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New Advances in Fabry-Perot Cavities for Sensing Applications

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Outline

- Historical Overview of Fabry-Perot (FP) cavities
- Basic Principles
- FP based on Fibre Bragg Gratings (FBG) structures
- Chemical etching fabrication
- Microstructured Fibre/Photonic Crystal Fibre (PCF)
- Focused Ion Beam technology
- Conclusions

Historical Overview

First publication in 1979

Fiber optic hydrophone: improved strain configuration and environmental noise protection

P. G. Cielo

It is shown that the pressure sensitivity of a fiber-optic hydrophone is strongly dependent on the fiber's strain configuration. Longitudinal strain is found to be much more effective than uniform strain, and consequently modifications to the sensor's design are proposed. Environmental noise sources such as ocean motion and mechanical vibrations are then discussed, and a new double-cavity configuration, which is unaffected by those perturbations, is presented. A tunable-cavity detection method is finally proposed, and it is shown how this method can overcome problems related to drift of the point of operation, laser intensity fluctuations, and nonlinearity for high dynamic ranges.

Introduction

Fiber-optic hydrophones have recently been pro-
osed[1–7] as a novel approach to underwater acoustic
ensing. The configuration considered most fre-
uently[1–5] consists of two laser excited monomode fibers
the two arms of an interferometer, with one
the sensing element and the

Other sources of environmental noise arise from pressure fluctuations near the surface due to ocean motion,[8] as well as from elongations generated by drag forces on the fiber-cable link with the sensing element.[9,10] These perturbations introduce random phase differences between the interfering beams, unless the light beams are transmitted through the same monomode fiber. This can be done by including two reflectors along a single fiber so that the beams reflected back along the highly perturbed portion of the fiber are subject to the same random phase modulation. Unfortunately, this simple scheme is faced with problems of source coherence and drift of the operating point, as will be explained in more detail later.

In this paper it is first shown that the sensitivity of a fiber-optic hydrophone is strongly dependent on the strain configuration. It is found that longitudinal compression produces much higher sensitivity than uniform 3-D compression. Consequently, some hydrophone designs leading to longitudinal compression and enhanced sensitivity are proposed. In Sec. III it is shown how the coherence requirements of a double-reflector configuration can be relaxed by the introduction of a reference cavity along the same fiber. Environmental noise of the kind previously considered does not affect such a double-cavity configuration. Moreover, the reference cavity—in the double-cavity configuration—can be tuned to avoid problems related to drift of the operating point, laser intensity fluctuations, and nonlinearity when the condition $\Delta\phi \ll \pi$ is not satisfied.

II. Pressure Sensitivity

A number of investigations have been reported concerning the phase-modulation induced in the optical beam transmitted by an optical fiber subject to

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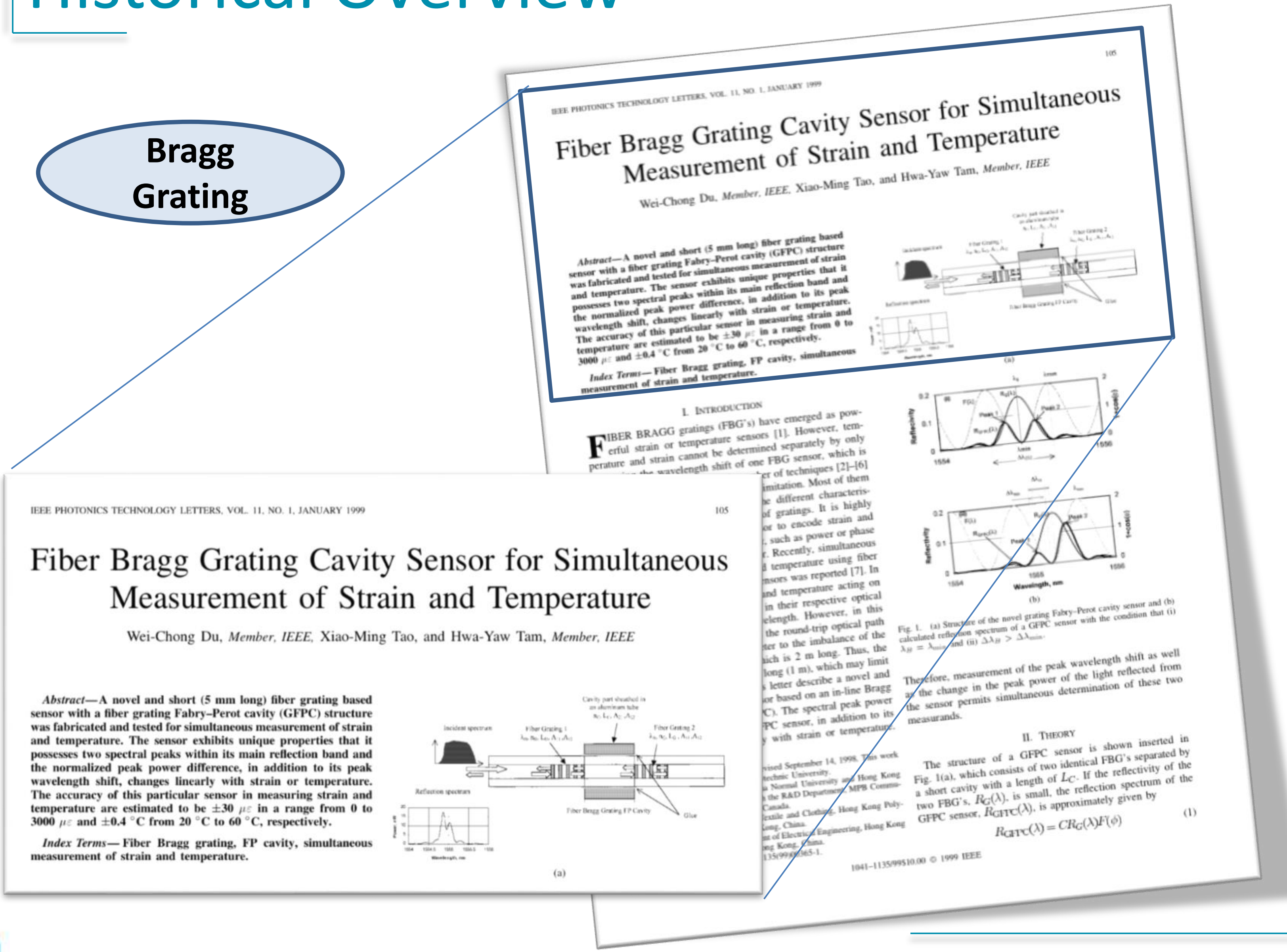
Historical Overview

Bragg Grating



IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 11, NO. 1, JANUARY 1999 105

Fiber Bragg Grating Cavity Sensor for Simultaneous Measurement of Strain and Temperature

Wei-Chong Du, *Member, IEEE*, Xiao-Ming Tao, and Hwa-Yaw Tam, *Member, IEEE*

***Abstract*—A novel and short (5 mm long) fiber grating based sensor with a fiber grating Fabry–Perot cavity (GFPC) structure was fabricated and tested for simultaneous measurement of strain and temperature. The sensor exhibits unique properties that it possesses two spectral peaks within its main reflection band and the normalized peak power difference, in addition to its peak wavelength shift, changes linearly with strain or temperature. The accuracy of this particular sensor in measuring strain and temperature are estimated to be ±30 $\mu\varepsilon$ in a range from 0 to 3000 $\mu\varepsilon$ and ±0.4 °C from 20 °C to 60 °C, respectively.**

***Index Terms*— Fiber Bragg grating, FP cavity, simultaneous measurement of strain and temperature.**

(a)

I. INTRODUCTION

FIBER BRAGG gratings (FBG's) have emerged as powerful strain or temperature sensors [1]. However, temperature and strain cannot be determined separately by only

Fig. 1. (a) Structure of the novel grating Fabry–Perot cavity sensor and (b) calculated reflection spectrum of a GFPC sensor with the condition that (i) $\lambda_B = \lambda_{min}$ and (ii) $\Delta\lambda_B > \Delta\lambda_{min}$.

Therefore, measurement of the peak wavelength shift as well as the change in the peak power of the light reflected from the sensor permits simultaneous determination of these two measurands.

II. THEORY

The structure of a GFPC sensor is shown inserted in Fig. 1(a), which consists of two identical FBG's separated by a short cavity with a length of L_C. If the reflectivity of the two FBG's, $R_G(\lambda)$, is small, the reflection spectrum of the GFPC sensor, $R_{GFPC}(\lambda)$, is approximately given by

$$R_{GFPC}(\lambda) = CR_G(\lambda)F(\phi) \quad (1)$$

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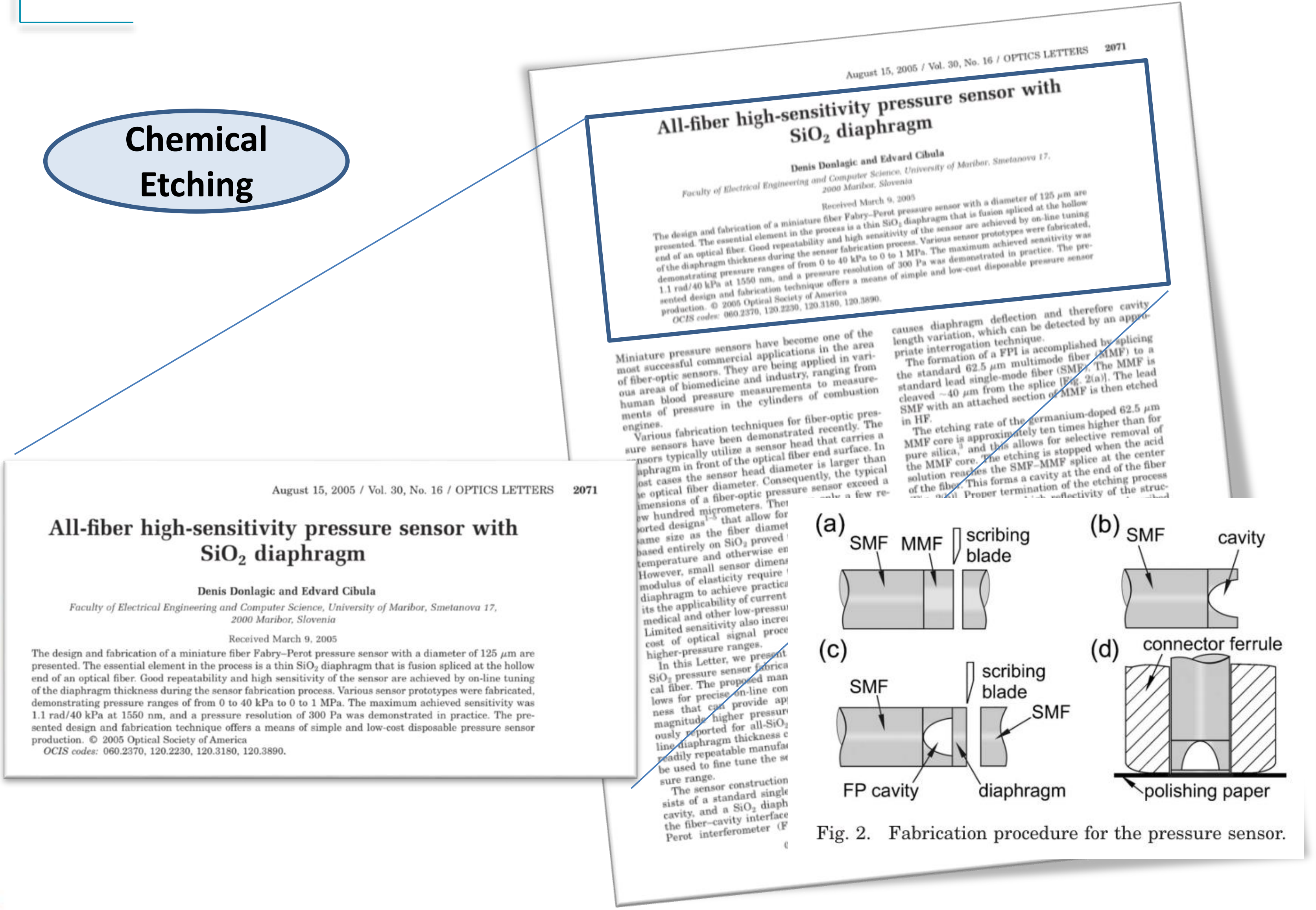
Historical Overview

Chemical Etching



August 15, 2005 / Vol. 30, No. 16 / OPTICS LETTERS 2071

All-fiber high-sensitivity pressure sensor with SiO_2 diaphragm

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The design and fabrication of a miniature fiber Fabry–Perot pressure sensor with a diameter of 125 μm are presented. The essential element in the process is a thin SiO_2 diaphragm that is fusion spliced at the hollow end of an optical fiber. Good repeatability and high sensitivity of the sensor are achieved by on-line tuning of the diaphragm thickness during the sensor fabrication process. Various sensor prototypes were fabricated, demonstrating pressure ranges of from 0 to 40 kPa to 0 to 1 MPa. The maximum achieved sensitivity was 1.1 rad/40 kPa at 1550 nm, and a pressure resolution of 300 Pa was demonstrated in practice. The presented design and fabrication technique offers a means of simple and low-cost disposable pressure sensor production.

OCIS codes: 060.2370, 120.2230, 120.3180, 120.3890.

Miniature pressure sensors have become one of the most successful commercial applications in the area of fiber-optic sensors. They are being applied in various areas of biomedicine and industry, ranging from human blood pressure measurements to measurements of pressure in the cylinders of combustion engines.

causes diaphragm deflection and therefore cavity length variation, which can be detected by an appropriate interrogation technique.

The formation of a FPI is accomplished by splicing the standard 62.5 μm multimode fiber (MMF) to a standard lead single-mode fiber (SMF). The MMF is cleaved ~40 μm from the splice [Fig. 2(a)]. The lead SMF with an attached section of MMF is then etched in HF.

The etching rate of the germanium-doped 62.5 μm MMF core is approximately ten times higher than for pure silica,[3] and this allows for selective removal of the MMF core. The etching is stopped when the acid solution reaches the SMF–MMF splice at the center of the fiber. This forms a cavity at the end of the etching process

Fig. 2. Fabrication procedure for the pressure sensor.

Historical Overview

PCF

2662 OPTICS LETTERS / Vol. 32, No. 18 / September 15, 2007

In-line fiber-optic etalon formed by hollow-core photonic crystal fiber

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A novel fiber-optic in-line etalon formed by splicing a section of hollow-core photonic crystal fiber (HCPCF) in between two single-mode fibers is proposed and demonstrated, for the first time to our knowledge. Such a HCPCF-based etalon acts as an excellent optical waveguide to form a Fabry–Perot interferometer and hence allows the cavity length to be as long as several centimeters with good visibility as the transmission loss of the HCPCF is much smaller than that of a hollow core fiber; this offers great potential to generate a practical dense fiber-optic sensor network with spatial frequency division-multiplexing. This novel etalon is demonstrated for strain measurement, and the experimental results show that a good visibility of 0.3 and a strain accuracy of better than ±5$\mu\varepsilon$ are achieved. © 2007 Optical Society of America

OCIS codes: 060.2370, 050.2230.

ing the ends of two SMF-28 fibers to the cleaved end of a HCPCF fiber (Blaze photonics: HC-1550-02). The core diameter and the distance between the centers of the cladding holes of the HCPCF are ~10.9 and ~3.8 μm, respectively. The fabrication of the etalon is simple and straightforward; i.e., splice the cleaved ends of the HCPCF to the cleaved ends of two SMF-28 fibers with an electric-arc fusion splicer (Fitel: S176) as shown in Fig. 2. The etalon length can be cleaved down to the order of micrometers with inspection under a microscope. In addition, the etalon length could be extended up to several centimeters because the transmission loss (<0.1 dB/m) of the HCPCF is much lower than that of the hollow core fiber configuration reported previously [2].

Figure 3(a) is the reflective spectrum of the HCPCF etalon, which is obtained by using a high-accuracy optical spectrum analyzer (OSA) (Micron Optics: Si720) with a wavelength resolution of 0.25 pm and a wavelength precision of 1 pm over a spectral range of 1520–1570 nm. It can be seen from Fig. 3(a) that the fringe visibility is relative low due to the splicing loss between the two single-mode fibers and the HCPCF, which was measured to be ~1 dB for each joint in our experiment. To compensate such a joint loss, a reflective film (Ti_2O_3) was coated on the

Fig. 1. Configuration of an in-line HCPCF etalon.

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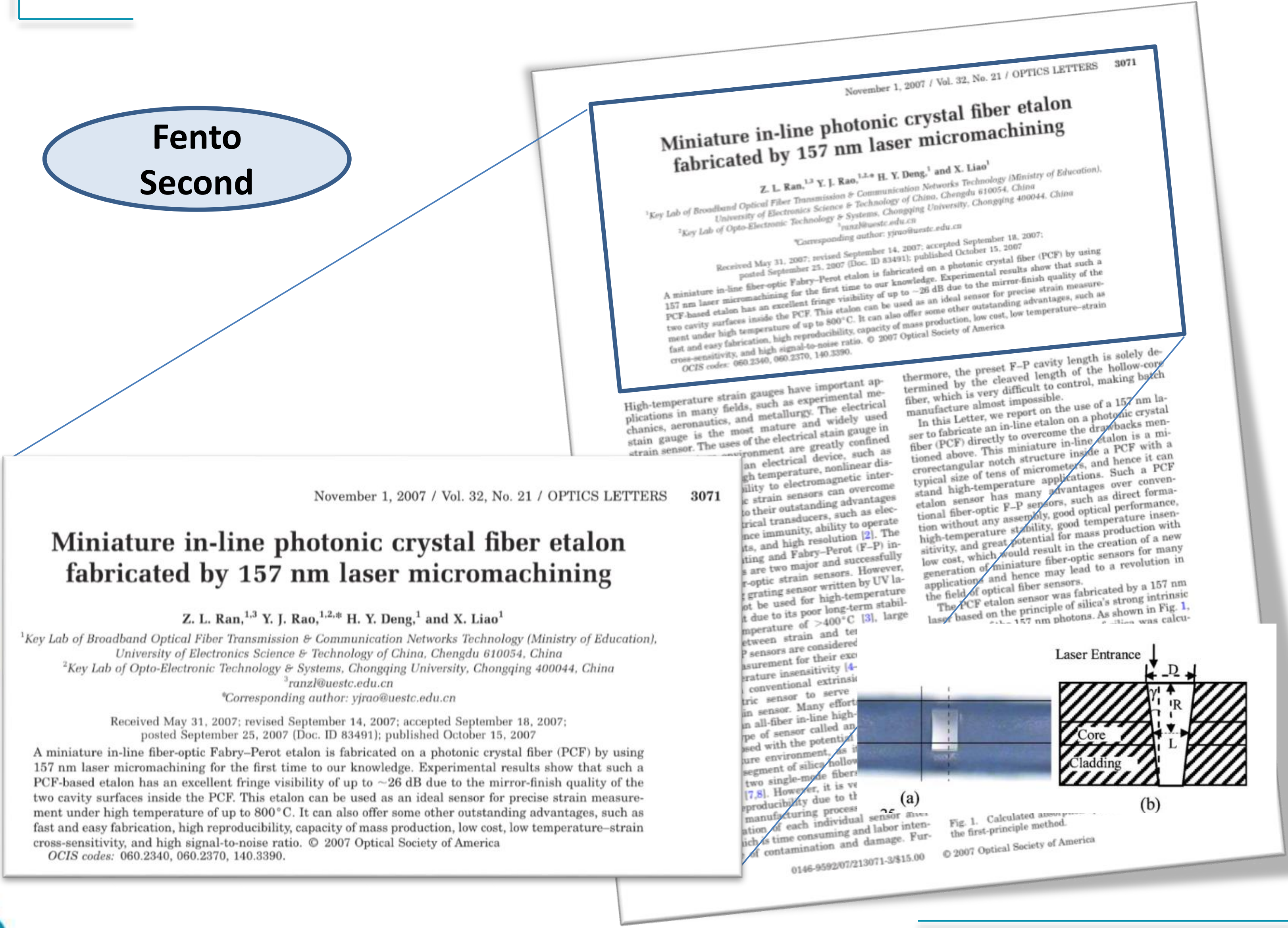
Historical Overview

Fento Second



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Miniature in-line photonic crystal fiber etalon fabricated by 157 nm laser micromachining

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A miniature in-line fiber-optic Fabry–Perot etalon is fabricated on a photonic crystal fiber (PCF) by using 157 nm laser micromachining for the first time to our knowledge. Experimental results show that such a PCF-based etalon has an excellent fringe visibility of up to ~26 dB due to the mirror-finish quality of the two cavity surfaces inside the PCF. This etalon can be used as an ideal sensor for precise strain measurement under high temperature of up to 800°C. It can also offer some other outstanding advantages, such as fast and easy fabrication, high reproducibility, capacity of mass production, low cost, low temperature–strain cross-sensitivity, and high signal-to-noise ratio. © 2007 Optical Society of America

OCIS codes: 060.2340, 060.2370, 140.3390.

thermore, the preset F–P cavity length is solely determined by the cleaved length of the hollow-core fiber, which is very difficult to control, making batch manufacture almost impossible.

In this Letter, we report on the use of a 157 nm laser to fabricate an in-line etalon on a photonic crystal fiber (PCF) directly to overcome the drawbacks mentioned above. This miniature in-line etalon is a microrectangular notch structure inside a PCF with a typical size of tens of micrometers, and hence it can stand high-temperature applications. Such a PCF etalon sensor has many advantages over conventional fiber-optic F–P sensors, such as direct formation without any assembly, good optical performance, high-temperature stability, good temperature insensitivity, and great potential for mass production with low cost, which would result in the creation of a new generation of miniature fiber-optic sensors for many applications and hence may lead to a revolution in the field of optical fiber sensors.

The PCF etalon sensor was fabricated by a 157 nm laser based on the principle of silica's strong intrinsic

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Historical Overview

FIB

2308 OPTICS LETTERS / Vol. 35, No. 13 / July 1, 2010

Microfiber-probe-based ultrasmall interferometric sensor

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We report an ultrasmall microfiber-probe-based reflective interferometer for highly sensitive liquid refractive index measurement. It has a 3.5 μm micronotch cavity fabricated by focused ion beam micromachining. A sensitivity of 110 nm/RIU (refractive index unit) in liquid is achieved with over 20 dB extinction ratio. Theoretical analysis shows this kind of device is a hybrid of Fabry–Perot and modal interferometers. In comparison with normal fiber interferometers, this probe sensor is very compact, stable, and cheap, offering great potentials for detecting inside sub-wavelength bubbles, droplets, or biocells. © 2010 Optical Society of America
OCIS codes: 060.2370, 280.4788.

Optical fiber interferometers have been extensively used in various sensing applications due to their advantages of versatility, linear response, and relatively simple structure. In the past two decades, many efforts have been made to develop intrinsic and extrinsic interferometers, especially the microcavity Fabry–Perot interferometers (MCFPIs). MCFPIs with tens-of-micrometers-length cavities are attractive because of the small size, large free spectrum range (FSR), and high sensitivity. The cavity can be assembled by inserting a silica single-mode fiber (SMF) and a multimode fiber into a glass capillary [1], cascading Fabry–Perot cavities formed with a short piece of multimode fiber and a hollow core fiber [2], splicing two SMFs to a hollow-core fiber [3], or splicing an SMF and an index-guiding photonic crystal fiber together [4]. Although much progress has been made, people are still pursuing new microcavity fabrication techniques to improve the cavity length precision, structure accuracy, and the process repeatability. Femtosecond laser technology thus was proposed recently showing great success in micromachining fiber devices. MCFPIs can be quickly fabricated by drilling a small hole in an SMF for liquid and gas sensing [5]. However, even the femtosecond-laser-machined MCFPIs still show low fringe visibility of several decibels in liquids due to the rugged surfaces insi the cavity; what is more, it is difficult to focus the las spot to a subwavelength scale owing to the diffraction li it [6]; thus the micromachining accuracy is limited and t size of the microcavity is large. The latest progress in cused ion beam (FIB) techniques has opened a n widow of opportunity for ultrasmall cavities. The f and controllable ion spot size and high beam current c sity are perfect for nanofabrication. Microcavities v nanometer-scale accuracy in a subwavelength micro could be fabricated by FIB, which is relatively difficul the femtosecond laser approach.

In this Letter, we demonstrated an ultrasmall inlin flective interferometric sensor with an open microc on the side of a single microfiber probe by direc machining. The cavity has the dimensions of only s micrometers, which is much smaller than pr MCFPIs. A theoretical analysis reveals that this k device is a hybrid of Fabry–Perot and modal interf

eters. Experimental results show our fiber probe interferometer has high extinction ratio and sensitivity. The compact size, simple fiber-probe structure, all fiber connection, and easy fabrication further make the microfiber-probe-based reflective interferometer (MPRI) a great candidate for chemical and biological sensing applications. It even could offer fantastic potential in detecting inside a biocell, thanks to its unique tiny probe structure.

Standard optical microfiber probes generally consist of tapered fiber tips and taper transitions. Since the microfiber probe is for analyte detecting rather than launching the light, it should be short enough in order to be rigid. However, too short and sharp a shape results in high losses owing to the poor adiabaticity of the taper profiles [7]. During the past decade, much work has been carried out to study and optimize microfiber taper profiles for telecom devices. Using a taper manufacturing rig it is possible to tailor the taper shape to an ideal profile [8], but it is not easy to fabricate a short fiber probe. In this work, we make taper probes using a commercial pipette puller (model P2000, Sutter Instrument). The fabrication process is simple, convenient [9], and extremely fast. The obtained microfiber taper probe is then checked under a microscope, as shown in Fig. 1. The profile is described

Fig. 2. SEM image of the micronotch cavity from the side.

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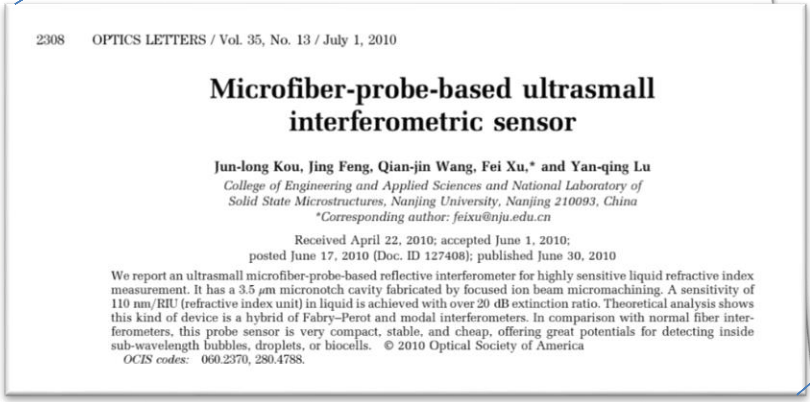

2308 OPTICS LETTERS / Vol. 35, No. 13 / July 1, 2010

Microfiber-probe-based ultrasmall interferometric sensor

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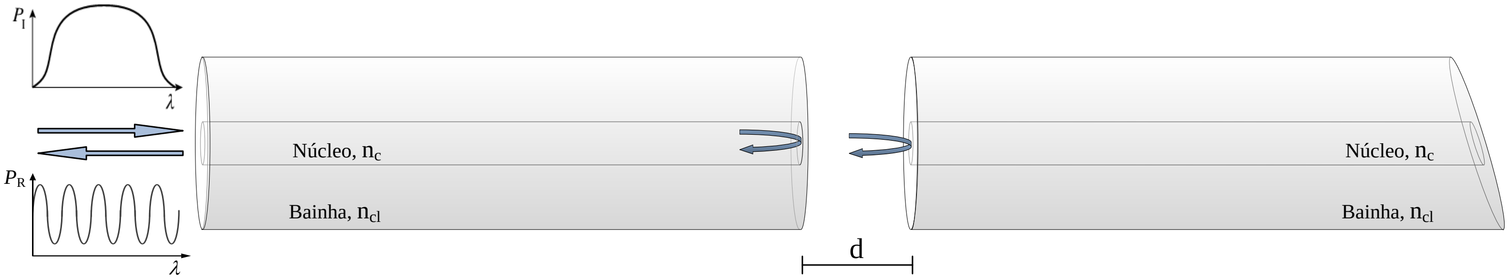
We report an ultrasmall microfiber-probe-based reflective interferometer for highly sensitive liquid refractive index measurement. It has a 3.5 μm micronotch cavity fabricated by focused ion beam micromachining. A sensitivity of 110 nm/RIU (refractive index unit) in liquid is achieved with over 20 dB extinction ratio. Theoretical analysis shows this kind of device is a hybrid of Fabry–Perot and modal interferometers. In comparison with normal fiber interferometers, this probe sensor is very compact, stable, and cheap, offering great potentials for detecting inside sub-wavelength bubbles, droplets, or biocells. © 2010 Optical Society of America
OCIS codes: 060.2370, 280.4788.

Fibre Fabry-Perot

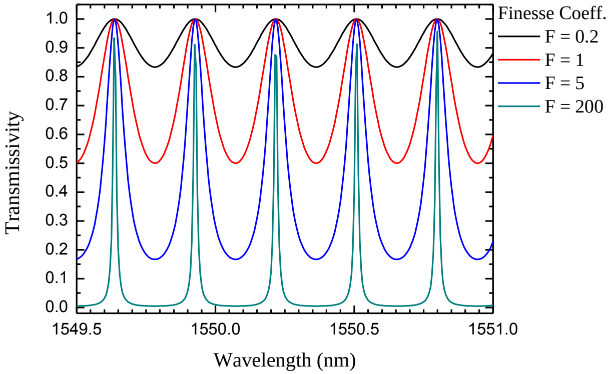
PRINCIPLES

Principles

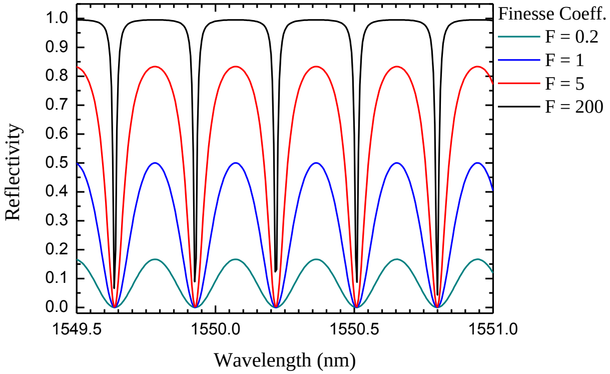


Finesse	Refractive index varitation in the FP cavity	Spectral range between two consecutive maxima
$F = \frac{\Delta\delta}{FWHM}$	$\Delta n = \frac{\Delta\lambda_m}{\lambda_m} n_0$	$\Delta\delta = \frac{\lambda^2}{2nd}$

Transmissivity



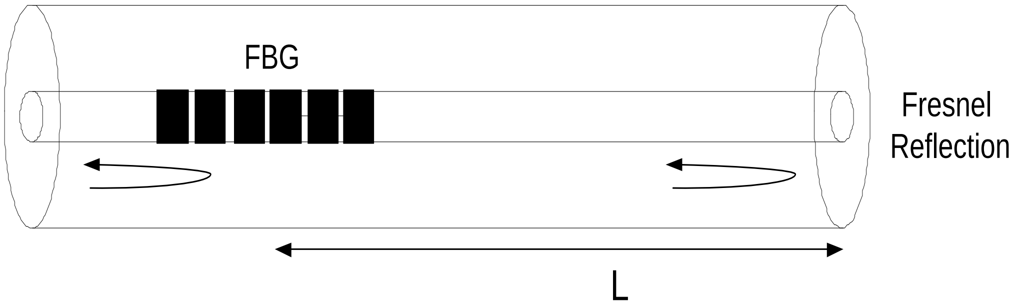
Reflectivity

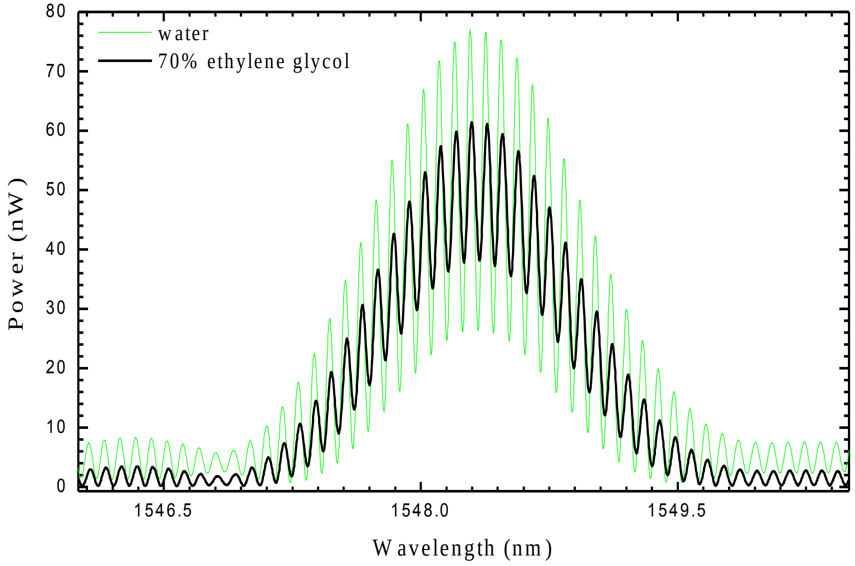


Fibre Fabry-Perot

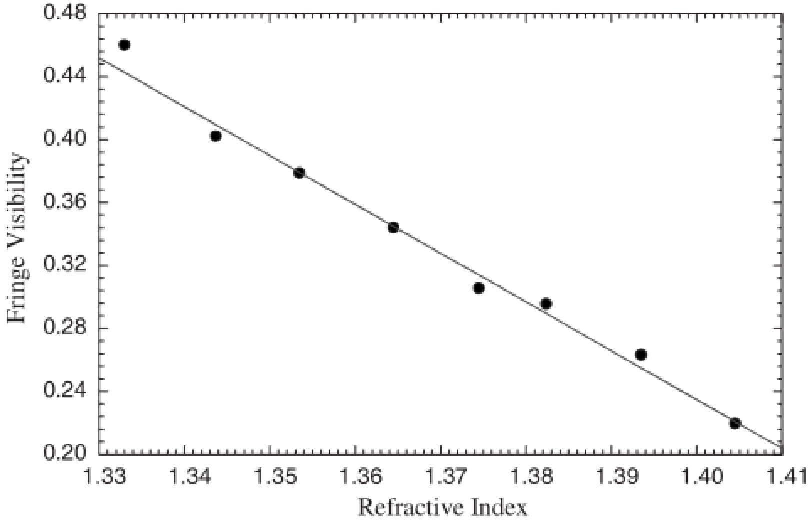
Fibre Bragg Grating

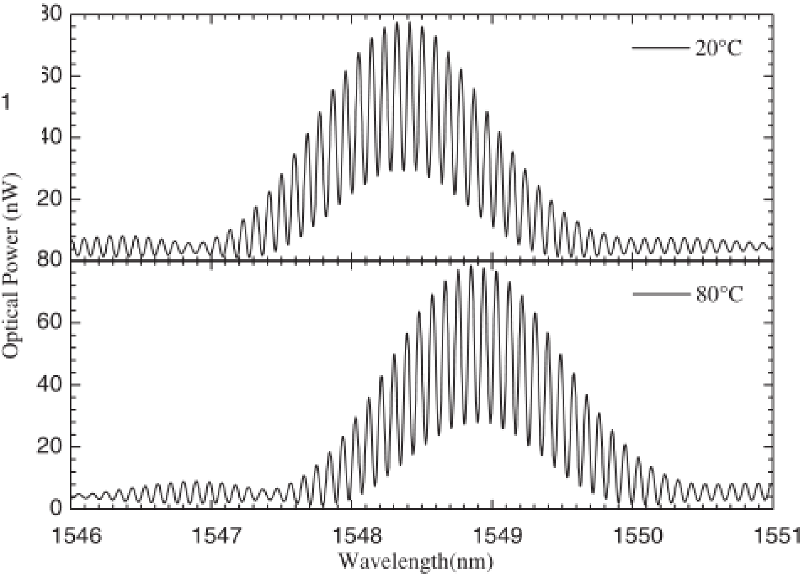
FP based on Fibre Bragg Grating





FP based on Fibre Bragg Grating





FP based on Fibre Bragg Grating

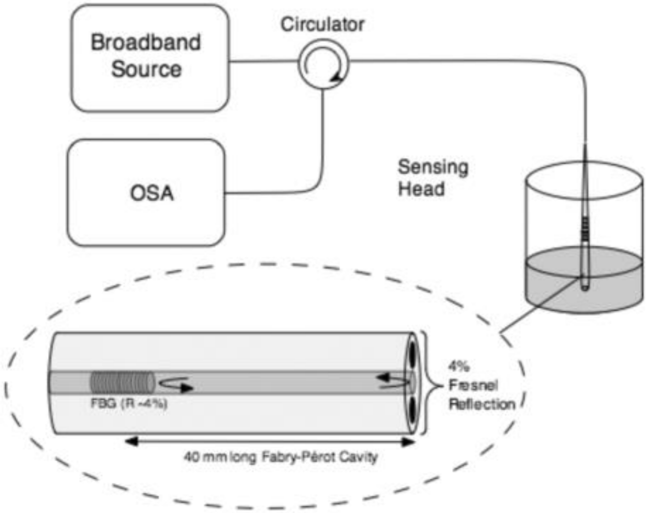
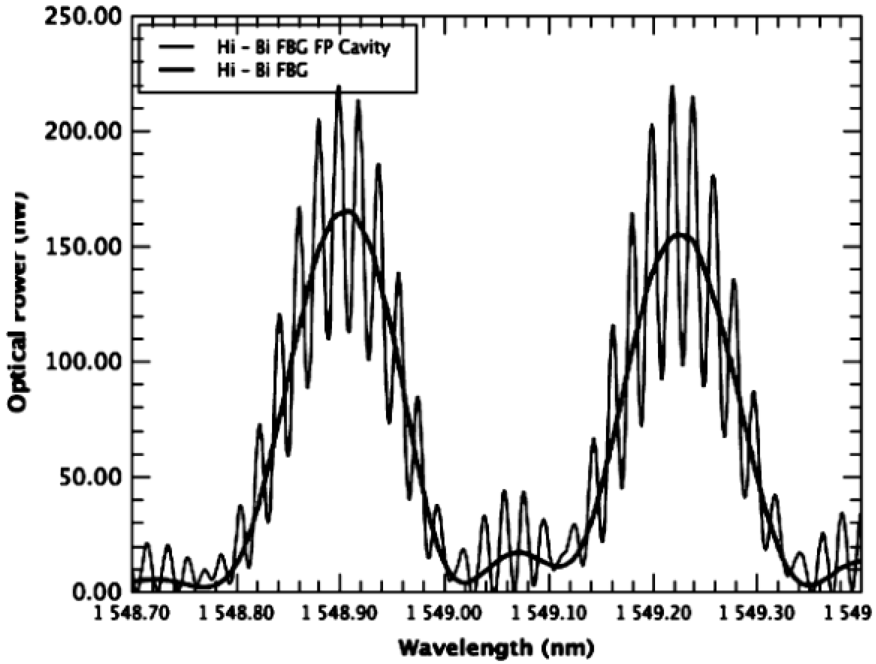


Fig. 1. Experimental setup.



FP based on Fibre Bragg Grating

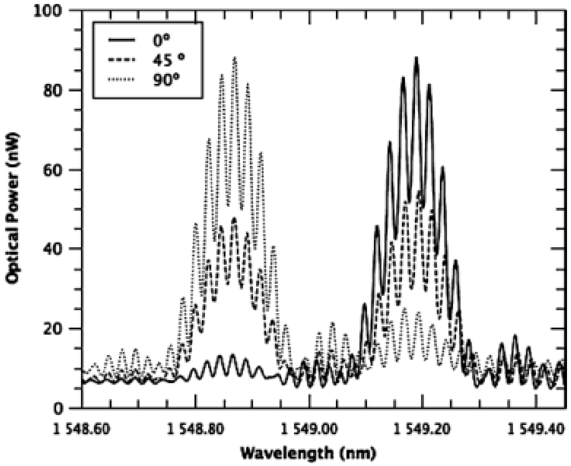


Fig. 3. Channeled spectra for different polarization angles.

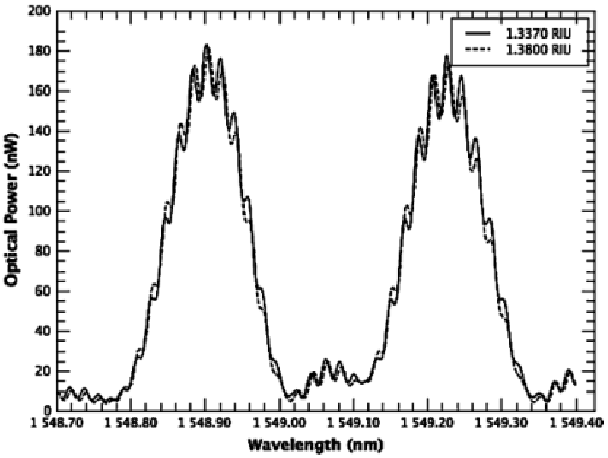


Fig. 5. Channeled spectra for two different RI solutions.

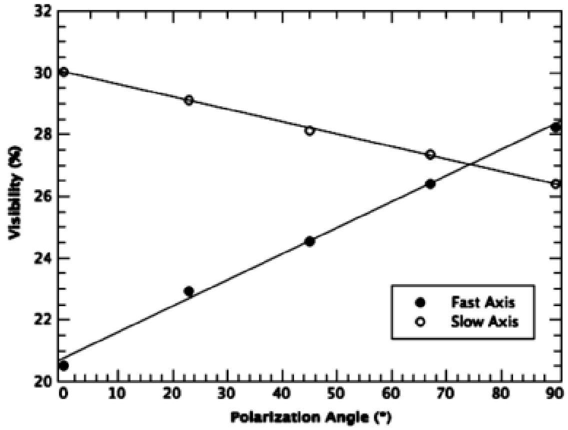


Fig. 4. Peaks visibility as a function of the polarization angles.

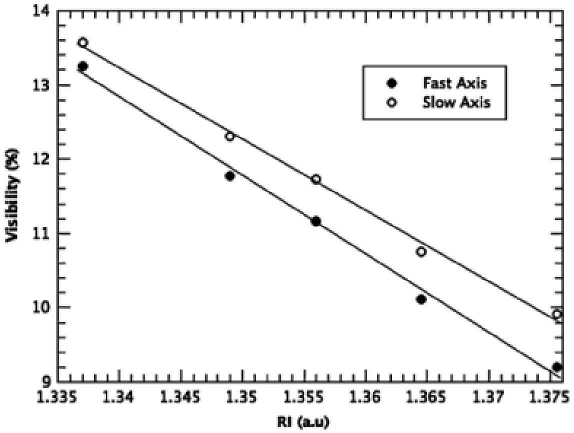
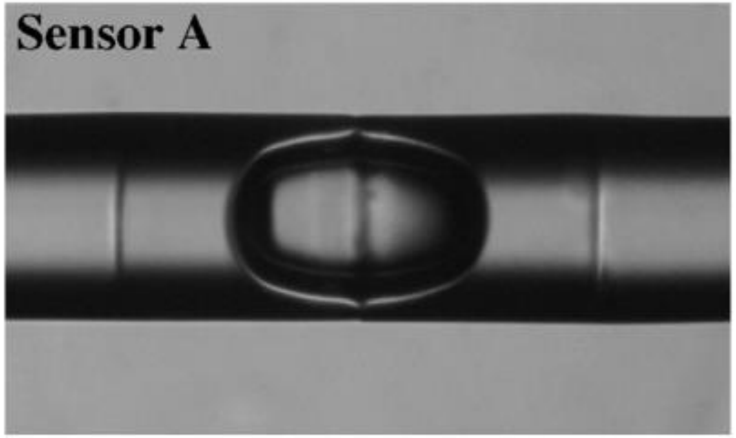


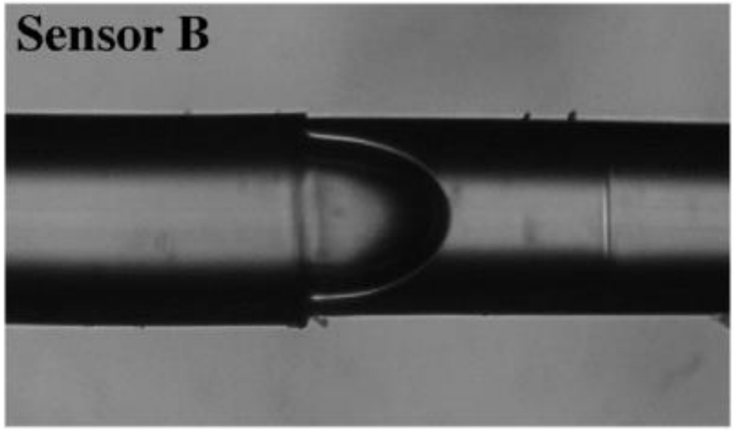
Fig. 6. Sensing head response (two peaks) for external refractive index changes.

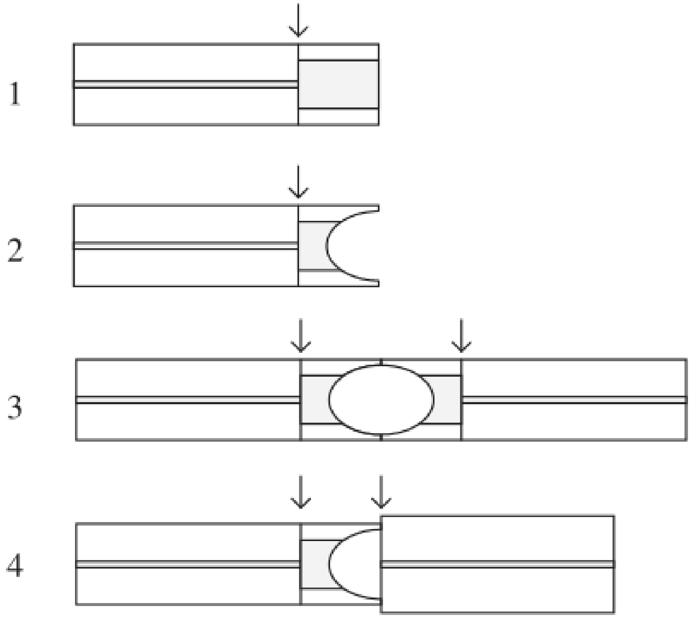
Fabry-Pérot cavities

Chemical etching

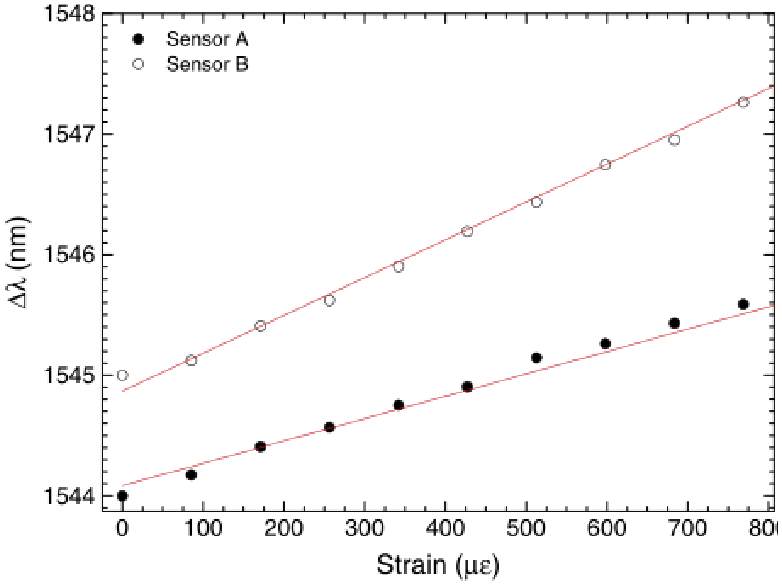
Fiber FP based on chemical etching

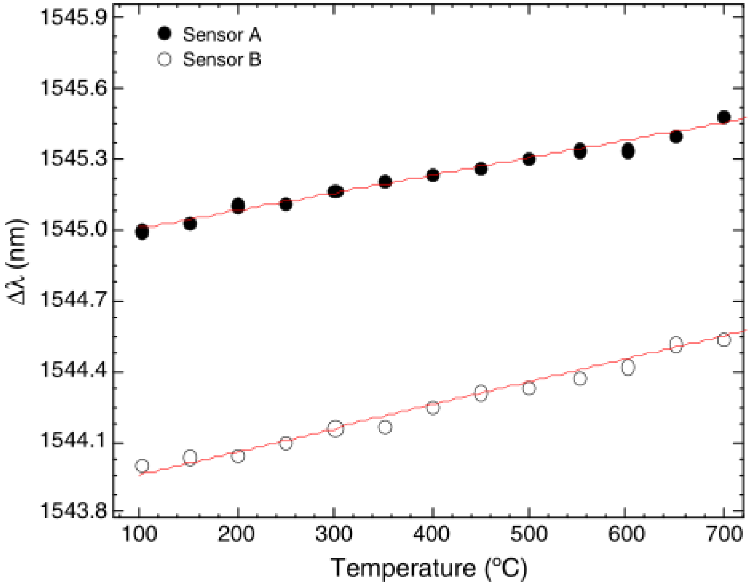




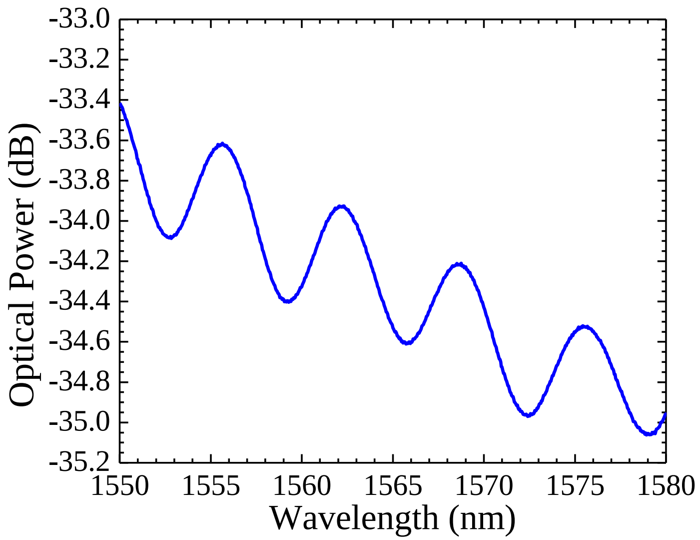


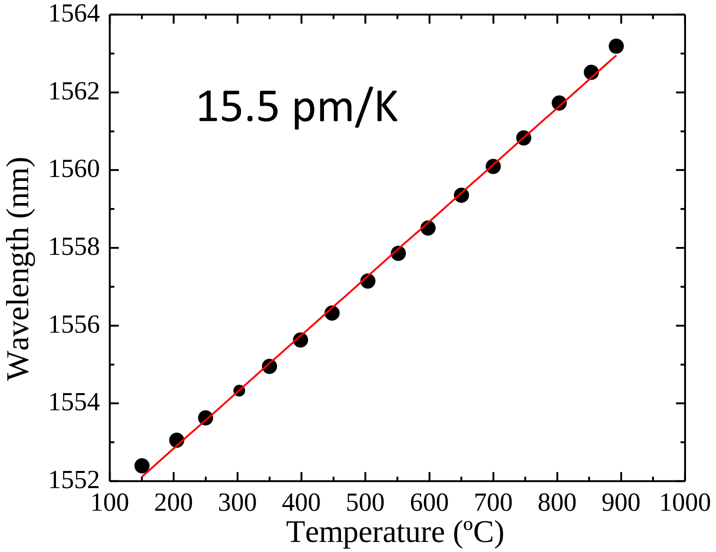
Fiber FP based on chemical etching





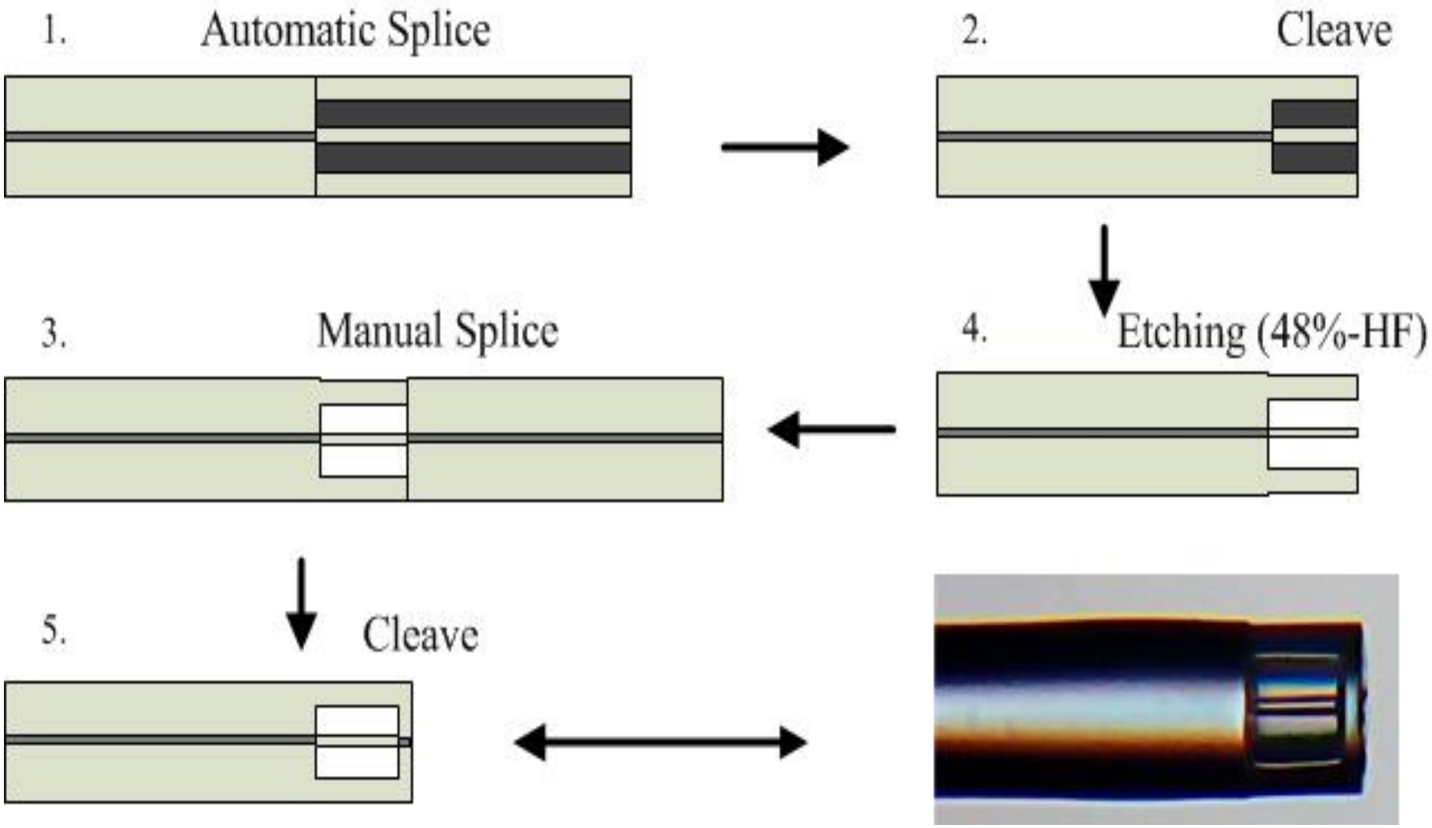
Fiber FP based on chemical etching



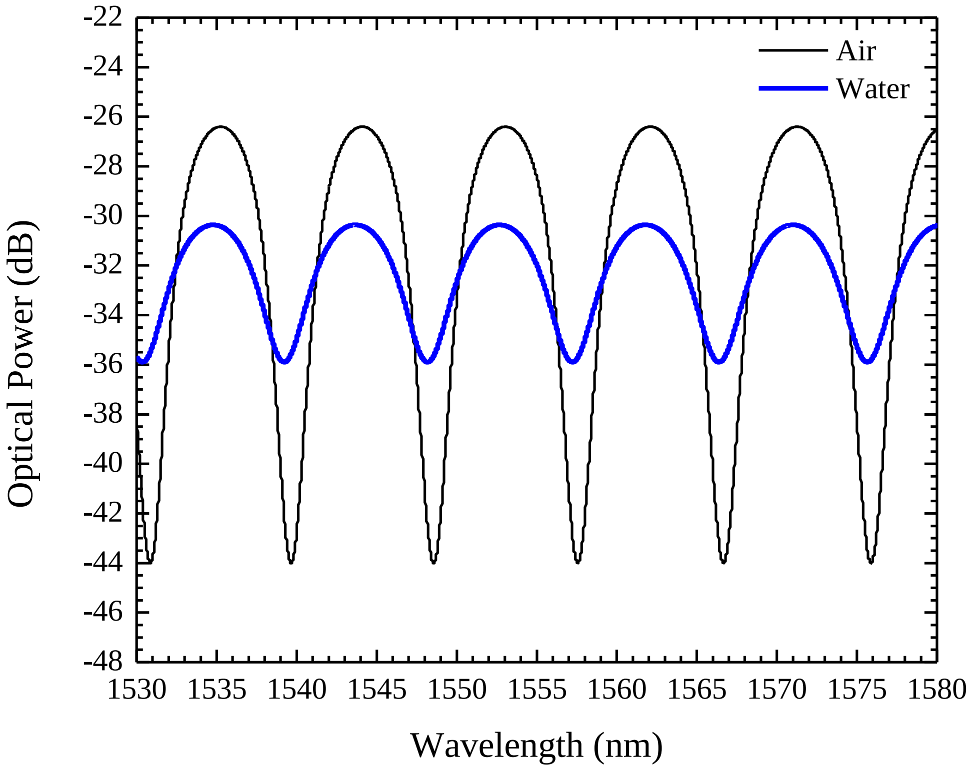


M. S. Ferreira, et al, Post-Processing of Fabry-Pérot Microcavity Tip Sensor, *IEEE Photon. Tech. Lett.*, 25 (16), 1593-1596, August 2013.

Fiber FP based on chemical etching



Fiber FP based on chemical etching



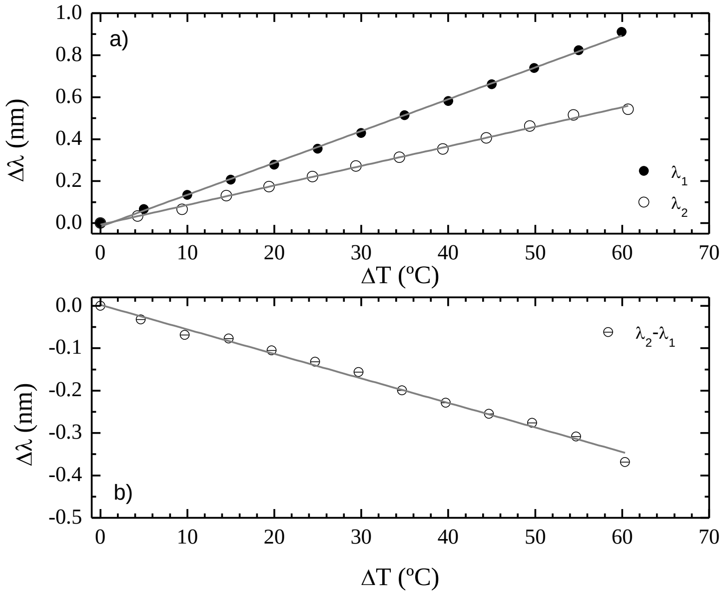
Long diaphragm

- The visibility is changed

Short diaphragm

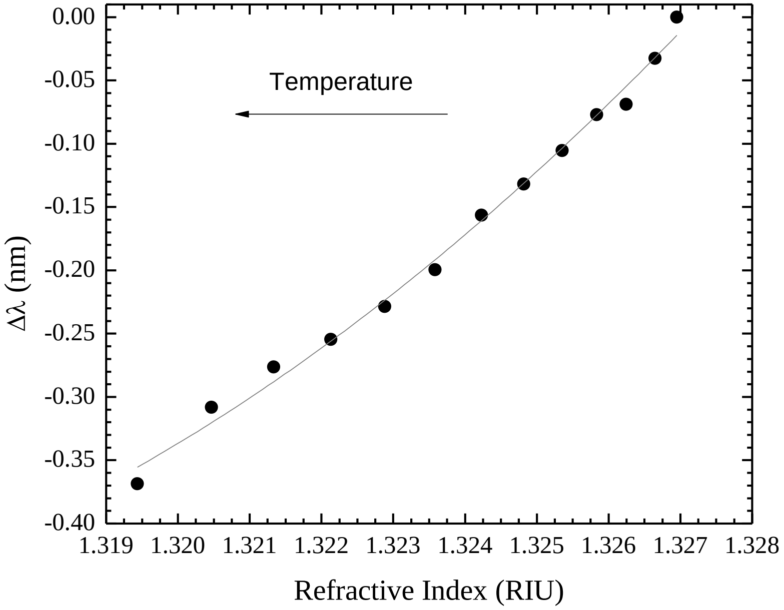
- The visibility and the wavelength is changed

Fiber FP based on chemical etching



The sensitivity is of **~14 pm/k** in the air. The sensing head was also immerged in water in the same temperature range and a wavelength shift was observed as the temperature changed. In this case, the sensitivity is of **~9 pm/k.**

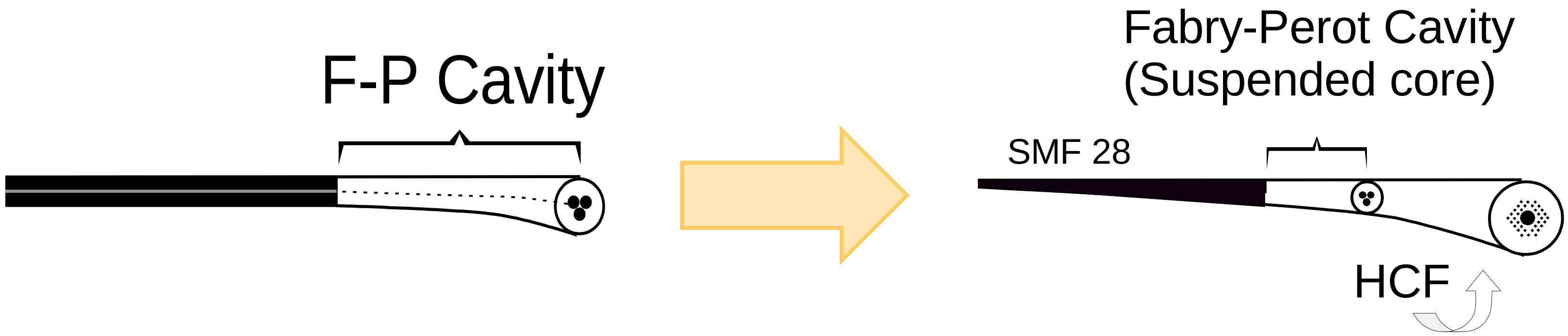
A sensitivity of **38.70 nm/RIU** was obtained for the former, whilst a sensitivity of **54.68 nm/RIU** was obtained for the last region.

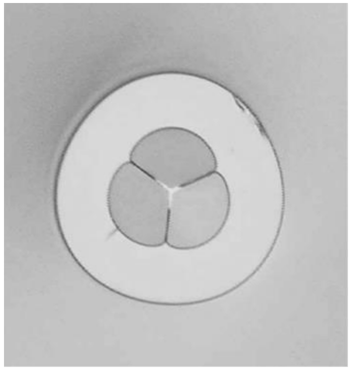


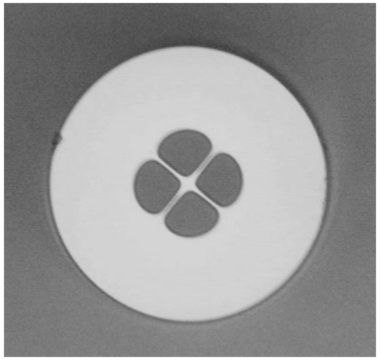
Fabry-Pérot cavities

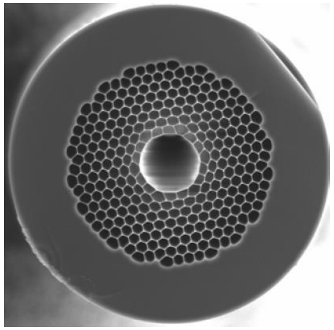
Microstructured Fibre

Suspended core fibre

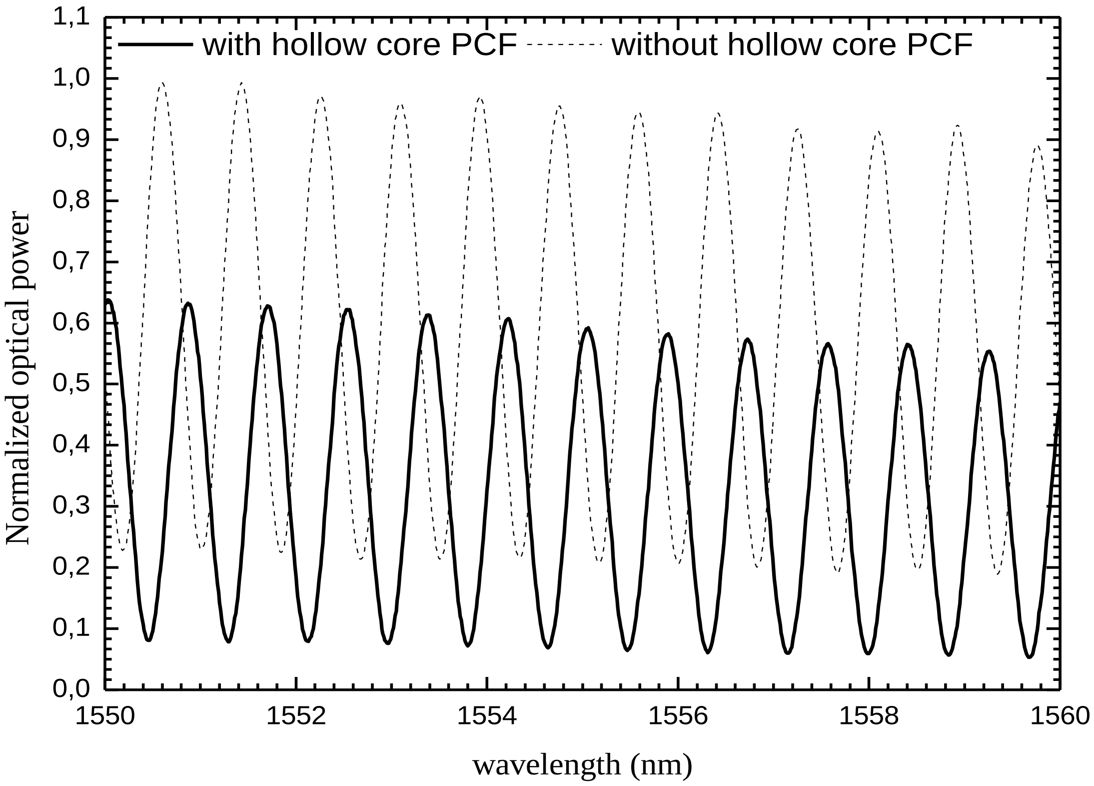








Suspended core fibre



Suspended core fibre

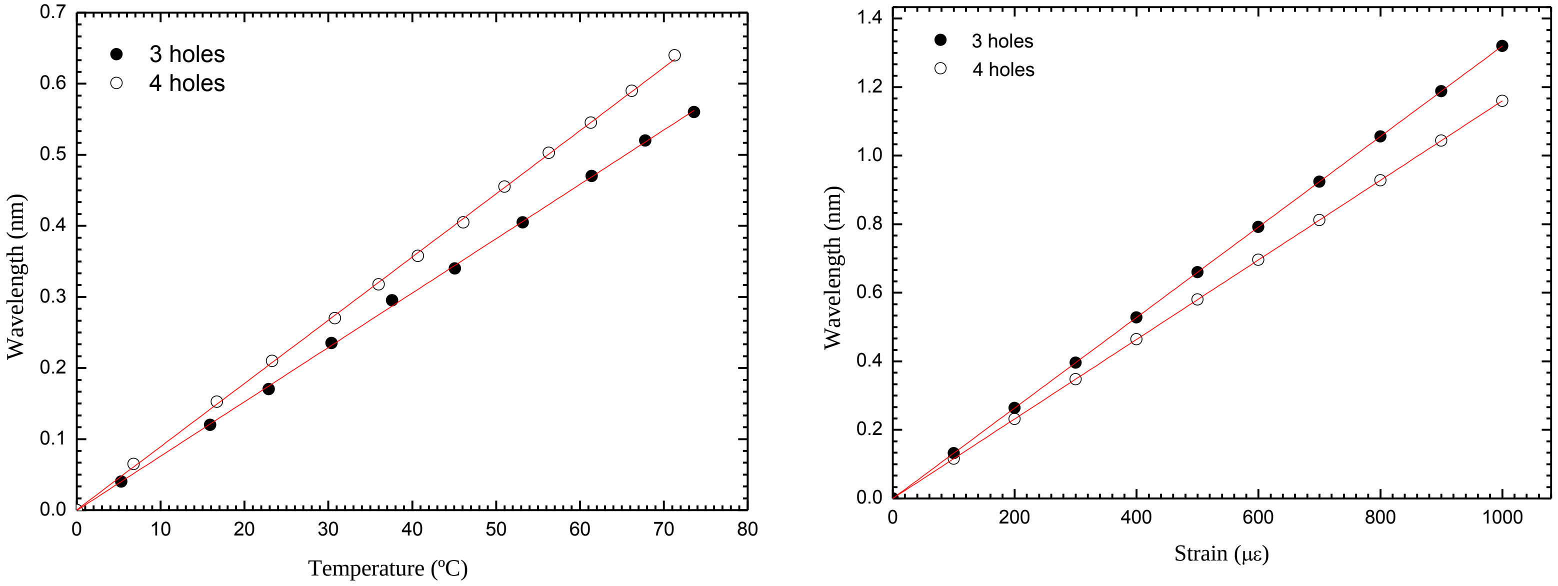
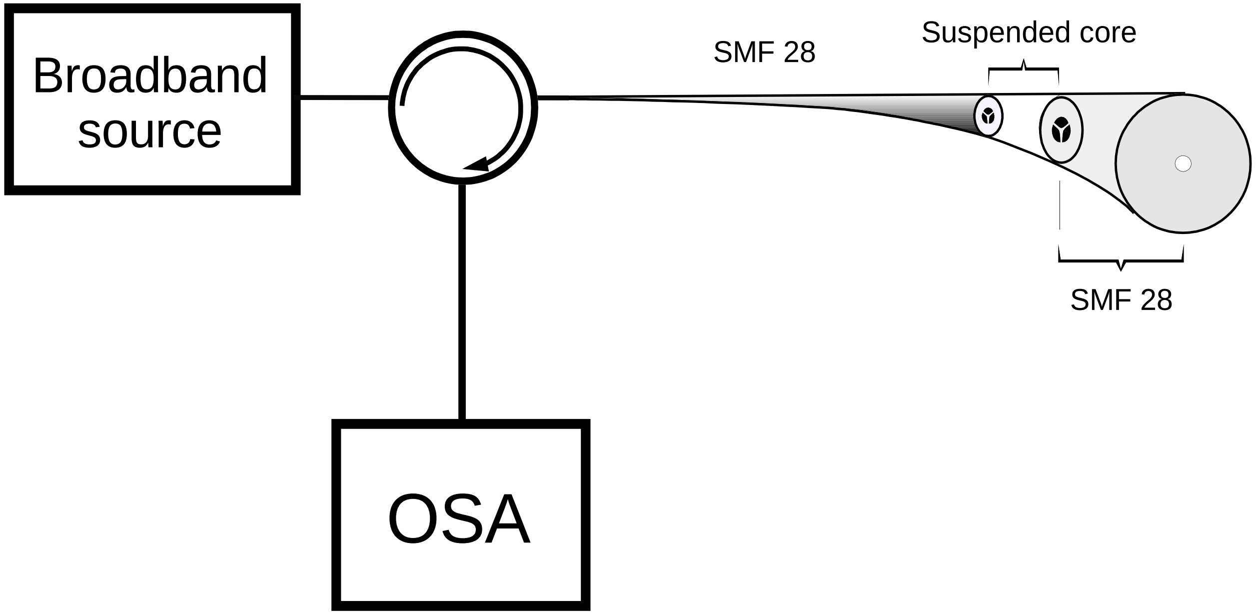


TABLE I

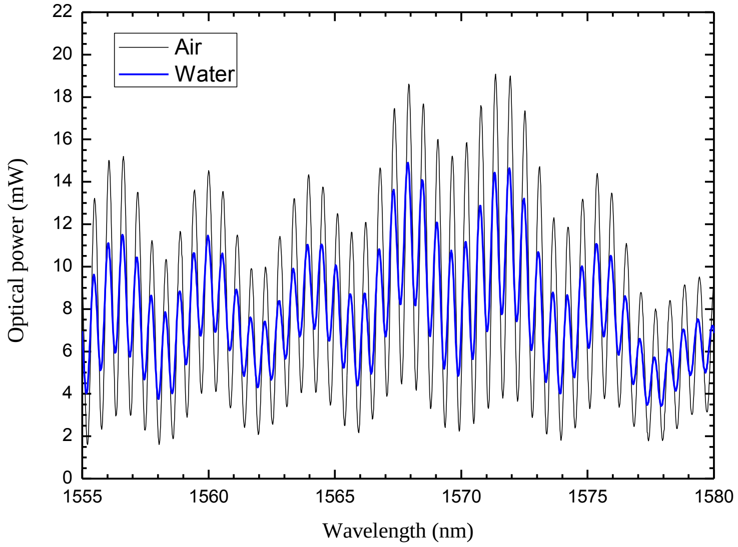
STRAIN AND TEMPERATURE COEFFICIENT SENSITIVITY

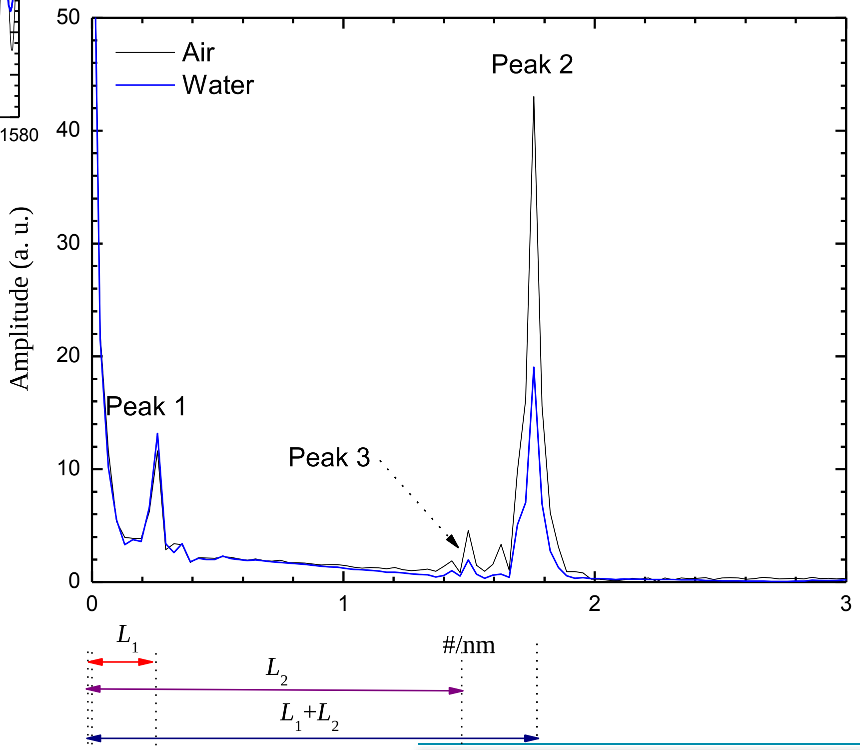
Fabry-Perot	Strain sensitivity (pm/με)	Temperature sensitivity (pm/K)
Three holes	1.32	7.65
Four holes	1.16	8.89

Suspended core fibre

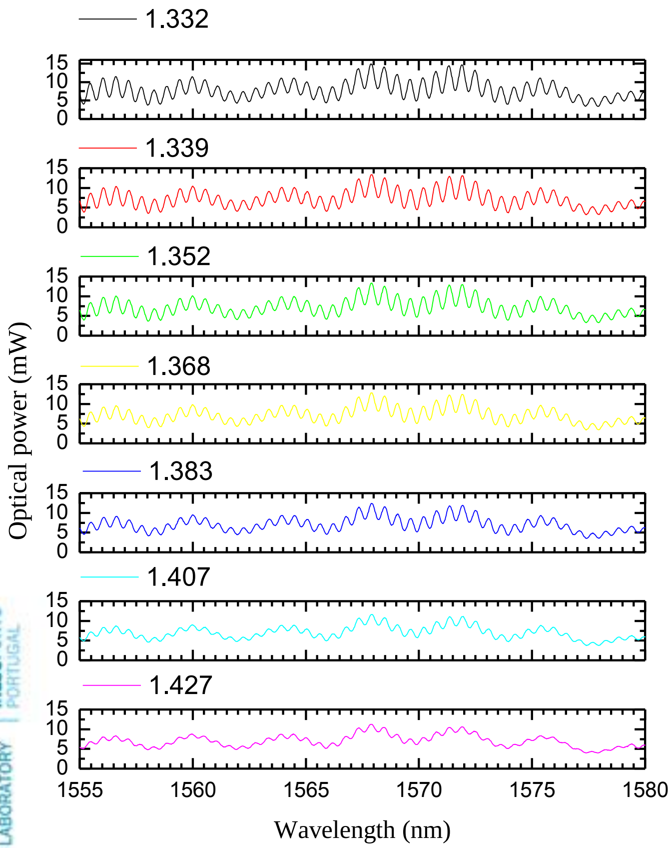


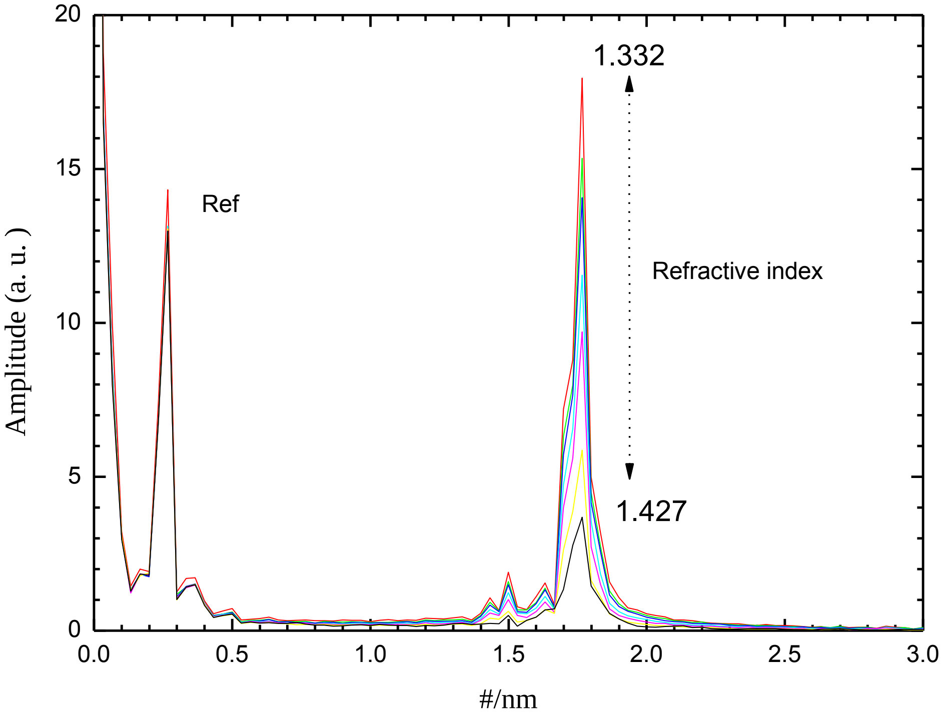
Suspended core fibre



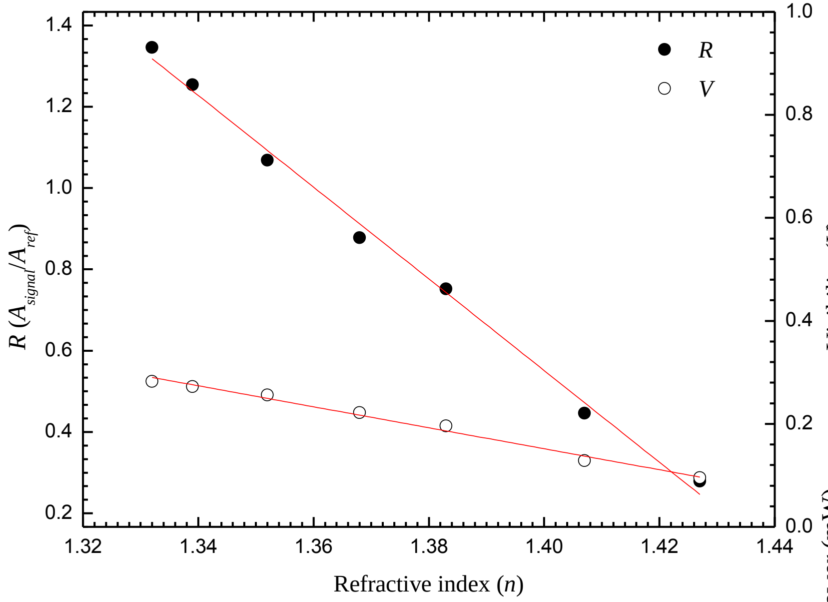


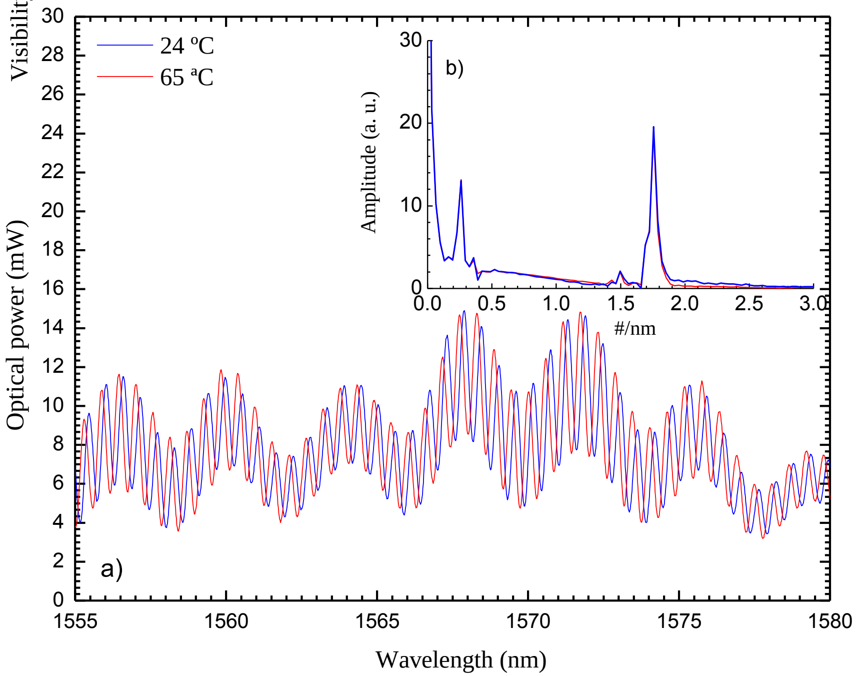
Suspended core fibre





Suspended core fibre





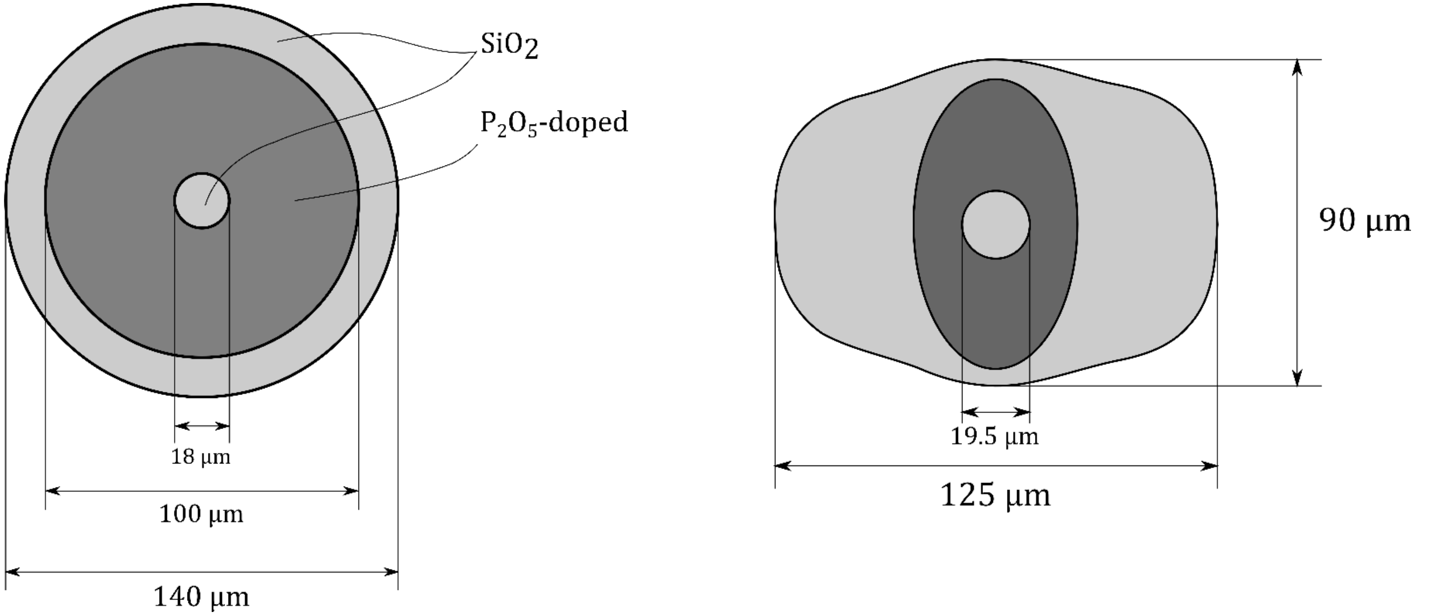
FFT -11.27±0.34 /RI
with a resolution of 2×10⁻⁵
Visibility - 2.03±0.09 /RI
with a resolution of 7.2×10⁻⁵

Fabry-Pérot cavities

Focused Ion Beam

Structure Forming Fibers (SFF)

- P_2O_5-doped fibers;
- Much higher etching rate than pure silica;

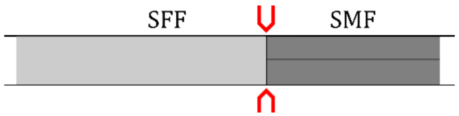


R. M. André, et al, Focused ion beam post-processing of optical fiber Fabry-Perot cavities for sensing applications, *Optics Express*, 22 (11), 13102-13108, June 2014

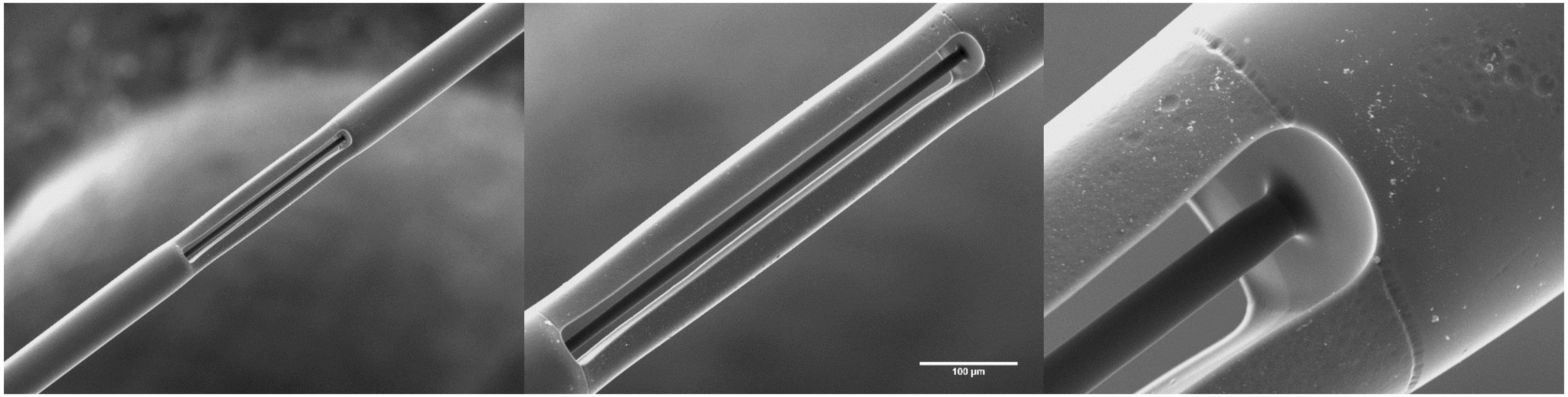
HF Etching

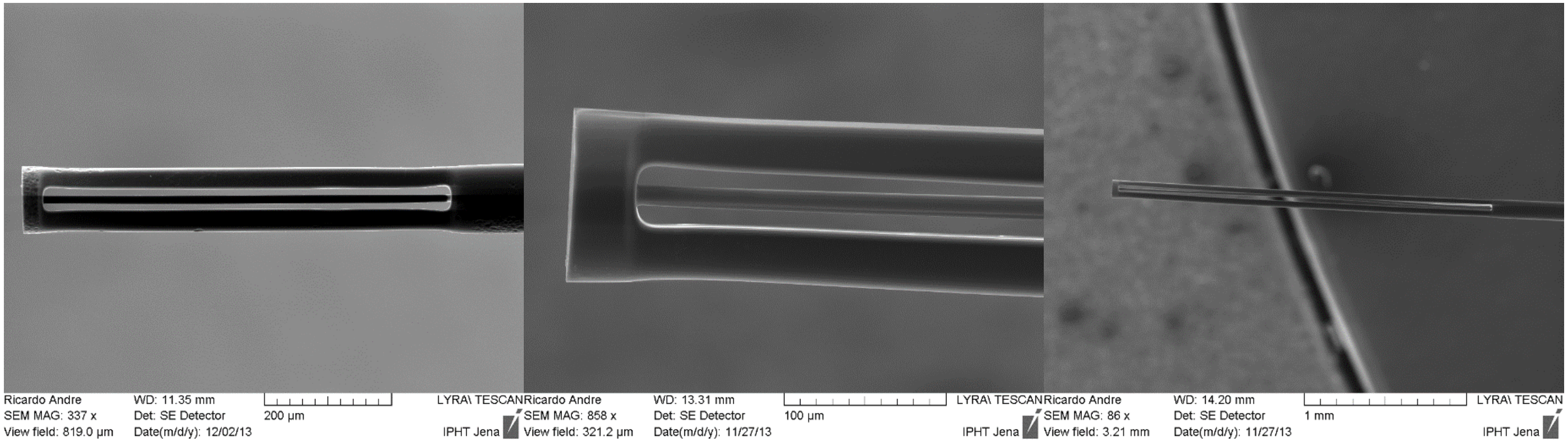
a) SMF-SFF fusion-splicing;
b) Cleaving to desired SFF length;
c) cMMF-SFF fusion-splicing;
d) Cleaving cMMF (30-40 µm);
e) Etching;

(a)



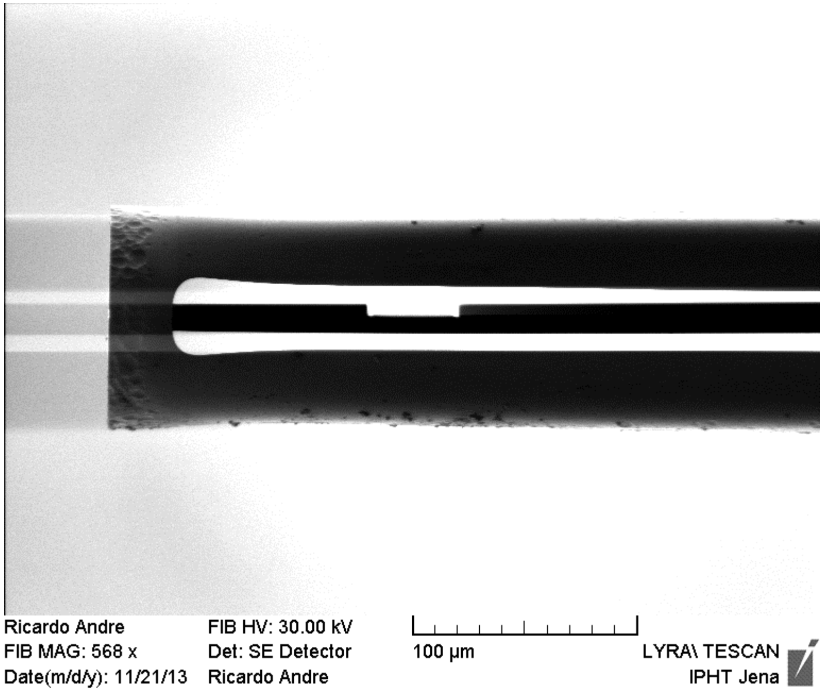
Chemically Etched Devices

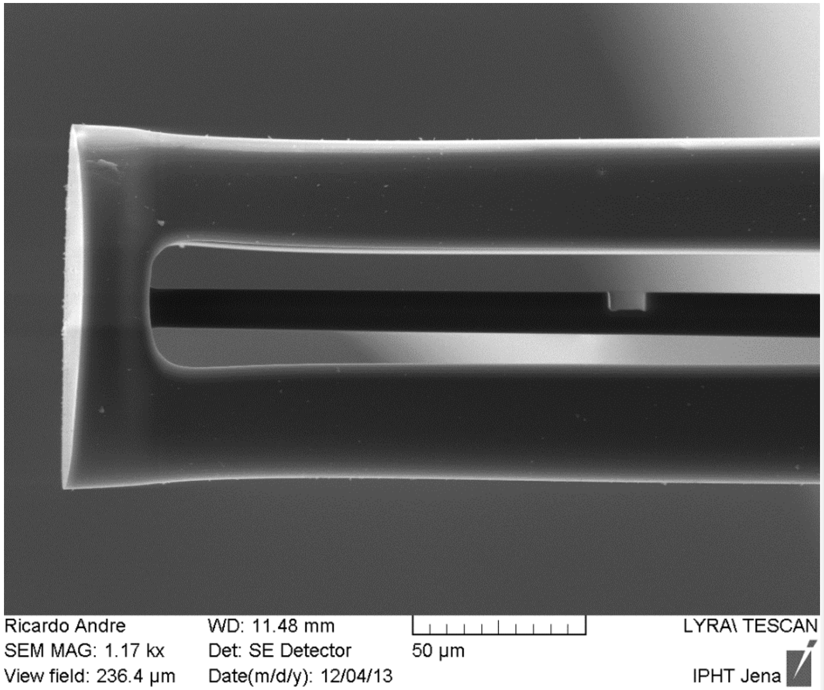




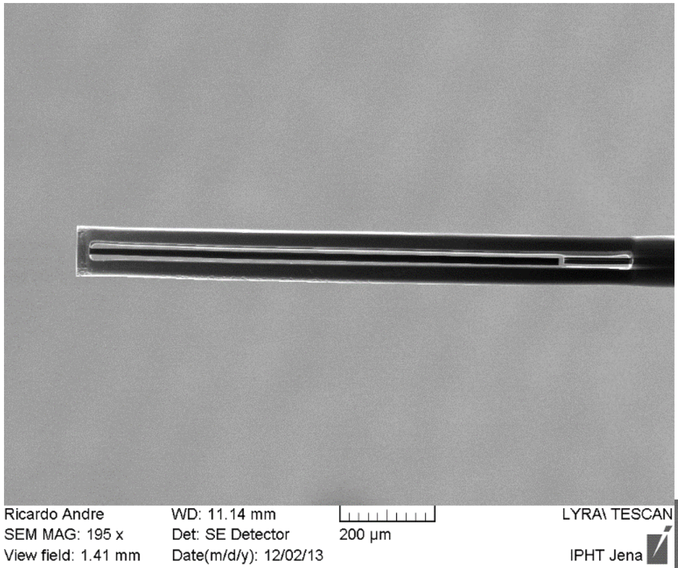
FIB – Indented Fabry-Pérot

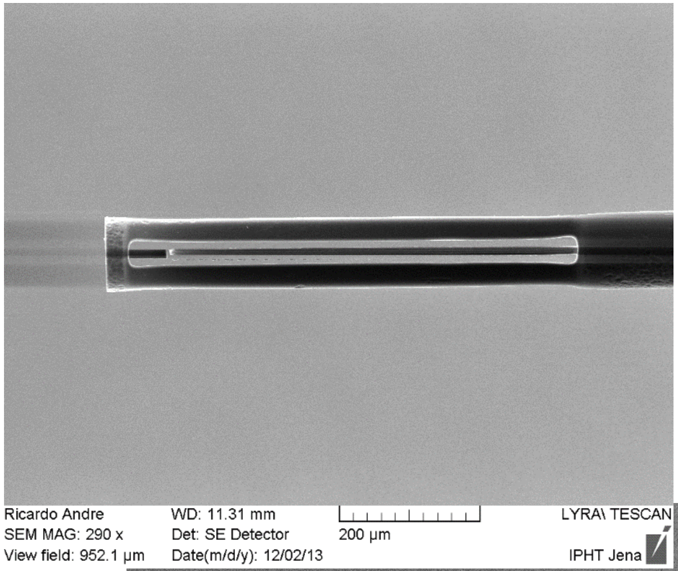
- Fabry-Pérot Cavities with a length of 170 µm;
- Different indentation lengths;

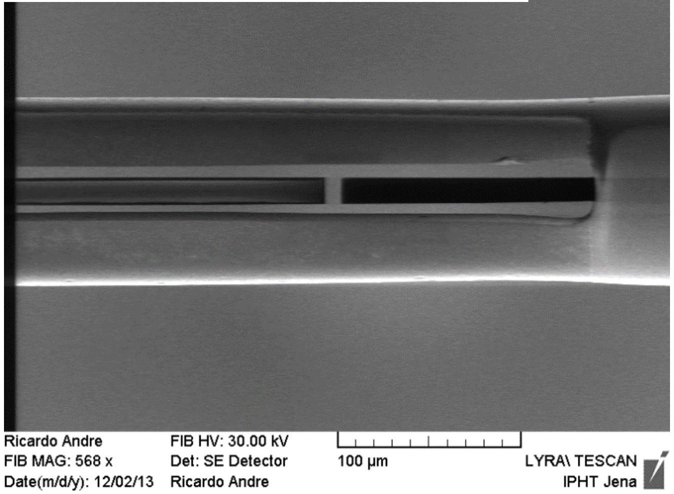


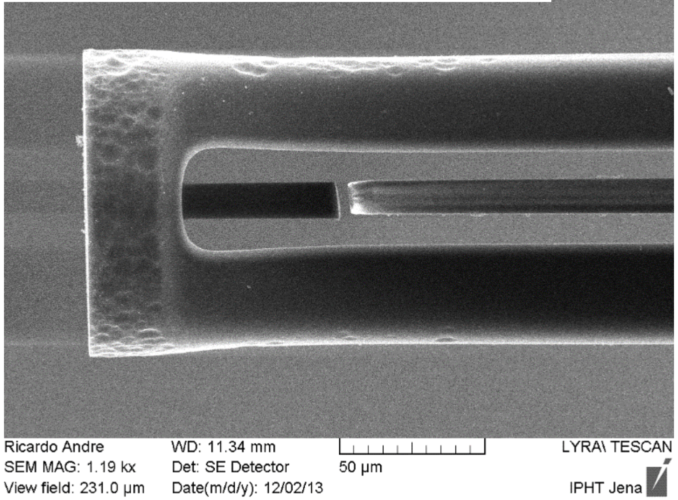


FIB – Fabry-Pérot Cantilever



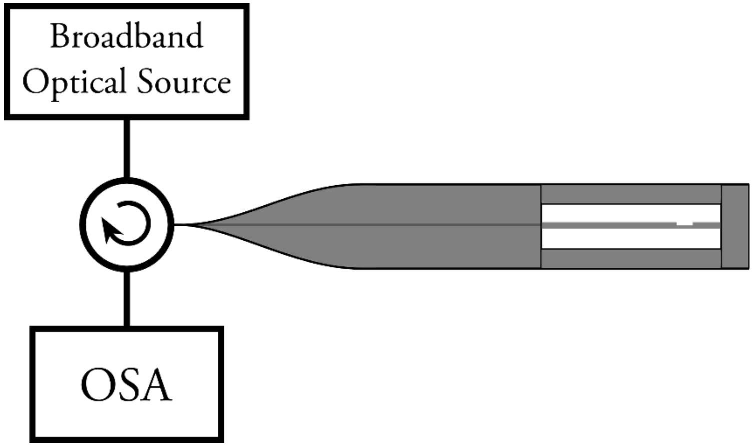






Optical Spectra

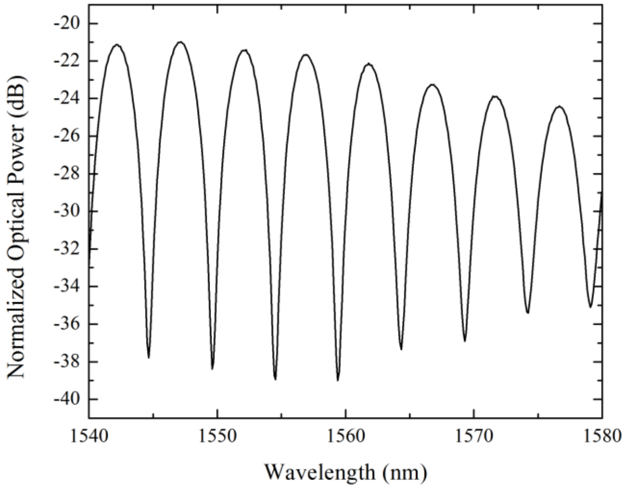
- Simple reflection setup;
- Different length cavities;



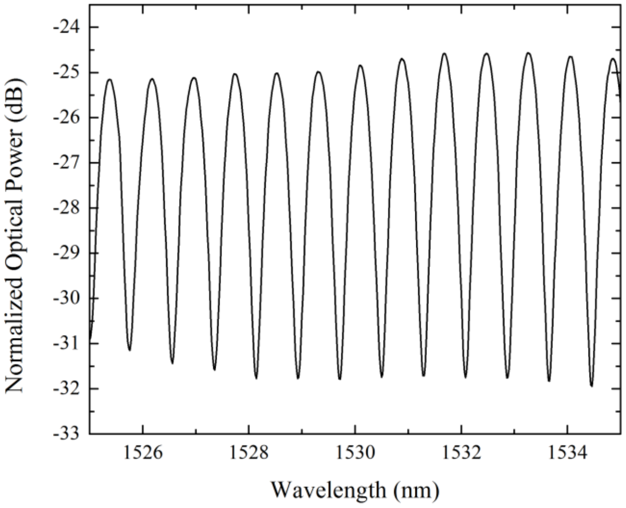
Broadband Optical Source

OSA

Indented Fabry-Pérot



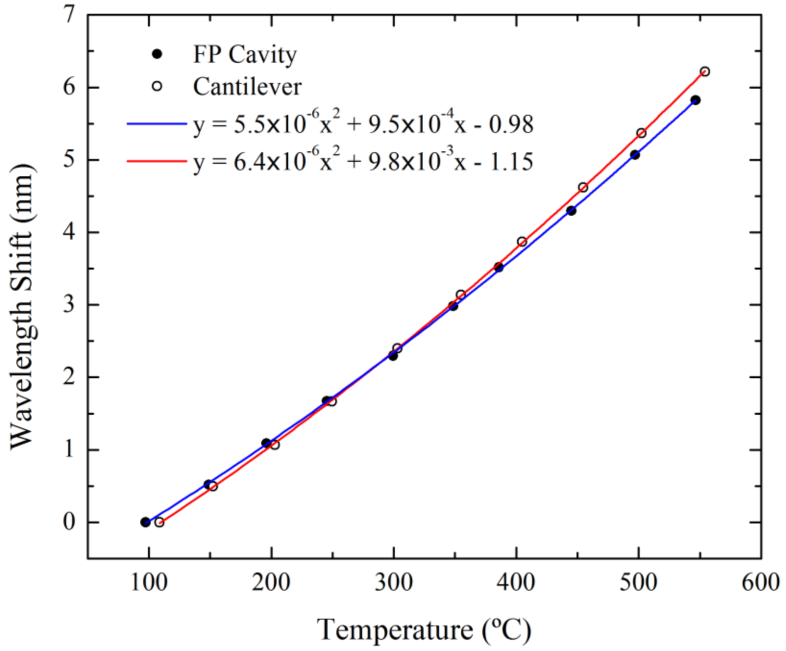
Cantilever Fabry-Pérot



Temperature Characterization

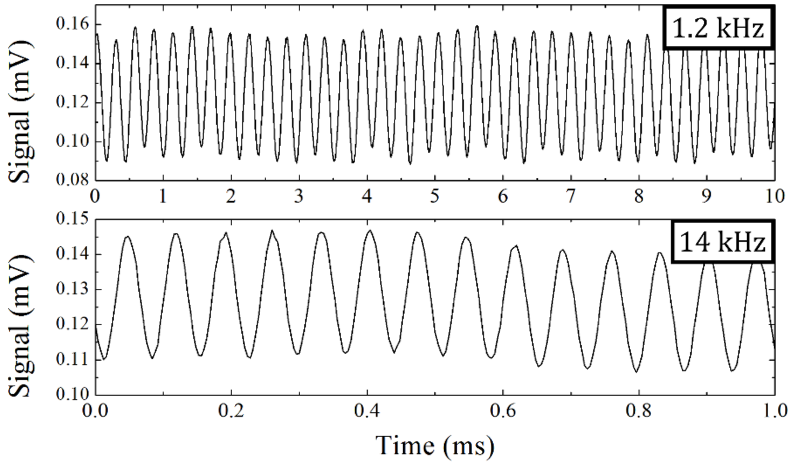
- Similar quadratic temperature responses;

- Indented Fabry-Pérot:
  - 100-300°C: 11.5 pm/K
  - 300-550°C: 14.2 pm/K
- Fabry-Pérot Cantilever:
  - 100-300°C: 12.3 pm/K
  - 300-550°C: 15.5 pm/K

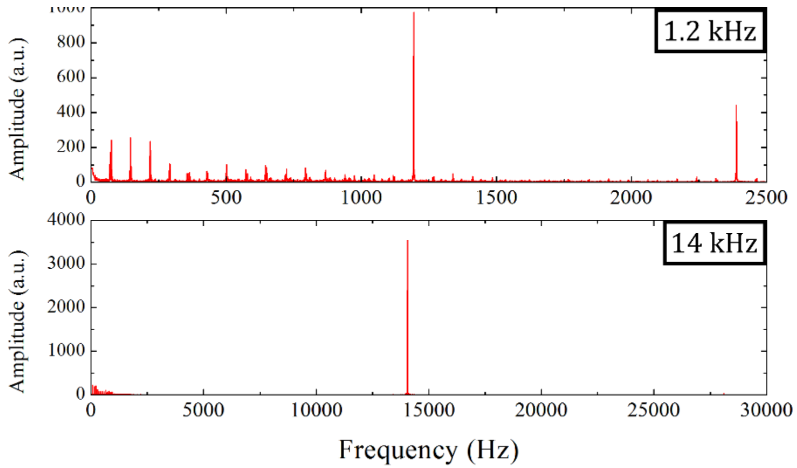


Vibration Results

- Acoustic vibrating system;
- Tunable laser;
- Photodiode.



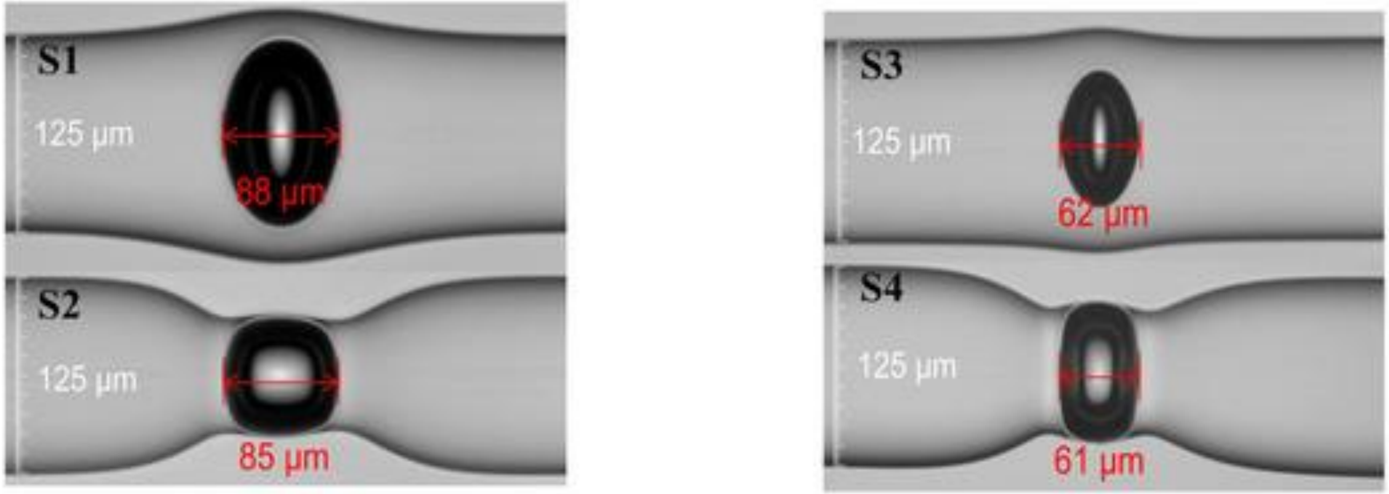
Time Domain Signals



Fast Fourier Transforms

Concluding remarks

Today, FP cavities in microstructured fibre present new challenges in optical fibre sensors namely in gas or liquids measurements and it will be expected its use in applications for medical solutions.



(a) Microscope image (b) Microscope image

Shen Liu, et al, High-sensitivity strain sensor based on in-fiber rectangular air bubble, Nature vol. 5, no. 7624, 2015. doi:10.1038/srep07624.

Acknowledgments

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