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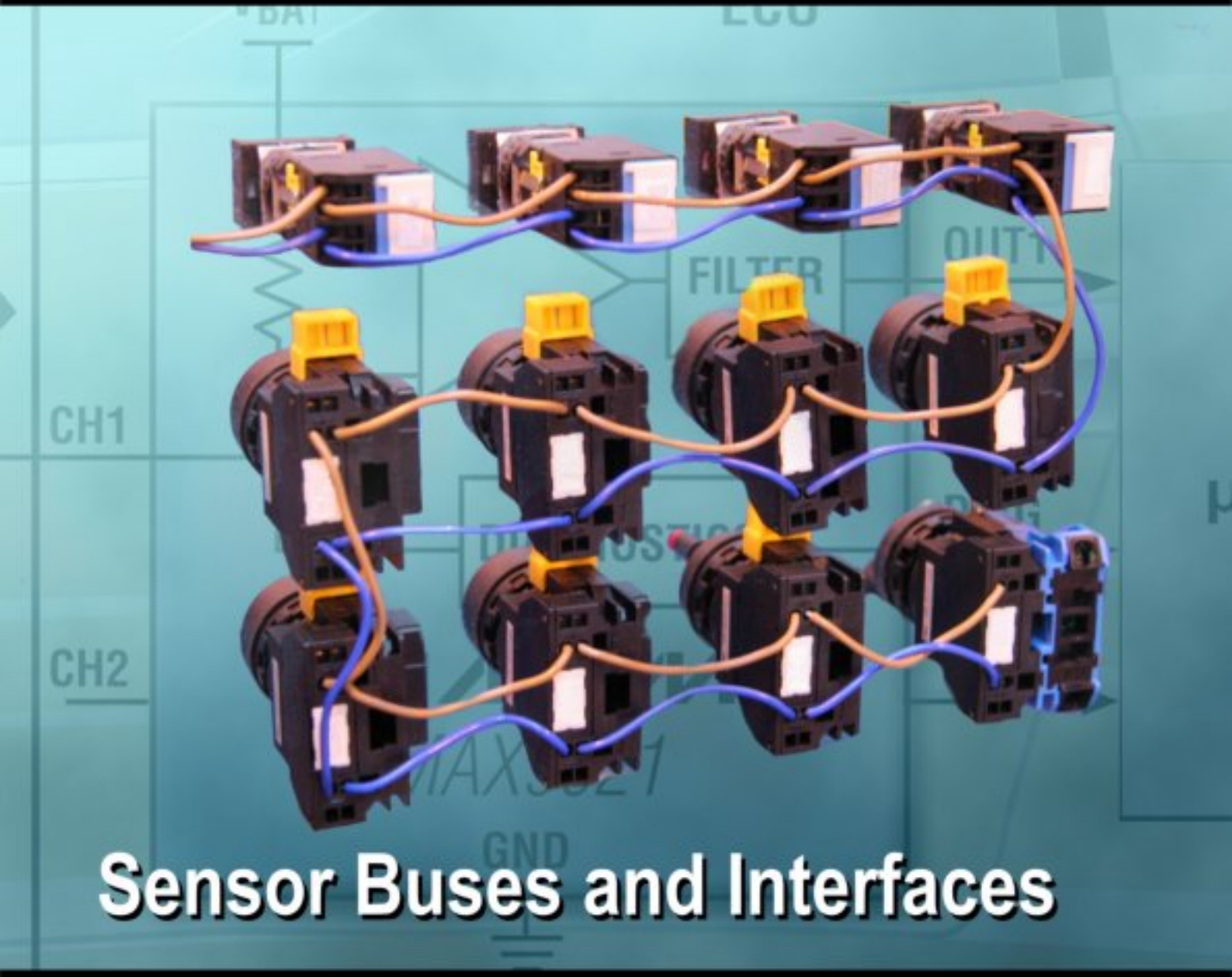

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Contents

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Research Articles

Composite Cavity Fiber Laser for Sensor Applications
Asrul Izam Azmi, Ian Leung, Paul Childs and Gang-Ding Peng 1

Design, Development and Testing of a Semi Cylindrical Capacitive Sensor for Liquid Level Measurement
Sagarika Pal, Rasmiprava Barik 13

Humidity Sensitivity of $MgCr_2O_4$-TiO_2-LiO_2 Ceramics Sensor Prepared by Sol-Gel Routes
H. Y. He 21

Effect on Ethanol Gas Sensing Performance of Cu Addition to TiO_2 Thick Films
C. G. Dighavkar, A. V. Patil, S. J. Patil and R. Y. Borse 28

Feasibility of Passive Gas Sensor Based on Whispering Gallery Modes and its RADAR Interrogation: Theoretical and Experimental Investigations
Hamida Hallil, Franck Chebila, Philippe Menini and Hervé Aubert. 38

Simulation-Driven Development and Optimization of a High-Performance Six-Dimensional Wrist Force/Torque Sensor
Qiaokang Liang, Dan Zhang, Quanjun Song and Yunjian Ge 49

Kalman Smoothing and Wavelet Analysis for Inertial Data of Human Movement Disorder Motion
Wesley Teskey, Mohamed Elhabiby and Naser El-Sheimy. 61

Two-Phase Flow Regime Identification by Ultrasonic Computerized Tomography
Mohd Hafiz Fazalul Rahiman, Ruzairi Abdul Rahim, Jaysuman Pusppanathan 76

Approximations in Calculating Stray Capacitance of Printed Spiral Inductors
R. C. Woods 83

Harmonic Response of Magneto-electro-elastic Sensors Bonded to Cylindrical Shells
B. Biju, N. Ganesan and K. Shankar 89

Ultra High Voltage Surge Waveforms Measurement Using an Optical Transducer
Francisco G. Peña-Lecona, J. Muñoz-Maciel, G. Gómez-Rosas, Francisco J. Casillas-Rodríguez, M. Mora-González, Víctor M. Durán-Ramírez and C. Castillo-Quevedo 104

Transverse Micro-structuring of Photonic Crystal Fibers for Industrial Sensors and Side Viewing Probes for Optical Coherence Tomography Applications
Sanjay Kher, Manoj Kumar Saxena, Smita Chaube, Amit Keskar, Subhashish Tiwari, S. M. Oak ... 112

Stability of High Temperature Standard Platinum Resistance Thermometers at High Temperatures
Y. A. Abdelaziz and F. M. Megahed 122

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Transverse Micro-structuring of Photonic Crystal Fibers for Industrial Sensors and Side Viewing Probes for Optical Coherence Tomography Applications

Sanjay KHER, Manoj Kumar SAXENA, Smita CHAUBE, [1]Amit KESKAR, [2]Subhashish TIWARI, S. M. OAK

Fiber Optics Lab, SSLD, RRCAT, Indore-452013, India
Tel.: +91-731-2442325, fax: +91-731-2442300
[1]School of Instrumentation, DAVV, Indore
[2]Department of applied Physics, SGSITS, Indore
E-mail: kher@rrcat.gov.in

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Abstract: In this work, we report a simple and easily adaptable technique of lateral micro-machining of Photonic Crystal fibers (PCFs) using modulated CO_2-laser in conjunction with electrical arc system. The technique is controlled, convenient and precise over wide dimensions (50-250 μm). Lateral access to the holes of PCF provides additional flexibility for sensitive real time detection of gases such as green-house gases. Long period gratings are made in PCF through inscription of micro-grooves for sensitive detection of longitudinal strain. A unique and versatile PCF based probe for possible endoscopic Optical Coherence Tomography (OCT) applications is reported. *Copyright © 2010 IFSA.*

Keywords: Micro-machining, CO_2 laser, Lateral access, Optical coherence tomography, Micro-grooves

1. Introduction

PCF is a class of optical fiber based on the properties of photonic crystals. A PCF is generally composed of a single material with an array of air holes running along the fiber. It has the ability to confine light in hollow cores with confinement characteristics which are not possible in conventional optical fibers. PCF can be broadly classified into: hollow core PCF and solid core PCF.

Processing of silica glass or silica optical fibers by standard methods of photolithography or ultrasonic methods either results in micro-cracks on the surface or the process is complicated. Laser based micro-machining has been proved to be promising for drilling of grooves, trenches or holes in silica fibers. However, laser beam precision micro-machining requires expensive Femtosecond laser and precise focus control [1, 2]. There is only one report [3] wherein a pulsed CO_2 laser has been used for hole drilling in silica. However, this work reports hole drilling only in silica substrates by using a pulsed CO_2 laser. Micro-structuring silica fibers especially photonic crystal fibers (PCFs) is technically challenging and require very high precision, beam control, gas flow control and fiber alignment. In this paper, we are reporting micro-structuring of PCF fibers using a modulated CO_2 laser.

Many industrial segments produce gaseous emissions as a by-product of the processes performed such as chemical processing, glass melting, metal casting, transportation, pulp and paper, and energy production industries. Emissions monitoring and control has become an increasingly important consideration in the broader context of global environmental awareness. Optical fiber based sensors have been demonstrated to be attractive for measurement of a variety of physical and chemical parameters. In parallel to the increased fiber sensor research, photonic crystal fibers have been showing profound effects in gas sensing applications.

The holes in PCF open up new opportunities for exploiting the interaction of light with gases. With the possibility of filling the air holes of PCF with gas, with large interaction lengths, new ways to monitor or detect gases are possible. With the possibility of gas entry laterally by providing side access through drilling of micro-holes, while both tips are free for evaluation can provide single ended, high speed, sensitive detection of hazardous gases. Our technique provides easy and faster method to provide side access at multiple locations for real time gas sensing applications.

A long period grating (LPG) can be made either by index change at regular periods or by inscription of V-grooves on PCF. The depth of grooves can also be controlled to increase sensitivity for measurement of strain. A long-period fiber grating couples light from a guided mode into forward propagating cladding modes which eventually lose its power due to scattering and absorption in the fiber coating. The coupling from the guided mode to cladding modes is wavelength dependent, so we can obtain a spectrally selective loss. Simplistically saying, it is an optical fiber structure with the properties periodically varying along the fiber, such that the conditions for the interaction of several co-propagating modes are satisfied. The LPG has a period typically in the range 100 μm to 1 mm. The exact form of the spectrum, the centre wavelengths of the attenuation bands are sensitive to the period of the LPG, the length of the LPG and to the local environment such as temperature, strain, bend radius and to the refractive index of the medium surrounding the fiber. An important application of LPG is the measurement of strain. LPG based strain sensors are wavelength encoded and are highly sensitive while offering high insensitivity to temperature [4, 5].

PCF can also be used as probes for biological and medical diagnostics. A ball lens is made on tip of PCF for optical imaging systems such as OCT due to their compactness and flexible design parameters [6]. Further, these probes can be designed meticulously with various features such as side viewing or angle viewing capability. One such probe has been reported in [7]. However, such probe requires complicated and time consuming processing while using a precision focused Femtosecond laser. In this report, we have suggested more flexible, versatile side viewing lensed probes for endoscopic OCT applications. These newly proposed probes can be used for angle viewing of tissue structures over a wide range from say 20 to 180 degrees. The probes are compatible for OCT imaging of internal organs based on catheter-endoscope system capable of delivering, focusing, scanning and collecting in a low order fiber mode. These probes are compact, low cost, flexible and offer tremendous potential for endoscopic OCT.

2. Experimental Setup

A modulated, X-Y scanning CO_2 laser with maximum average power of 10 W, is placed such that its beam falls on optical fiber (PCF) at required angle as shown in Fig. 1. The spot location, size, beam power, modulation depth and repetition rate of laser can be controlled. The optical fiber is fixed between the mounts on a translational stage. A lens is placed between the laser and fiber such that the focused beam falls on the fiber. The PCF can be kept connected through patch cords to an optical spectrum analyzer (OSA) for on-line monitoring of light coupling while the micro-structuring is being done.

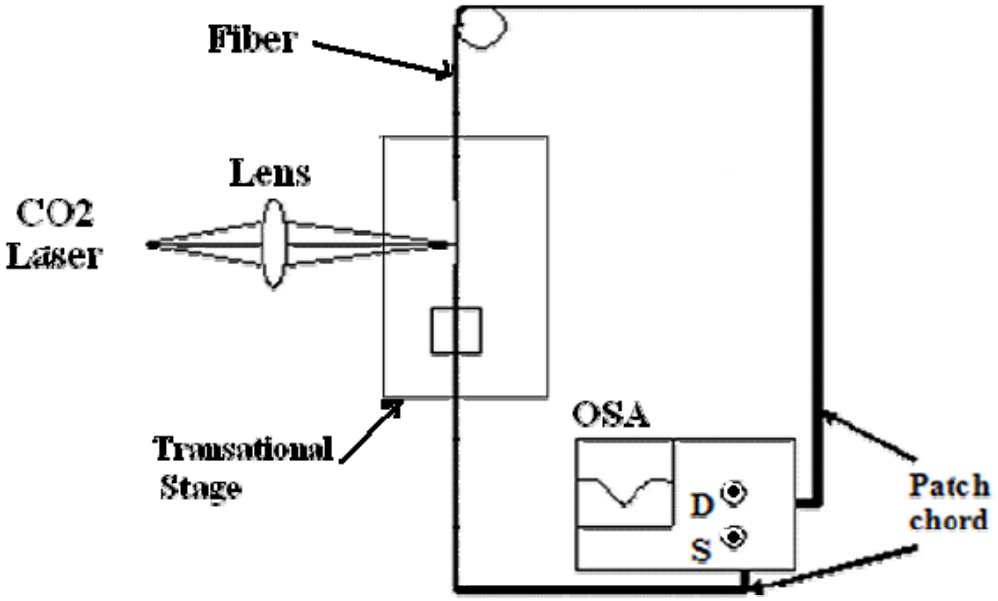

Fig. 1. Experimental Setup.

By rotating the micrometer screw of the translational stage, grooves in PCF can be made at different spacings /period when the beam is not scanned. Alternatively, the fiber is fixed and beam is moved on fiber to make grooves at specified period. Laser beam could be made to fall on the tip of PCF by keeping the edge of the PCF directly below the focus of laser beam. For OCT probes, suitable PCF fiber is chosen and the coating is removed near one end. A small section (5-15 mm) of this fiber is then processed by CO_2 laser for permanently bending and shaping for angled viewing. The tip is then processed for fabrication of a ball lens using a controlled electrical arc system. The coupling of light in forward and angular channels is then tested using He-Ne laser.

3. Results and Discussion

V-Grooves with different depths and surface area have been formed on high-birefringence PCF (Hi-Bi PCF), large mode area (LMA) PCF and hollow core PCFs. A microscope image of a V-groove fabricated in LMA PCF is shown in Fig. 2.

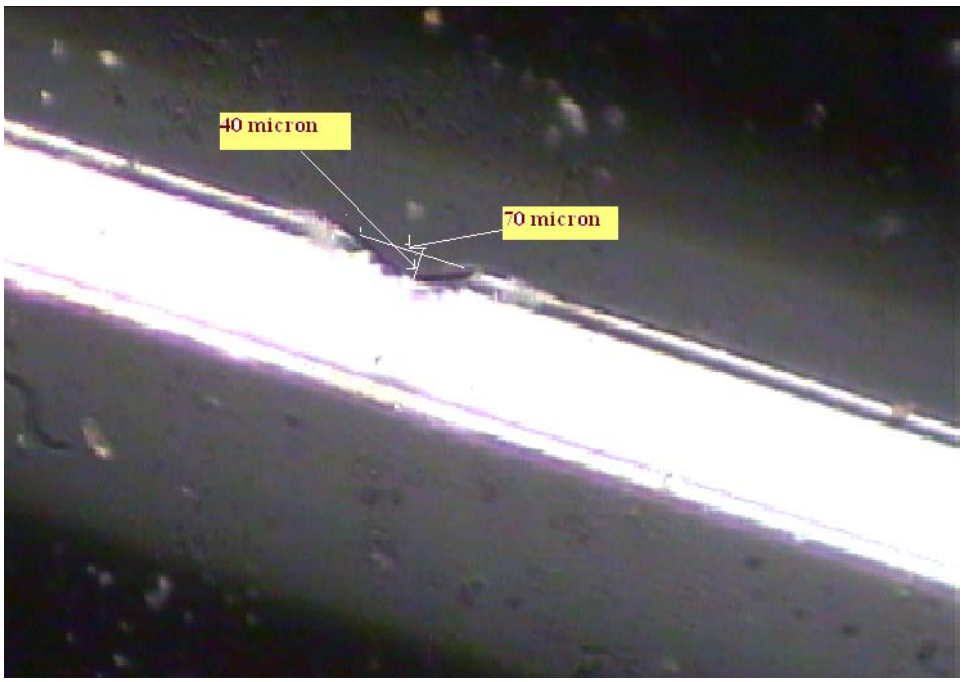

Fig. 2. V-Groove fabricated in LMA-PCF.

The data related to making of grooves with the CO_2 laser viz. mark speed of laser required, mark times, V-groove depth formed and groove width on surface for Hi-Bi PCF and hollow core PCF's are given in tabular format in Tables 1 and 2 respectively. This data is taken when both the Hi-Bi PCF or hollow core PCF was not connected to the OSA and coupled output power is not being monitored.

Table 1. Crystal Fiber: Hi-Bi PCF-1550.

Mark Speed (mm/sec)	Mark Time (nos)	V-Groove depth formed (%)*	Groove width on surface (micron)
16	2	10	60+/-2
16	3	20	70+/-2
16	4	40	100+/-2

Table 2. Crystal Fiber: Hollow Core.

Mark Speed (mm/sec)	Mark Time (nos)	V-Groove depth formed (%)*	Groove width on surface (micron)
16	1	80	100+/-2
18	1	25	60+/-2
18	2	40	75+/-2
18	3	60	90+/-2

The data clearly show that the groove depth can be precisely controlled b CO_2 laser based method. Further, the Hi-Bi PCF was connected to the OSA to see the effect of groove depth on loss of optical coupled power. The results are tabulated in Table 3. It is clear from the table that we can choose the depth of groove to optimize the interaction with evanescent field. In case of hollow core PCF, this will help us to reach the hollow zone for full interaction of probe gases with optical field.

Table 3. Crystal Fiber: Hi-Bi PCF-1550, Light Coupled at 1550 nm (59 pW +/-3 pW).

Mark Speed (mm/sec)	Mark Time (nos)	V-Groove depth formed (%)*	Groove width on surface (micron)	Power coupled (pW)
20	1	5	60+/-2	55+/-3
20	2	10	70+/-2	50+/-3
20	3	15	85+/-2	45+/-3
20	4	20	95+/-2	40+/-3
20	5	25	100+/-2	35+/-3
20	6	30	100+/-2	30+/-3
20	7	35	100+/-2	25+/-3

*For column 3 (Tables 1, 2, 3), the parameters were separately measured by cutting the fiber at the center of groove and the cross-section was seen on a video microscope screen. The groove depth was estimated based on this image.

The technique of making a groove can be exploited to inscribe long period gratings in Hi-Bi PCF and large mode area (LMA) PCF. An LMA fiber falls under the category of solid core PCF. The cross-sections of Hi-Bi PCF and LMA PCF used in the present paper have been shown in Figs. 3 and 4 below respectively.

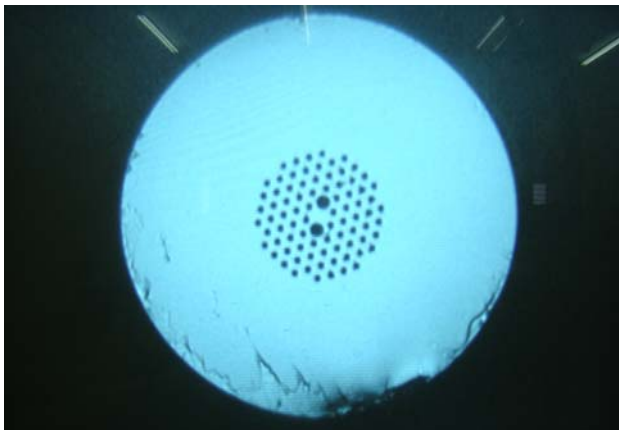

Fig. 3. Microscope image of Hi-Bi fiber cross-section.

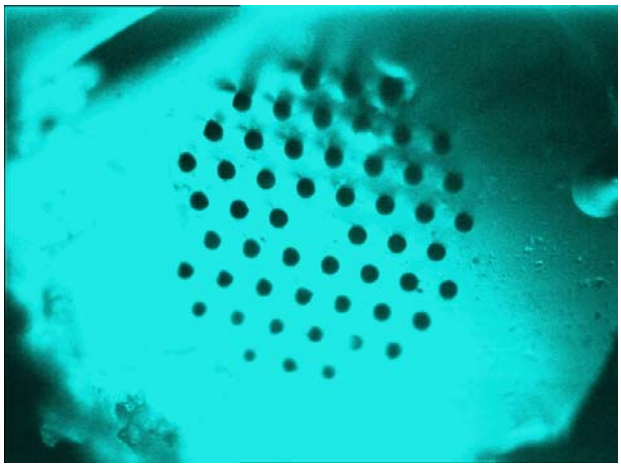

Fig. 4. Microscope image of Large Mode Area (LMA) fiber.

The transmission spectrums of LPG fabricated in Hi-Bi PCF and LMA PCF have been shown in Figs. 5 and 6 below respectively. The microscope image of longitudinal section of LPG is shown in Fig. 7.

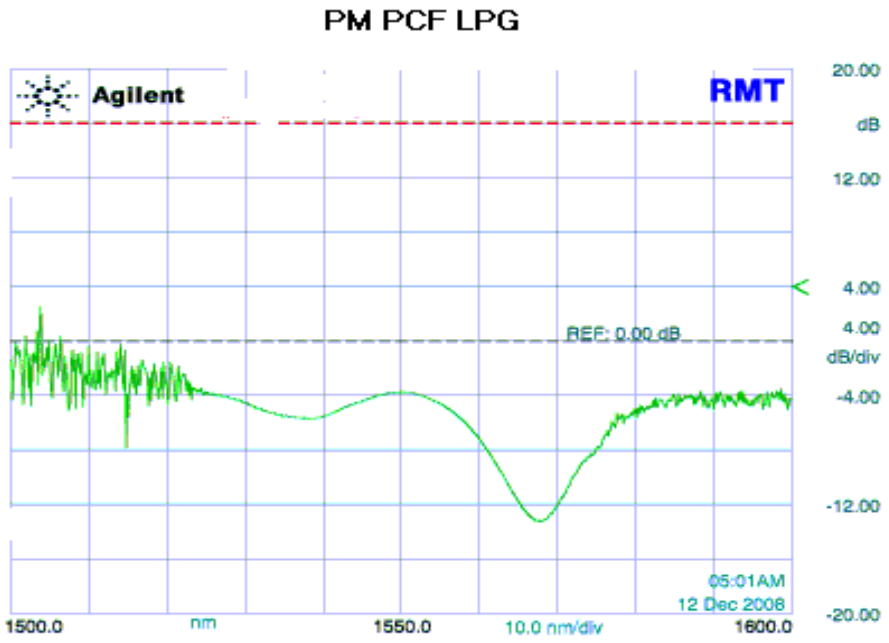

Fig. 5. Transmission spectrum of Long period fiber grating fabricated in Hi-BI PCF fiber.

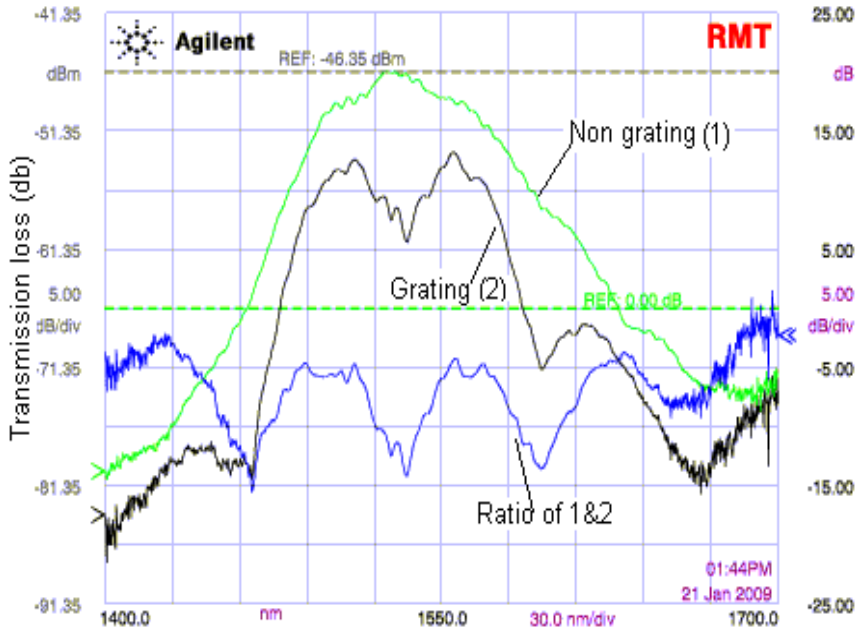

Fig. 6. Transmission spectrum of Long period fiber grating fabricated in LMA- PCF fiber.

Fig. 7. Microscope side view of regular V-grooves for LPG inscription in LMA fiber.

The data related to resonance peak shift (monitored at 1534 nm) viz. strain applied is recorded while the PCF is kept connected to the OSA. This data is given below in Table 4.

Table 4. Resonance peak shift vs. applied strain.

Applied strain (%)	Peak Shift(nm)
0 .00	0
0.0294	1.7
0.0588	3.5
0.0882	4.4
0.1176	5.3

3.1. Probes for Biological and Medical Diagnostics

Lensed fibers are very useful for optical imaging systems such as OCT due to their compactness and flexible design parameters. In such designs, there is no necessity of alignment as the focusing ball lens is directly fabricated on fiber tip. Fig. 8 shows the ball lens fabricated on the tip of PCF fiber. Further, these probes can be designed meticulously with various features such as side viewing or angle viewing capabilities. One such probe based on femtosecond laser processing reported recently [7] requires precision focus control, expansive laser system, optimization of processing parameters and is time consuming. Besides, these probes can not be made for accurate normal viewing.

In this report, we are suggesting a more flexible and versatile side viewing lensed probes for endoscopic OCT applications. Theses newly proposed probes can be used for angle viewing of tissue structures over a wide range from say 20 to 180 degrees. Various lensed, angled probes for side viewing and imaging have been fabricated using controlled heating and cooling of PCF fibers by CO_2 laser and electrical arc system. Figs. 9, 10 show the angled tip images of such implemented probes

recorded by CCD camera for side view OCT applications. In one such probe made for 90 Degree OCT applications, the power coupling ratio between transverse direction to longitudinal direction (along fiber axis) is more than 10 dB (data not shown) and the focused beam quality is also near Gaussian (Fig. 11). Moreover, the probes can be designed and optimized for viewing at any angle from say 20 degree to 180 degrees. The probes are compatible for OCT imaging of internal organs based on catheter-endoscope system capable of delivering, focusing, scanning and collecting in a low order fiber mode. These probes are compact, low cost and flexible and offer tremendous potential for endoscopic OCT.

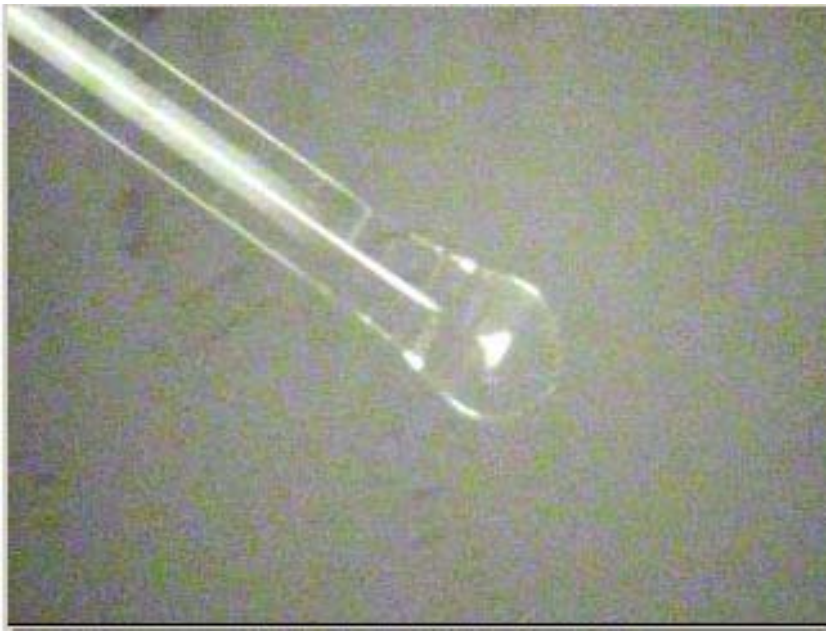

Fig. 8. Ball lens fabricated on tip of PCF.

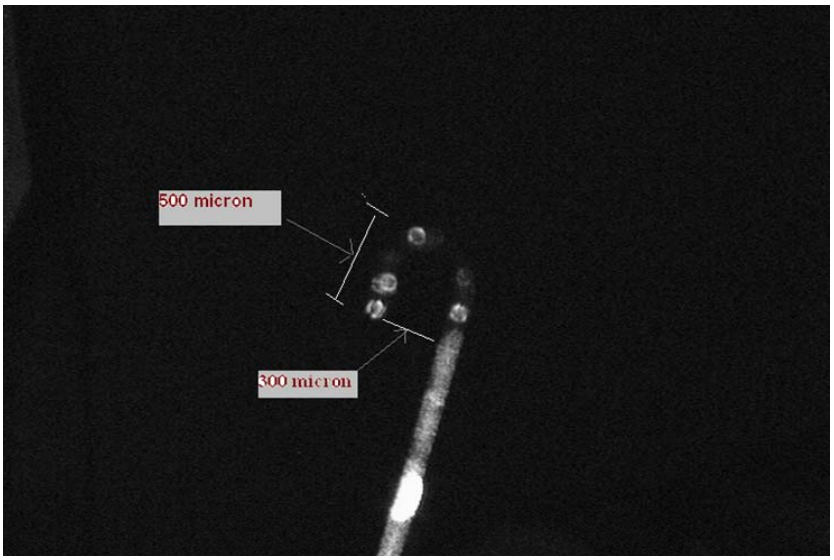

Fig. 9. Image of U-shaped (180 deg.) lensed tip taken through a CCD camera.

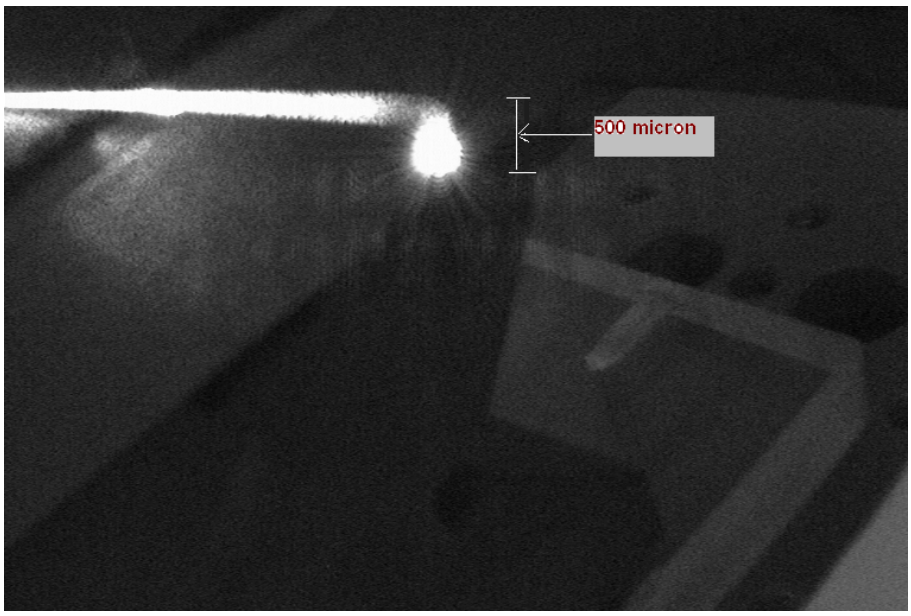

Fig. 10. Image of an L-shaped tip (90 degree) of LMA-PCF taken through a CCD camera.

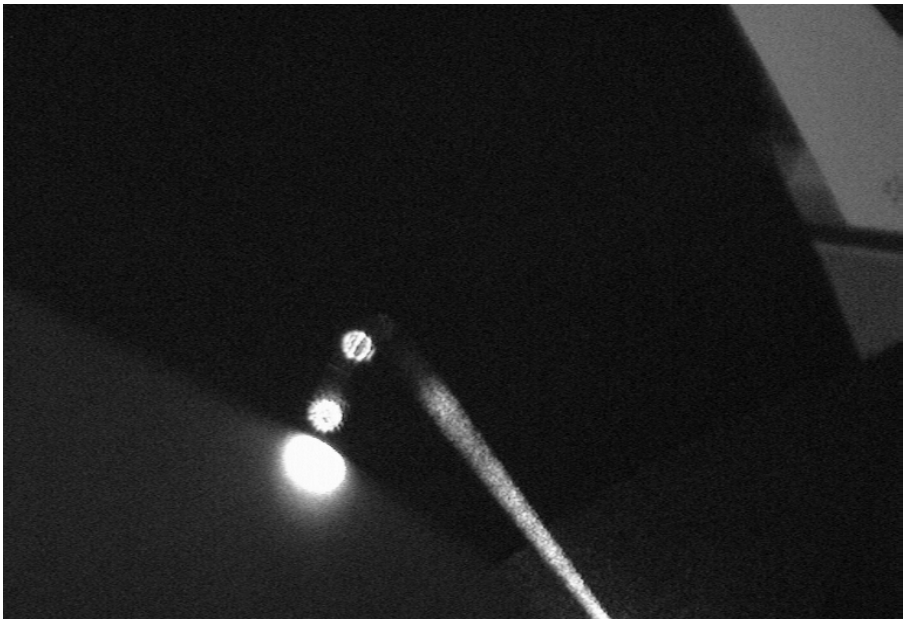

Fig. 11. Image of focus of He-Ne laser through the L-shaped tip through a CCD camera.

4. Conclusion

We have developed technology to microstructure optical fibers especially PCF fibers which can be exploited to develop novel sensor heads for real time gas sensing applications. The technique is adaptable for micro-structuring silica substrates for microwave applications. Multiple V-grooves with a spacing as small as 2 mm can be made for real time gas sensing applications. The groove shape such V-groove, U shape Groove and channels on the surface can be made for novel sensing applications. The ball lenses can be made in communication fiber as well as on PCF fibers for imaging and efficient power coupling applications. The versatile probes for OCT applications will definitely open new frontiers in medical diagnostics.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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