



New Advances in Fabry-Perot Cavities for Sensing Applications

Orlando Frazão

ofrazao@fc.up.pt

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



First publication in 1979

iber optic hydrophone: improved strain configuration nd environmental noise protection

> It is shown that the pressure sensitivity of a fiber-optic hydrophone is atrongly dependent on the fiber's it is snown tost the pressure sensitivity of a tiber-optic hydrophone is atrongly dependent on the (bler's strain configuration. Longitudinal strain is found to be much more effective than uniform strain, and consestrain consugurations. Longituminal strain is found to be much more effective than uniform strain, and conser-quently modifications to the sensor's design are proposed. Environmental noise sources such as occan mo-tion and exclaminal divergences the divergence of the divergence of the sense of the sen questly monthestness to the sensor's using are proposel. Environmental noise sources such as occars mo-tion and mechanical vibrations are then discussed, and a new double-cavity configuration, which is unaffect as her here researchesters in memory of the structure double-cavity method is in the structure method in the structure method is in the structure method in the structure method is in the structure method in the structure method is in the structure method in the structure method is in the structure method is in the structure method in the structure method is in the structure method in the structure method in the structure method is in the structure method in the structure method is in the structure method in the structure method is in the structure method in the structure method is in the structure method in the structure method in the structure method is in the structure method in the structure method is in the structure method is in the structure method in the struct tion and mechanical vortations are tone uncaster, and a new outlot-cavity contiguration, which is unatter (-index how be perturbations, in presented. A tunable-cavity detection method is finally proposed, and it is detected as the method of the presented of the detected of the method is control to the present of the second of the secon ed by those perturbations, in presented. A tunable-cavity detection method is rinally proposed, and it is shown how this method can overcome problems related to drift of the point of operation, laser intensity fluc-luctions and evolves of the high decourse reason. tuations, and nonlinearity for high dynamic ranges.

Fiber-optic hydrophones have recently been proosed1-7 as a novel approach to underwater acoustic The configuration considered most fre--b consists of two laser excited monomode fibers w the two arms of an interferometer, with one ensing. the sensing element and the uently perposition of the

lox 1012, Darter

Received 26 March 1979. 0003-6935/79/172933-05\$00.50/0. © 1979 Optical Society of America.

G. Cielo

and alignment deulation reproducing sensed by the imy sensitive to enviaximum phase shift iations has to satisfy and a signal dynamic th variations as small underwater applicato be overshadowed tical elements relative

as avoiding most of the where the interfering the same multimode of ever, these approaches as excessive optical co-en sensitivity and diffi-e operating point (of the ifference variations) in a

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 9.0 These perturbations introduce random phase differences between the interfering beams, unless the light beams are transmitted through the same monought usams are transmitted through the same mono-mode fiber. This can be done by including two reflec-tors 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

fortunately, this simple scheme is faced with problems of source coherence and drift of the operating point, as ill be explained ir more detail later. In this paper i is first shown that the sensitivity of a fiber-optic bydrophone is strongly dependent on the a ther-optic pyuropaone is strongly dependent of the strain configuration. It is found that longitudinal compression produces much higher sensitivity than uniform 3-D compression. Consequently, some hydructiona de L'ompression. Consequentity, some ny-dructione designs leading to longitudinal compression and enhanced sensitivity are proposed. In Sec. III it is

shown how the coherence requirements of a doublereflector 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.

A number of investigations have been reported con-A number or investigations have been reported optical cerning the phase-modulation induced in the optical н. beam transmitted by an optical fiber subject to 1 September 1979 / Vol. 18, No. 17 / APPLED OPTICS 2933

Fiber optic hydrophone: improved strain configuration and environmental noise protection



DORDWATED BY ESCPORTO

LABORATORY

INESCT

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.





4

Chemical **Etching**

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

All-fiber high-sensitivity pressure sensor with SiO₂ diaphragm

Denis Donlagic and Edvard Cibula

Faculty of Electrical Engineering and Computer Science, University of Maribor, Smetanova 17, 2000 Maribor, Slovenia

Received March 9, 2005

The design and fabrication of a miniature fiber Fabry-Perot pressure sensor with a diameter of 125 μ m are presented. The essential element in the process is a thin SiO₂ 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. © 2005 Optical Society of America

OCIS codes: 060.2370, 120.2230, 120.3180, 120.3890.

PORTUGAL PORTUGAL

LOGY & SCIENCE ATE LABORATORY

INESCT

whundred micrometers. The orted designs¹⁻⁵ that allow for ame size as the fiber diamet based entirely on SiO2 proved temperature and otherwise en However, small sensor dimens modulus of elasticity require diaphragm to achieve practice its the applicability of current medical and other low-pressu Limited sensitivity also increa cost of optical signal proce higher-pressure ranges. In this Letter, we present SiO₂ pressure sensor fabrica cal fiber. The proposed man lows for precise on-line con ness that can provide ap magnitude higher pressur ously peported for all-SiO₂ line diaphragm thickness c eadily repeatable manufa be used to fine tune the se

sure range. The sensor construction sists of a standard single cavity, and a SiO2 diaph the fiber-cavity interface Perot interferometer (F

All-fiber high-sensitivity pressure sensor with SiO₂ diaphragm Denis Donlagic and Edvard Cibula Faculty of Electrical Engineering and Computer Science, University of Maribar, Smetanova 17, 2000 Maribar, Slavenia responses numbers results in some time the sensor with a diameter of 125 µm arethe donign and fabrication of a miniature fiber Vahry-Peret greature sensor with a diameter of 125 µm aresensored. The example almost is the source is a thin SOC disables are that is form which at the bollowThe design and fabrication of a miniature ther Fabry–Peret pressure sensor with a manneter of 120 µm are presented. The essential element in the process is a thin SiO₁ displaying that is fusion spliced at the holice presented. The essential element in the precess is a thin 5004 dispirage that is unten spirced as the nonzer end of an optical fiber. Good repratability and high sensitivity of the sensor are achieved by on-line tuning of the disphesion thickness during the sensor fabrication mesons. Variane sensor centerones were fabricated. end of an optical liker. Used repeatability and high senserivity of the sensor are achieved by un-nie unang of the displaring thickness during the sensor fabrication process. Various sensor prototypes were fabricated commutation encourse reasons of from 0 to 40 kBa in 0 to 1 MDa. The receivery adjusted enclution and of the displicages threatness 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 second of the second temporarising pressure ranges or true 0 to 40 kPa to 0 to 1 2015. The maximum actureed semicirry was 1.1 rol/40 kPn at 1550 nm, and a pressure resolution of 300 Pa was demonstrated in practice. The pressure protect duality and federication temporary offers a means of simple and low-rout discoundly pressure sense. 1.1 rad/40 kPa at 1550 nm, and a pressure resolution of 300 Pa was demanstrated in practice. The pre-rested design and fabrication technique effers a means of simple and low-cost disposable pressure sensor production. O 2000 Optical Society of America OCUS code: 060.2370, 120.2329, 120.3180, 120.3890.

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

2071

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 measure ments of pressure measurements to measurements of pressure in the cylinders of combustion

Various fabrication techniques for fiber-optic pressure sensors have been demonstrated recently. The engines. nsors typically utilize a sensor head that carries a aphragm in front of the optical fiber end surface. In ost cases the sensor head diameter is larger than the optical fiber diameter. Consequently, the typical ie optical fiber diameter. Consequently, the exceed a imensions of a fiber-optic pressure sensor exceed a

(a)

(c)

causes diaphragm deflection and therefore cavity length variation, which can be detected by an appr

priate interrogation technique. The formation of a FPI is accomplished by oblicing the standard 62.5 μ m multimode fiber (MMF) to a standard lead single-mode fiber (SMF). The MMF is cleaved $\sim 40 \ \mu$ m from the splice (EW, 2(a)). The lead SMF with an attached section of MMF is then etched is UF

The etching rate of the germanium-doped 62.5 μ m The opening rate of the germanian appendix of the fun-MMP core is approximately ten times higher than for pure silica,³ and this allows for selective removal of pure silica," and Drs 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 fiber of the fiber. This forms a cavity at the etching process of the structure of the structure of the struc-ent structure of the structure of the struc-

(b) _{SMF} scribing cavity SMF MMF blade connector ferrule (d) scribing SMF blade SMF FP cavity diaphragm polishing paper

Fig. 2. Fabrication procedure for the pressure sensor.

5

PCF

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

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

Y. J. Rao,^{1,*} T. Zhu,² X. C. Yang,² and D. W. Duan²

¹Kev Lab of Broadband Optical Fiber Transmission and Communication Networks Technologies (Education Ministry of China), University of Electronic Science & Technology of China, Chengdu, Sichuan 610054, China, and Key Laboratory of Optoelectronic Technology and Systems (Education Ministry of China), Chongqing University,

Chongqing 400044, China ²Key Laboratory of Optoelectronic Technology and Systems (Education Ministry of China), Chongqing University, Chongqing 400044, China

*Corresponding author: yjrao@cqu.edu.cn

Received May 31, 2007; revised July 26, 2007; accepted August 5, 2007; posted August 6, 2007 (Doc. ID 83604); published September 4, 2007

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 ±5µε are achieved. © 2007 Optical Society of America OCIS codes: 060.2370, 050.2230.

stric sensors have found nuitary, and civil applications in lave a number of outstanding ntional electrical sensors such magnetic interference, capabilwide variety of measurands, high accuracy, small size, etc. atrinsic Fabry-Perot interferoline etalon sensors have been cialized and widely used for ous parameters, such as strain, acceleration, refractive index, 2-6]. However, it is hard to realptic sensor network, which can umber of sensors, based on these due to their poor multiplexing ca-EFPI sensor structure called the is the cavity length to be enlarged meters; this means that more than sensors can be multiplexed simulatial-frequency division multiplex-However, in the Fizeau configurain the cavity length will make the e., signal-to-noise ratio (SNR) of the gnal, worse. In addition, further inrity length becomes impossible with in of the SNR of the interferometric atter, a novel fiber-optic in-line etalon demonstrated, which is constructed tion of hollow-core photonic crystal fibetween two standard single-mode SMF-28) to form a Pabry-Perot interan in-line HCPOF etalon can greatly FDM capability due to the substantial atic diagram of the in-line etalon in Fig. 1, is fabricated by splic-

0146-9592/07/182662-3/\$15.00

show

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

2662

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

photonic crystal fiber

¹Key Lab of Broadband Optical Fiber Transmission and Communication Networks Technologies (Education Ministry of Open-1 December of Photoenic Concerning Technologies (Education Activity) Y. J. Rao,^{1,4} T. Zhu,² X. C. Yang,² and D. W. Duan² Sty Lab of Broadflund Optical Fiber Transmission and Cammunication Networks Technologies (Education Minish of China). University of Electronic Science & Technology of China. Chengdu, Sichum e10054, China, and Key Indocessories of Outstandorstance Technologies and Contemport (Education Ministers of China). Chematical Halomatica Indocessories of Outstandorstance Technologies and Contemport (Education Ministers of China). Chematical Halomatica Indocessories of Outstandorstance Technologies and Contemport (Education Ministers of China).

of Granos, University of Electronic Sciences & Technology of Granos, Gaengin, Stranger (2009), Gaine, and APJ Gaberoloty of Ophoelectronic Technology and Systems (Bducation Ministry of China), Chongqing University, Chonester Anno.4, China Chongging 400044, China ¹Key Laboratory of Optoelectronic Technology and Systems (Education Ministry of China), Chongqing University, Changeding, Laboratory China *Corresponding author: yjrao@cqu.edu.cn Beceived May 31, 2007; necked hdy 26, 2007; accepted August 5, 2007; pointed August 6, 2007 (Doc. ID 05004); published September 4, 2007 A novel fiber-optic in-line etalon formed by splicing a section of ballow-core photonic crystal fiber (HCPCP) in between two shorts enables there is measured and demonstrated. For the first time to see beneficity of the A novel inter-optic in-time etation terms is spacing a section of native-core photonic crystal ther HURVD's and between two single-mode fibers in prepared and demonstrated, for the first time to our knowledge. Such a HURVF-hurde solar sets or an another restored control content of the form a Folger. Durat interdemonstrate and human terveren teu sugge-more mers a proposes ana oemonstratea, tet tae mer teo ear sinovrege, oara a ICOCC*hand etalon arts as an excellent optical waveguide to form a Fabry-Perot interferenceter and hence New the consist barsh to be as here as research continuators with each stability or the transmission base of ILCENT-manual ensuits as an encourse operat waveguine to intrin a rany-reve intervenenter and near allows the cavity length to be as long as several centimeters with good visibility as the transmission loss of the technologies is much encoder when of a believe encode their this affairs around resential to constant a conannee the covery energia to be an imag as several continueurs with goin visionity as the transmission and in the HCCP is much smaller than that of a hollow core fiber, this offers great potential to generate a price which does a fiber order reteres states being several dominance distance endications which are a fiber order is done. the HCPCF is much smaller than that of a hollow care liber, this offers great potential to generate a pre-tical dense fiber-optic senses network with spatial frequency division-multiplexing. This nevel statute of a n-on-constraint for static measurement, and the sense invariant security above that a result static result of a n-on-

tical dense fiber-optic senser network with spatial frequency division-multiplexing. This nevel etaton is dem-entrated for strain measurement, and the experimental results show that a good visibility of 0.3 and a train accessry of better than ±5µe are achieved. © 2007 Optical Society of America OCUS cedes: 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 or a nor or mor chinae photonics: no 1000-027, the core diameter and the distance between the centers of the cladding holes of the HCPCF are ~10.9 and $-3.8 \ \mu m$, respectively. The fabrication of the galon is simple and straightforward; i.e., splice the reaved ends of the HCPCF to the cleaved ends of two ends of the HCPCF to the cleaved ends of two SMF-25 fibers with an electric-arc fusion splicer (Fi-tel: S176) as shown in Fig. 2. The etdon length can be cleaved down to the order of mic_ometers with inspection under a microscope. In addition, the etalon spection under a microscope. In Journal of even length could be extended up 166 several continueters because the transmission Joss (<0.1 dB/m) of the HCPCF is much lower than that of the hollow core fi-

ber configuration reported previously [2]. Figure 3(a) is the reflective spectrum of the HCPCF etalon, which is obtained by using a highaccuracy optical spectrum analyzer (OSA) (Micron occuracy option spectrum analyzer (OOA) cancelon Optics: Si728) with a wavelength resolution of 0.25 pm and a wavelength precision of 1 pm over a spectral rarge of 1520-1570 nm. It can be seen from Fig. (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





Fento

Second

beneficie in the energy of the

High-temperature strain gauges have important applications in many fields, such as experimental mechanics, aeronautics, and metallurgy. The electrical stain gauge is the most mature and widely used strain sensor. The uses of the electrical stain gauge in everyonment are greatly confined accorrent and device, such as

November 1, 2007 / Vol. 32, No. 21 / OPTICS LETTERS 3071

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

Z. L. Ran,^{1,3} Y. J. Rao,^{1,2,*} H. Y. Deng,¹ and X. Liao¹

¹Key Lab of Broadband Optical Fiber Transmission & Communication Networks Technology (Ministry of Education), University of Electronics Science & Technology of China, Chengdu 610054, China
²Key Lab of Opto-Electronic Technology & Systems, Chongqing University, Chongqing 400044, China
³ranzl@uestc.edu.cn
⁴Corresponding author: vira@@uestc.edu.cn

"Corresponding author: yjrao@uestc.edu.cn

Received May 31, 2007; revised September 14, 2007; accepted September 18, 2007; posted September 25, 2007 (Doc. ID 83491); published October 15, 2007

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.

an electrical device, such as gh temperature, nonlinear disility to electromagnetic interc strain sensors can overcome o their outstanding advantages rical transducers, such as elecnce immunity, ability to operate ts, and high resolution [2]. The ting and Fabry-Perot (F-P) inare two major and successfully optic strain sensors. However, grating sensor written by UV laot be used for high-temperature due to its poor long-term stabilnperature of >400°C [3], large etween strain and ter sensors are considered surement for their exce rature insensitivity [4conventional extrinsic tric sensor to serve in sensor. Many effort n all-fiber in-line highpe of sensor called an ed with the potential are environment, as egment of silica nolle

we single-mode fibers 7.8]. However, it is ve reductivity due to th analyfeuring process tion At each individual sensor axes the time consuming and labor intenthe total consuming and labor intenter contamination and damage. Fur-

61 containing 0146-9592/07/213071-3/\$15.00

thermore, the preset F–P cavity length is solely determined by the cleaved length of the hollow-corr fiber, which is very difficult to control, making back in the sole of the sole of the sole of a 157 nm la-

3071

November 1, 2007 / Vol. 32, No. 21 / OPTICS LETTERS

IDEG, which we report on the use of a 157 nm la-In this Letter, we report on the use of a 157 nm laser to fabricate an in-line etalon on a photomic crystal ther (PCF) directly to overcome the drawbacks mentioned above. This miniature in-line fallon is a mitrorectangular notch structure inside a PCF with a structure of the structure inside a PCF with a stand high-temperature applications. Such a PCF with and fiber-optic F-P sendors, such as direct formation without any assembly, good optical performance, high-temperature spenders, such as direct formattion without any assembly, good temperature inseehigh-temperature applications 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 a photomic and fiber sensors.

applications and hence merces. the field of optical fiber sensors. The field of optical fiber sensors was fabricated by a 157 nm The CCF etalon sensor was fabricated by a 157 nm host of selection of the sensor was calculased based on the principle of silica's strong intrinsic lased based on the principle of silica's strong was calcu-



7

Fig. 1. Calculated assurption the first-principle method. © 2007 Optical Society of America

COORDINATEDBY INESCPORTO PORTUGAL



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

Microfiber-probe-based ultrasmall interferometric sensor

Jun-long Kou, Jing Feng, Qian-jin Wang, Fei Xu,* and Yan-qing Lu College of Engineering and Applied Sciences and National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China *Corresponding author: feixu@nju.edu.cn

DODRIDINATED BY NESCPORTO

LOGY & SCIENCE ATE LABORATORY

NESCT

Received April 22, 2010; accepted June 1, 2010; posted June 17, 2010 (Doc. ID 127408); published June 30, 2010

We report an ultrasmall microfiber-probe-based reflective interferometer for highly sensitive liquid refractive index measurement. It has a $3.5 \ \mu m$ 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.

OPTICS LETTERS / Vol. 35, No. 13 / July 1, 2010 Microfiber-probe-based ultrasmall interferometric sensor

Jun-long Kou, Jing Feng, Qian-Jin Wang, Fei Xu.* and Yan-qing Lu Calego of Engineering and Applied Sciences and National Laboratory Sollage of Engineering and Applied Sciences and National Laboratory Solid State Microatractures, Nanjing University, Nanjing 210093, China *Corresponding author: feixu@nju.edu.cn

posted base 17, 2010 (Dor. ID 127408); published and 30, 2010 We report an ultraumal indication probabilished with the interferometer for highly semainten liquid refractive index for an a 3.5 am intercentic active biological with over 20 direction comparison with normalishing. A semaintent of the major of the state of the second second second second second second second second this kind of this probe sensor is no evolved with over 20 direction comparison with normalisher inter-tor second OCIS codes: 000.2770, 326(7188). Received April 22, 2010; accepted June 1, 2010;

2308

eters have been extensively used in various sensing applications due to their advantages of versatility, linear response, and relatively simple strucvension, incar response, and removely sumple arou-ture. In the past two decades, many efforts have been made to develop intrinsic and extrinsic interferometers, especially the microcavity Fabry-Perot interferometers especially the nucleocavity range extent and (MCFPIs). MCFPIs with tens-of-micrometers-length cav-(MCCT18), MCT18 WHI PERSONAL CONSTRUCTION CON-tices are attractive because of the small size, large free spectrum range (FSR), and high sensitivity. The cavity spectrum range (FSR), and ruge sensativity, the carry can be assembled by inserting a silica single-mode fiber can be assembled by newcore a since surger state (SMF) and a multimode fiber into a glass capillary [1], cas-(SMF) and a multimore most and a gass capmary (1) car cading Fabry-Perot cavities formed with a short piece of caung range-reror cavines ionined wait a stort preve or 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]. an unex-guinning prozentic crystal more togenier [4]. Although much progress has been made, people are still pursuing new microcavity fabrication techniques to improvents new neurocarea intercation recurrence to are and the process repeatability. Femtosecond laser technot are process repeatoney, remanerout any receiver notice receiver and the proposed recently showing great success notogy thus was proposed recently subverse proposed ease in micromachining fiber devices. MCPPIs can be quickly fabricated by drilling a small hole in an SMP for liquid and fabricated by drilling a small hole in an SMF for liquid and gas sensing [5]. However, even the featosecond-base-machined MCPPs still book logs frage visability of sev-eral decibes in liquids due to the rugged surfaces insi-the cavity, what is more of its difficult to focus the las-erated to environmentational source or sensing to the different to the second second second sensing to the different to its different to environmentation. the cavity, what is more a is omneun to rous are an spot to a subwavelength scale owing to the diffraction li It [6], thus the micromaching accuracy is limited and it [0]; thus the micromac many accuracy is informed and size of the microcavity is large. The latest progress in size or the high-rocavity is large. The arces progress in cused ion beam (FIB) techniques has opened a n widow of opportunity for ultrasmall cavities. The and controllable ion spot size and high beam current of sity are perfect for nanofabrication. Microcavities nanometer-scale accuracy in a subwavelength micro could be fabricated by FIB, which is relatively difficu-

In this Letter, we demonstrated an ultrasmall inlin the femtosecond laser approach. flective interferometric sensor with an open micror on the side of a single microfiber probe by direc machining. The cavity has the dimensions of only s maching intervents is much smaller than po micrometers, which is much smaller than po MCPFis. A theoretical analysis reveals that this b Fig. 2. SEM image of the micromotch cavity from the side. MCFFis. A theoretical analysis percent and modal intervents. device is a hybrid of Fabry-Perot and modal inter-

© 2010 Optical Society of America

0146-9592/10/132308-03415.00/0

ferometer has high extinction ratio and sensitivity. compact size, simple fiber-probe structure, all ther

compact size, sample inter-prone surveiure, any any connection, and easy fabrication further picke the microfiber-probe-based reflective interferoparter (MPRI) nucronnec-prone-uased renective interrerogenere (MPRI) a great candidate for chemical and biological sensiti applications. It even could offer fantastic potential in applications. It even could offer preasure potential in detecting inside a biocell, thanks to its unique tiny probe

Standard optical microtiber probes generally consist of Standard optical microfifter probes generally consist of inpered fiber the any/caper transitions. Since the micro-fiber probe is for analyte detecting rather than hanching the light, is should be short enough in order to be right. However, five short and samp a shape results in high leasest advante to the wave advantative of the twee worked losses using to the poor adiabaticity of the taper profiles 7) buring the past decade, much work has been carried to study and optimize microfiber taper profiles for out to study and opanize incroace taper promotion to telecom devices. Using a taper manufacturing rig it is possible to tailor the taper shape to an ideal profile [8]. possible to anor the aper snape to an ideal profile [9], but it is not easy to fabricate a short fiber probe. In this out it is not easy to introduce a single entropy processing a commercial pipette puller (model P2000, Sutter Instrument). The fabrication process is simple, converient [9], and extremely fast. The process is sample, convenient [2], and exitences insi- the obtained microfiber taper probe is then checked under a and concernancer properts then checked under a ne, as shown in Fig. 1. The profile is described



Fibre Fabry-Perot

PRINCIPLES





Fibre Fabry-Perot

Fibre Bragg Grating













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



INESCI





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



20



Long diaphragm

 The visibility is changed

Short diaphragm

 The visibility and the wavelength is changed



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. 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.



22

Fabry-Pérot cavities

Microstructured Fibre



DORDINATED BY ESCPORTO

INESCTE





 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







ESCPOI

ESC.





29



Fabry-Pérot cavities

Focused Ion Beam

Structure Forming Fibers (SFF)

- P₂O₅-doped fibers;
- Much higher etching rate than pure silica;





HF Etching

- a) SMF-SFF fusion-splicing;
- b) Cleaving to desired SFF length;
- c) cMMF-SFF fusion-splicing;



- d) Cleaving cMMF (30-40 μ m);
- e) Etching;



Chemically Etched Devices

NESCT





FIB – Indented Fabry-Pérot

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



FIB – Fabry-Pérot Cantilever



February 7th, 2014

INESCTE

Optical Spectra

- Simple reflection setup;
- Different length cavities;









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.



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.







Faculty of Electrical Engineering and Computer Science





Thank you for your attention