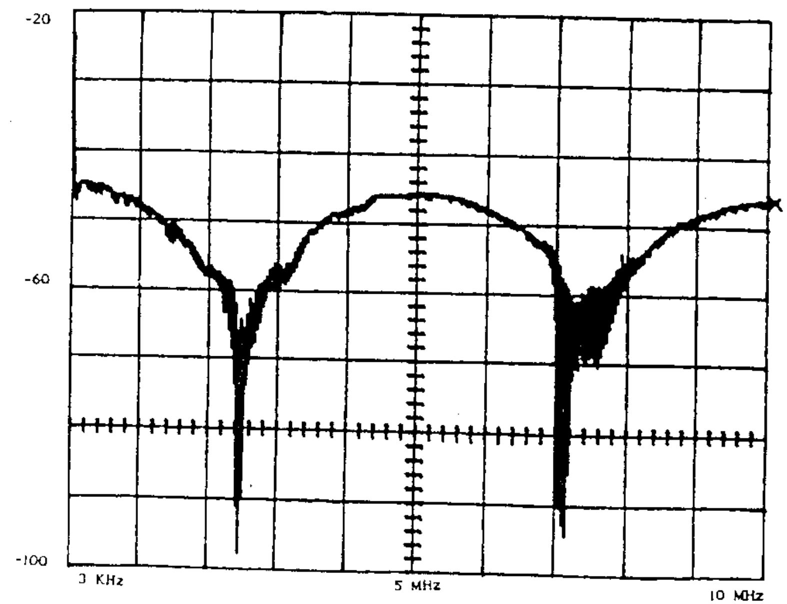
Amplitud relativa (dBr)



Frecuencia (MHz)

TEÓRICA

Señal detectada (dBm)



Frecuencia

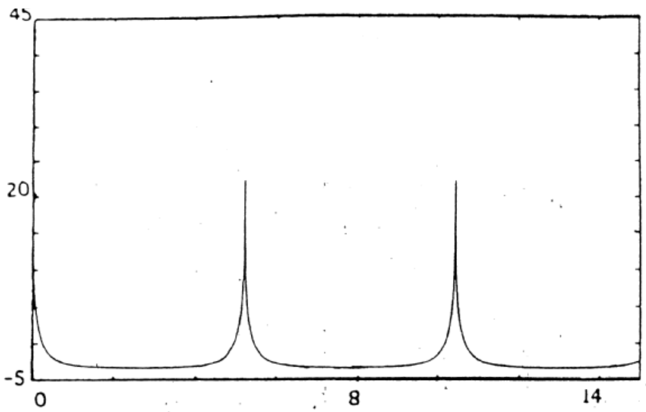
EXPERIMENTAL

upna

Respuesta en frecuencias eléctricas del anillo simple con amplificación (II)

SE CUMPLE LA CONDICIÓN DEL POLO

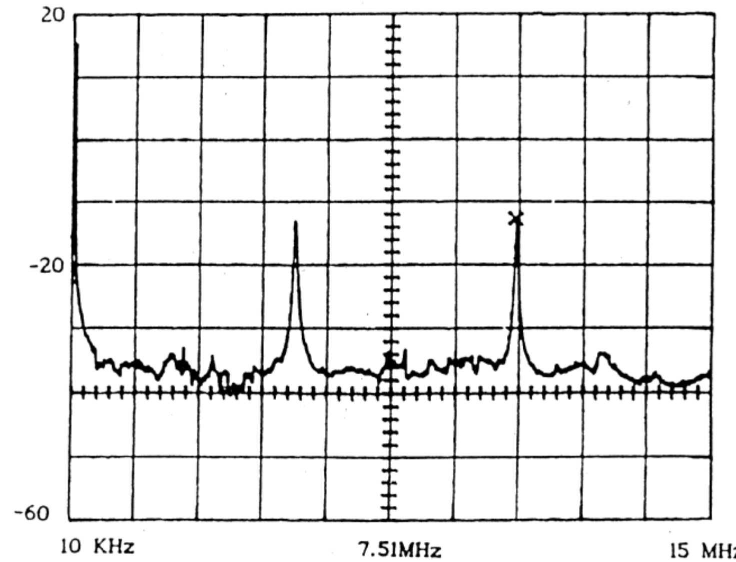
Amplitud relativa (dBr)



Frecuencia (MHz)

TEÓRICA

Señal detectada (dBm)

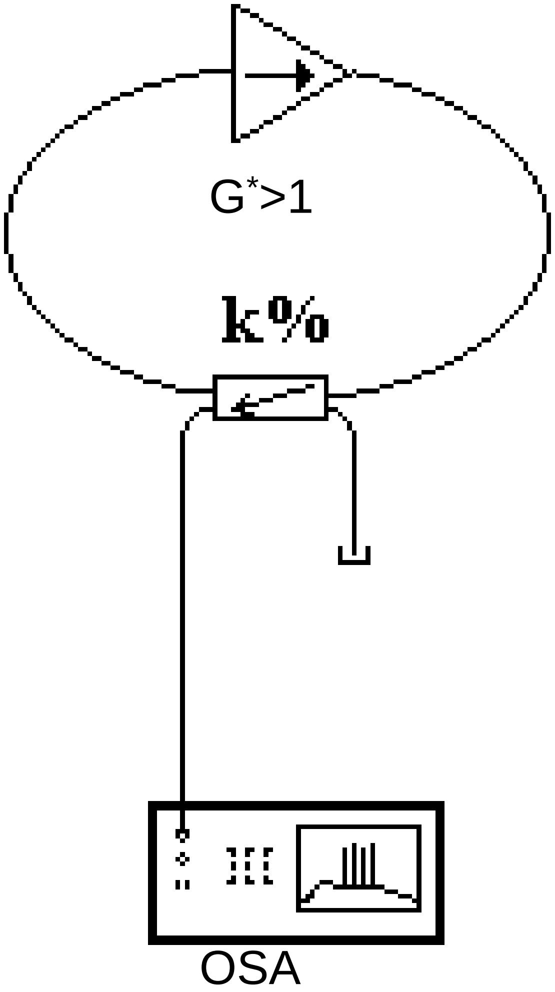


Frecuencia

EXPERIMENTAL

upna

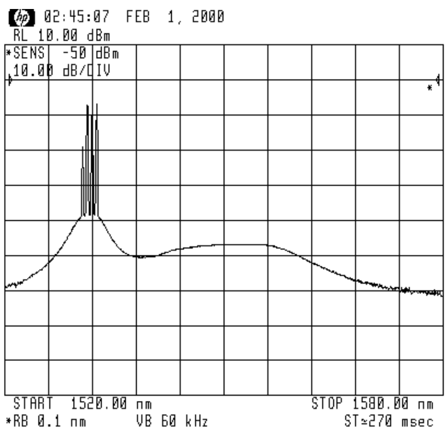
Oscilación natural de un láser en anillo con EDFA



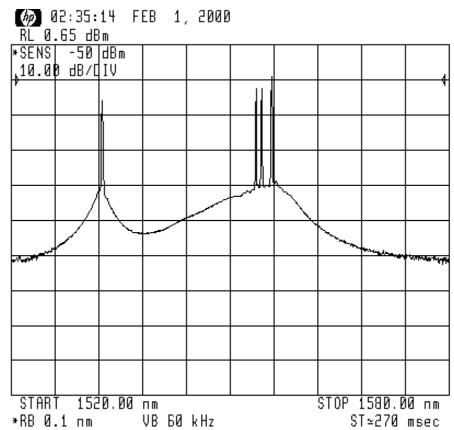
- Acoplador dentro del anillo para extracción de potencia.
- No se incluye filtro óptico de selección de λ de operación.
- Acoplador con relación de acoplo (K) variable
- Amplificador comerciad de Fibra dopada con Erbio

upna

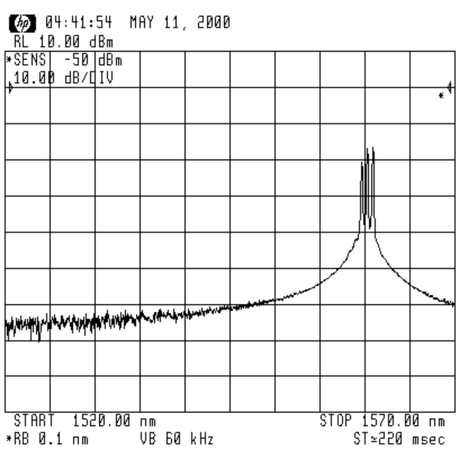
Oscilación natural de un láser en anillo con EDFA



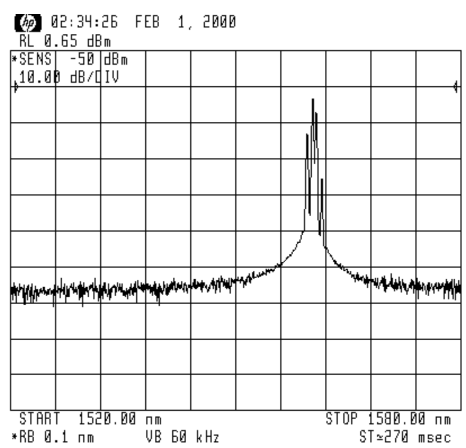
k=95%



k=90%



k=50%



k=10%

- El perfil de ganancia del EDFA depende de la potencia de la señal realimentada:
  - K alto

    mayor en 1530 nm

  * K bajo

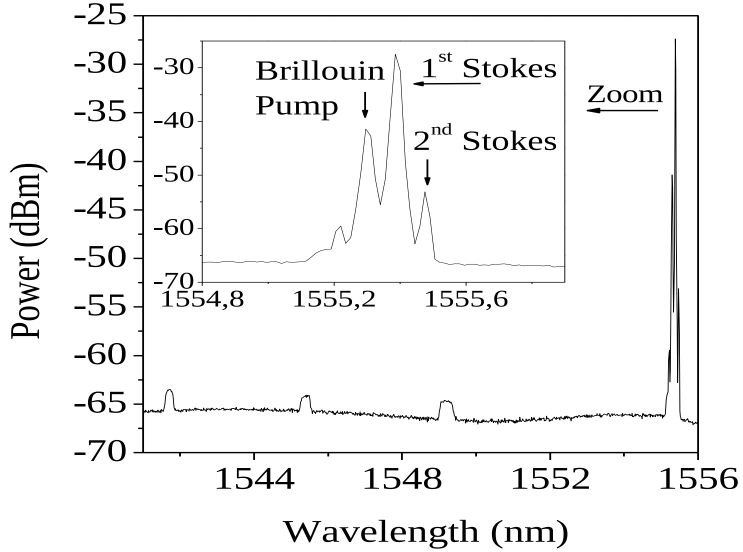
    mayor en 1560 nm

upna

- **100 km system, by Fernandez-Vallejo *et. al. [2011]***

MODE OPERATION: The Raman pump laser provides enough gain in the cavity so that the system is set just below the lasing threshold ➞ The tunable laser makes sweeps in wavelength

$\lambda_{tunable\ laser} = \lambda_{FBG}$: The hybrid Raman-Brillouin gain is enough for laser action to take place

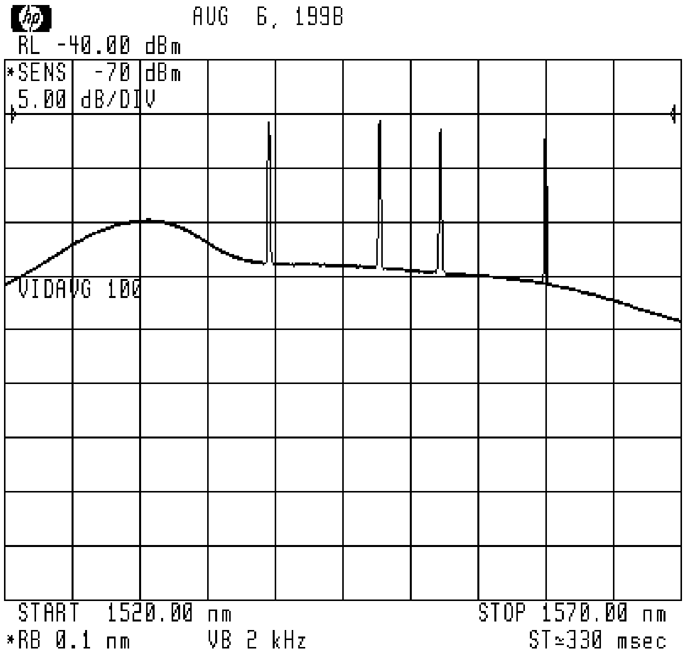


M. Fernandez-Vallejo et al. "Fiber Bragg Grating interrogation technique for remote sensing (100km) using a hybrid Brillouin-Raman fiber laser," (OFS-21), Proceedings of the SPIE,7753, art. no. 77537I, Ottawa (Canada), 2011.

ASE REDUCTION RESULTS

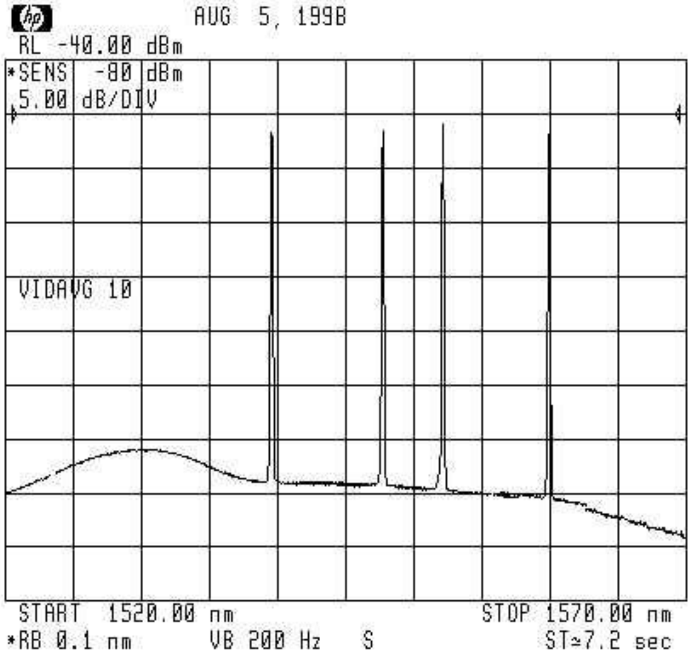
SINGLE BUS

- Average signal power: -41.5 dBm
- Average noise power: -54.6 dBm
- Average SNR: 13.1 dB



DOUBLE BUS

- Average signal power: -41.5 dBm
- Average noise power: -74.7 dBm
- Average SNR: 33.2 dB



- Equal signal power, but 20 dB reduction on received ASE noise.
- Good power equalization between channels.