Directional Force Measurement Using Specialized Single-Mode Polarization-Maintaining Fibers

Mohammad Karimi, Frederic Surre, Tong Sun, Kenneth T. V. Grattan, W. Margulis, and P. Fonjallaz

***Abstract*—Two different types of specialist single-mode polarization-maintaining side-hole(s) fibers have been specifically chosen in this paper for the direct measurement of transverse force, and their performance characteristics have been recorded and cross compared. To achieve this, side-hole fibers have been used which were investigated both theoretically and experimentally for their respective pressure sensitivities as a function of rotation angles and magnitudes of the applied external force. The experimental results obtained have shown good agreement with theoretical predictions for situations where an external force applied was within a certain range. It was thus concluded that the pressure measurement sensitivities of these specialist fibers are strongly dependent upon the direction of the force applied (with reference to the fast or slow axis of the fibers). Therefore, devices based on these fibers can be used effectively as sensors for the measurement of pressure, force, and mass of an object through an appropriate device configuration, enabling measurements over a wide range and in real time.**

***Index Terms*—Fiber-optic sensor, polarization-maintaining fiber, pressure measurement sensitivity, side-hole fiber, transverse force.**

I. Introduction

FIBER-OPTIC sensors have been intensively developed over the last three decades [1]–[4], incorporating novelty both in fiber structural design and in the sensing mechanisms used. They have shown advantages over conventional sensors, such as being of small size, showing immunity to electromagnetic interference and resistance to chemical attack, thus showing potential for a breadth of industrial and other practical applications [5]. Pressure is considered to be the second most important physical parameter that is successfully addressed by using optical fiber sensors (OFSs). It was reported that pressure OFSs have gained new market shares in the last five years primarily due to their newly commercialized medical disposable sensors [6]. Among these, high birefringence optical fibers were the most widely investigated fiber candidates for the development of fiber-optic pressure sensors due to their polarization characteristics being dependent on the force or pressure applied to these fibers. There are different types of high-birefringence optical fibers, such as elliptical core, elliptical inner cladding, bow-tie, and panda fibers, which are commercially available and have been widely investigated across the community for different sensor applications. *Fiels et al.* [7] were the first to use fiber optics to measure the hydrostatic pressure, but the first studies on polarimetric (PM) pressure sensitivity were undertaken by *Xi et al.* [8]. This was followed by more extensive research in the field using a variety of PM fibers with different cores and cladding shapes and sizes [9], [10]. This paper has been focused on the discussions of the phase-based pressure sensor technique. There have been some other reports showing intensity-based technique, such as [11], which reported that the lateral pressure sensitivity of PM fibers is dependent on the magnitude and angle of external transverse forces theoretically and supported by one directional measurement data.

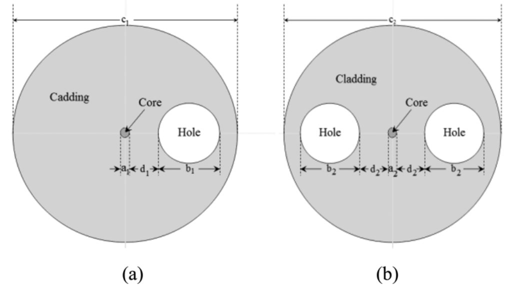

Fig. 1. (a) One-hole high-birefringence fiber that has a hole diameter b_1 of 30 μm and the distance between the right edge of the core to the left edge of the hole d_1 is 9 μm. (b) Two-hole high-birefringence fiber that has two holes with the same diameter b_2 of 27 μm and the distance between the right edge of the core to the left edge of the hole on the right d_2 is 14 μm.

Regarding the cross sensitivity to the other parameters, such as temperature, [12] has shown that such a sensor is not dependent on temperature variation and this conclusion was further confirmed by *Wierza et al.* [13] after the transverse force was applied, respectively, in the direction of fast and slow axis of a two-hole fiber. This paper, however, aims to undertake a more thorough investigation, coupled with an appropriate theoretical analysis, to evaluate the lateral pressure sensitivity of two types of side-hole(s) fibers, shown in Fig. 1, as a function of the angle and magnitude of the external transverse force applied and thus to cross compare the results obtained from these two different structured side-hole fibers and thus evaluate their potential for sensor applications.

These two specialist fibers have been designed, fabricated, and supplied by Acreo AB in Sweden. Both types of fibers have the cladding diameters of 125 μm ($c_1 = c_2 = 125$ μm) and

M. Karimi is with Azad University in Oxford, Oxford, OX29 4DA, U.K., and also with City University London, London, EC1V 0HB, U.K. (e-mail: mohammad.karimi.1@city.ac.uk).

F. Surre, T. Sun, and K. T. V. Grattan are with City University London, London, EC1V 0HB, U.K. (e-mail: f.surre@city.ac.uk; t.sun@city.ac.uk; k.t.v.grattan@city.ac.uk).

P.Fonjallaz and W. Margulis are with Acreo AB, Electrum 229, SE-164 40 Kista, Sweden (email: pierre-Yves.fanjallaz@acreo.se; walter.margulis@acreo.se)

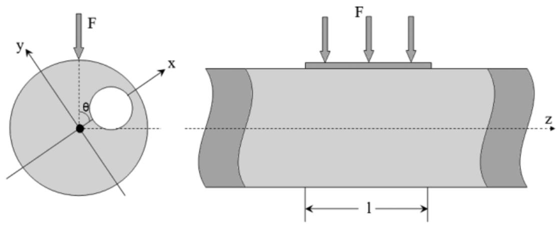

Fig. 2. Schematic diagram of the experimental setup of the PM fiber with force applied (θ is the angle between the applied force and the slow axis x of the fiber).

core diameters of 8.7 μm ($a_1 = a_2 = 8.7$ μm). The one-hole fiber as shown in Fig. 1(a) has a hole diameter b_1 of 30 μm and the distance between the right edge of the core to the left edge of the hole d_1 is 9 μm. The two-hole fiber shown in Fig. 1(b) has a hole diameter b_2 of 27 μm and the distance between the right edge of the core to the left edge of the hole on the right d_2 is 14 μm. The inclusion of holes in the fiber structures is intended to change the stress distribution inside the fibers; therefore, these side-hole fibers are expected to exhibit high sensitivity to the perturbation, which may arise from variations in temperature, twist, strain, stress, or pressure.

II. Theory

Polarization coupling in a birefringent fiber is related to the perturbation, applied perpendicular to the fiber axis as shown in Fig. 2, and such perturbation causes a conversion between the two polarization modes inside the birefringent fiber [13]. In fact, the phase difference between the two polarization modes HE_{11}^{x} and HE_{11}^{y} propagating in a birefringent fiber $\Delta\varphi$ is related to the applied pressure or transverse force through the change of differences between the propagation constants of polarization modes over a fiber length l, which can be expressed as follows [3]:

$$\Delta\varphi = (\Delta\beta - \Delta\beta_0)l \tag{1}$$

where $\Delta\beta_0$ is the difference between the propagation constants of polarization modes when there is no force and $\Delta\beta$ represents the difference between the propagation constants of polarization modes when a force is applied on a fiber unit segment, which is given by [4]

$$\Delta\beta\sqrt{(N_{11} - N_{22}) + |2N_{12}|^2} \tag{2}$$

where N_{11}, N_{22}, and N_{12} represent different coupling coefficients described in the following equations [1], [2]:

$$N_{11} - N_{22} = \frac{2\pi}{\lambda}\left[B - C\left(\frac{4f}{\pi r}\right)\cos(2\theta)\right] \tag{3}$$

$$N_{12} = N_{21} = -\frac{\pi}{\lambda}C\left(\frac{4f}{\pi r}\right)\sin(2\theta) \tag{4}$$

where C is the photoelastic constant, B is the modal birefringence of the fiber itself, and θ is the angle between the applied force and the slow axis of the fiber as illustrated in Fig. 2. f is the amount of force F applied in a direction which is vertical to the fiber axis per unit length of fiber, which is given by (5)

$$f = F/l. \tag{5}$$

By combining (2), (3), and (4), $\Delta\beta$ can be modified as (6) at the bottom of the page. Based on (5) and (6), (1) can thus be modified to be as (7), shown at the bottom of the page, where $\Delta\beta_0 = (2\pi)/(\lambda)lB$. When the PM fiber is used for pressure measurement, the sensitivity can thus be defined as the change of phase difference per unit applying force per unit length, as shown in [14]

$$K = \frac{\Delta\varphi}{f}. \tag{8}$$

This pressure sensitivity can be analyzed using Jones matrix algebra [4]. The sensitivity of a PM pressure sensor is dependent on the degree of polarization rotation angle introduced by a particular measurand, and it represents the minimum detectable pressure change as a function of rotation angle. The influence of a measurand on the polarization state can be calculated and the intensity detected after a polarization analyzer can be described by [4].

$$I = \frac{I_0}{2}(1 + \cos\Delta\varphi) \tag{9}$$

where I_0 is the maximum output power. Therefore, the change in polarization will be observed as a change of signal intensity after the analyzer, producing a sinusoidal signal.

III. Experimental Setup

An experimental setup used in this study for pressure measurement using a PM fiber is shown schematically in Fig. 3. The light source is a single-mode laser with an output power of 10 mW at a wavelength of 1550 nm. The light is launched

$$\Delta\beta = \sqrt{\left(B - C\left(\frac{4f}{\pi r}\right)\cos(2\theta)\right)^2 + \left|-\frac{4\pi}{\lambda}C\left(\frac{4f}{\pi r}\right)\sin(2\theta)\right|^2} \tag{6}$$

$$\Delta\varphi = \frac{2\pi}{\lambda}l\sqrt{\left(B - C\left(\frac{4f}{\pi r}\right)\cos(2\theta)\right)^2 + \left|-\frac{4\pi}{\lambda}C\left(\frac{4f}{\pi r}\right)\sin(2\theta)\right|^2} - \frac{2\pi}{\lambda}lB \tag{7}$$

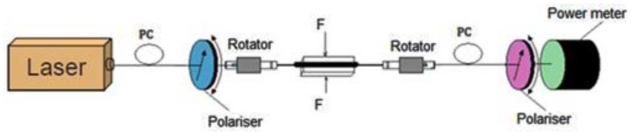

Fig. 3. Schematic diagram of the experimental setup of the pressure sensor system using a PM side-hole fiber.

into a PM fiber through a polarization controller that is used to achieve azimuthal control of the polarization of the light before entering the PM fiber. The polarization state of the light entering the fiber was adjusted to give equal intensity of light in each eigenmode of the sensing fiber. An in-line polarizer is fusion spliced in front of a high birefringent sensing fiber.

The intensity of the light, after traveling through the birefringent section of the fiber and the polarizing analyzer at the fiber output, is measured by a digital power meter. In order to apply pressure/force in different directions, two fiber rotators were used to allow a resolution of 5° in the change of rotation. As illustrated in Fig. 2, a PM side-hole fiber was sandwiched between two parallel plates with two additional "dummy" fibers (physically the same size carrying an optical signal) used as well to allow the plates to remain parallel when the force is applied, preventing the sensor fiber from twisting and the top plate from rocking.

The sensing length used was 45 mm and the PM fiber was loaded by applying a calibrated mass on the lever and measurements were undertaken, showing the intensity of the signal as a function of rotation angle of the fiber and the magnitude of the force applied.

Based on (8), the pressure sensitivity of the PM fiber can thus be obtained when the force is applied in different directions, this forming the basis of the sensor. As explained in Section II, a perturbation can cause polarization-mode coupling variation, which, therefore, can result in a change in the phase difference of the polarization modes. As a result, the phase change can be easily detected by monitoring the change in the output signal intensity.

IV. Experimental Results

Fig. 4 shows the phase differences obtained over a sensing length of the fibers and a cross comparison was made between the two sets of experimental data obtained and of the theoretical data obtained by using (7), when both types of side-hole fibers were subjected to different loads at different angles. The phase differences have shown to increase with the increase of applied load and when the angle of applied force in relation to the slow axis of the fiber increases, the change of the phase differences becomes more dramatic, indicating different sensitivities when the fibers are used for pressure measurements. For both types of fibers, a maximum sensitivity can be achieved when the force is applied at 90° in relation to the fiber slow axis. The experiments have also confirmed that the sensitivity of these specialized pressure sensors is independent of the fiber length and of the axial location of the force along the fiber length compared to the other sensors [11]. This makes the sensors more suitable for distributed force measurement.

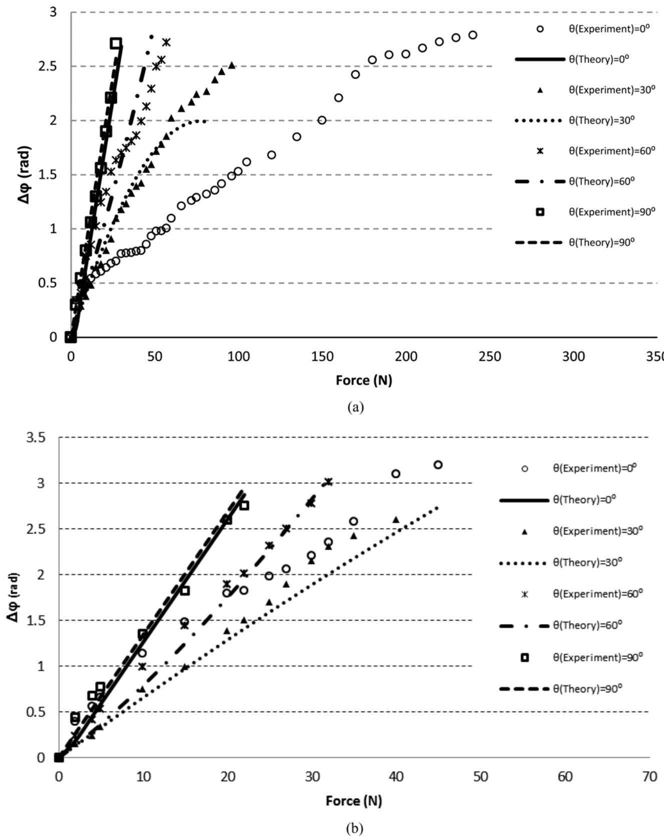

Fig. 4. Comparison of experimental and theoretical phase differences of the PM fibers when force is applied at different angles in relation to the slow axis of the (a) one-hole fiber and (b) two-hole fiber.

Fig. 4(a) shows the results obtained from the one-hole fiber, when it was, respectively, subjected to different loads at various angles of 0°, 30°, 60°, and 90°. It can be seen that when the applied force is lower than 50 N, there is a good agreement between the experimental and theoretical data for 30°, 60°, and 90°, but this is not seen for 0°. When the force applied is increased, there is an increasing discrepancy between the theoretical and experimental data. This disagreement arises from the assumption in theory that the hole(s) is/are not distorted under the pressure, which is true when the applied force is within a certain range. Therefore, the theory should be valid before the shape of the hole(s) and the cladding starts to change.

As a result, the assumption of the theory used in (1)–(8) will no longer be completely valid. This phenomenon can also be seen for the situation when θ is zero, i.e., the direction of the applied force is along the slow axis. Even when a small force is applied, the assumption of a circular hole used for the theory does not hold, and therefore, the agreement between theory and experimental data seen elsewhere is lost. Similar results have been observed for two-hole fibers in Fig. 4(b), when the force is applied at different angles and again within a limited range, there is agreement between theory and experimental data when the angels are 30°, 60°, and 90°, but not at an angle of 0°. Also, for both fibers, the increase of rotation angle enables the sensing range to be shortened and compared to the situation for the two-hole fiber, revealing that the sensing range of one-hole fiber is much wider.

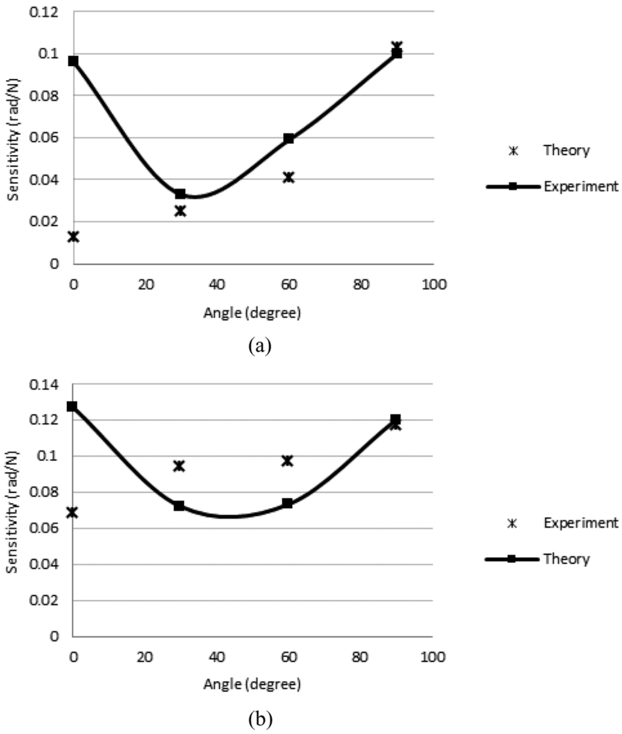

Fig. 5. Sensitivity as a function of rotational angle for (a) one-hole and (b) two-hole fibers.

Fig. 5 summarizes the sensitivity trend for one-hole and two-hole fibers, respectively, when the angle of the applied force varies. The solid square symbols in Fig. 5 show the sensitivities obtained from experimental data and the short lines show the results obtained from theory. As explained previously, when the force is applied along the fiber slow axis, there is a mismatch between the theory and experiments, due to the assumptions in the theory which then become invalid. However, when the rotation angle is at either 30°, 60°, or 90°, agreement is seen especially when the force applied is within a specific range and especially when the rotation angle approaches 90°.

In light of the aforementioned results obtained, it can be concluded that in the design of an optimized sensor device using such fibers, there is a compromise that can be struck between the sensitivity and the sensing range. Compared to the two-hole fiber, one-hole fiber has demonstrated wider sensing range, but smaller sensitivity when they are subjected to the same conditions. This will have implications for practical applications of the technique when these fibers are used for directional pressure measurements. Compared to the other phase-based techniques reported, these two sensors have demonstrated wider sensing ranges [14].

V. Conclusion

In this paper, a series of experimental tests has been undertaken to evaluate the performance of two types of side-hole fibers when they are subjected to various loads at different orientations with a view to designing an optimized sensor system. To support this, a detailed theoretical analysis has also been carried out and comparisons made between theory and experiment. As a result, it has been shown that the lateral pressure sensitivity of both one- and two-hole fibers has been successfully obtained and cross compared with the results from the theory, from which it was confirmed that to optimize the design of a device based on this effect in these fibers, a "tradeoff" between the sensing range and sensing sensitivity is seen. Thus, different designs can be proposed for different situations. The results further have shown that there is good agreement between the experimental data and the theoretical analysis when the applied force lies within a certain specific range and when the direction of applied force is further away from the slow axis. This is due to the fact that in the theory, an assumption has been made that the holes in the fibers remain fully circular, even when the force is applied to the fibers, and experimentally it is known that this does not hold. An important conclusion is that these theoretical and experimental results obtained can form an effective foundation for employing these side-hole fibers as OFSs for real-time pressure measurements. On-going research aims to understand better the optimization of such sensors and creating correct specifications for different sensing situations.

References

[1] J. Sakai and T. Kimura, "Breifringence and polarization characteristics of single-mode optical fibers under elastic deformations," *IEEE J. Quantum Electron.*, vol. QE-17, no. 6, pp. 1041–1051, Jun. 1981.
[2] J. Sakai and T. Kimura, "Polarization behavior in multiply perturbed single-mode fibers," *IEEE J. Quantum Electron.*, vol. QE-18, no. 1, pp. 59–65, Jan. 1982.
[3] K. T. V. Grattan and B. T. Meggitt, *Optical Fiber Sensor Technology*. Alphen aan den Rijn, The Netherlands: Kluwer, 2000.
[4] Y. Shizhuo, P. B. Ruffin, and T. S. Y. Francis, *Fiber Optic Sensor*. Boca Raton, FL: Taylor & Francis, 2008.
[5] T. R. Wolinski and A. W. Domanski, "Polarimetric optical fiber sensors of a new generation for industrial applications," *Bull. Polish Acad. Sci. Tech. Sci.*, vol. 56, no. 2, pp. 125–132, 2008.
[6] P. Éric, "Pressure measurement with fiber-optic sensors: Commercial technologies and applications," in *Proc. SPIE*, 2011, vol. 7753, pp. 775304–.
[7] J. N. Field, C. K. Asawa, O. G. Ramer, and M. K. Barnoski, "Fiber optic pressure sensor," *J. Acoust. Soc. Am.*, vol. 67, pp. 816–818, Mar. 1980.
[8] H. M. Xie, P. Dabkeiwicz, and R. Ulrich, "Side-hole for fiber-optic pressure sensing," *Opt. Lett.*, vol. 11, no. 5, pp. 333–335, May 1986.
[9] R. Guan, F. Zhu, Z. Gan, and D. Huang, "Stress birefringence analysis of polarization maintaining optical fibers," *Opt. Fiber Technol.*, vol. 11, pp. 240–254, 2005.
[10] A. N. Trufanov, O. Y. Smetannikov, and N. A. Trufanov, "Numerical analysis of residual stresses in preform of stress applying part for PANDA-type polarization maintaining optical fibers," *Opt. Fiber Technol.*, vol. 16, pp. 156–161, Jun. 2010.
[11] T. Xu, W. Jing, H. Zhang, K. Liu, D. Jia, and Y. Zhang, "Influence of birefringence dispersion on a distributed stress sensor using birefringent optical fiber," *Opt. Fiber Technol.*, vol. 15, no. 1, pp. 83–8, Jan. 2009.
[12] J. Gan, L. Shen, Q. Ye, Z. Pan, H. Cai, and R. Qu, "Orientation-free pressure sensor based on π-shifted single-mode-fiber Sagnac interferometer," *Appl. Opt.*, vol. 49, no. 27, pp. 5043–5048, 2010.
[13] Wierza, Pawel, and K. Bogdan, "Measurement of transverse force with polarization-maintaining side-hole fibers," in *Proc. SPIE*, Bellingham, WA, 2004, vol. 5576, pp. 355–361.
[14] T. Makoto, H. Tsunehito, and N. Yukiyasu, "Mode couplings due to external forces distributed along a polarization-maintaining fiber: An evaluation," *Appl. Opt.*, vol. 27, no. 1, pp. 166–173, 1988.

Mohammad Karimi (M'11) received the B. Sc. degree in physics from Urmia University, Urmia, Iran, in 1984, and the M.Sc. degree in physics from the Islamic University of Science and Technology (IUST), Tehran, Iran, 2000. He received the scholarship for Ph.D. degree at City University London, London, U.K., in 2009.

From 2000 to 2001, he was a Research Scientist at IUST in Optical Reaserch Centre, where he was involved in Holography Interferometry. From 2002 to 2009, he was a Lecturer and Research Scientist at Azad University, Oxford, U.K., where he was focused on diffusion in nanotubes. He is currently with Azad University and City University London.

Mr. Karimi is a member of the Institute of Physics and the International Society of Optics and Photonics.

Frederic Surre, biography not available at the time of publication.

Tong Sun received the B.Eng, M.Eng, and Dr.Eng degrees in mechanical engineering from the Department of Precision Instrumentation, Harbin Institute of Technology, Harbin, China, in 1990, 1993, and 1998, respectively. She received the D.Phil. degree from City University in applied physics in 1999.

She was an Assistant Professor at Nanyang Technological University in Singapore from year 2000 to 2001 before she re-joined City University in 2001 as a Lecturer. Subsequently she was promoted to a Senior Lecturer in 2003, a Reader in 2006 and a Professor in 2008 at City University, London. She has been leading a research team focused on developing a range of optical fibre sensors for a variety of industrial applications, including structural health monitoring, early fire detection, homeland security, process monitoring, food quality and automotive emission monitoring. She has been working closely with partners across disciplines from academia and industry, both in the UK and overseas. She has authored or co-authored some 130 scientific and technical papers.

Prof. Sun is a member of the Institute of Physics and of the Institution of Engineering and Technology and a Chartered Physicist and a Chartered Engineer in the U.K.

Kenneth T. V. Grattan received the B.Sc. degree (first-class hons.) in physics in 1974 and the Ph.D. in laser physics from Queen's University Belfast, and the D.Sc. degree from City University, London, U.K., in 1992 for his sensor work. His research involved the use of laser-probe techniques for measurements on potential new laser systems.

Following this, in 1978 he became a Research Fellow at Imperial College of Science and Technology, sponsored by the Rutherford Laboratory to work on advanced photolytic drivers for novel laser systems. This involved detailed measurements of the characteristics and properties of novel laser species and a range of materials involved in systems calibration. In 1983 he joined City University as a "new blood" Lecturer in Physics, being appointed Professor of Measurement and Instrumentation in 1991 and Head of the Department of Electrical, Electronic and Information Engineering. His research interests have expanded to include the use of fibre optic and optical systems in the measurement of a range of physical and chemical parameters. The work has been sponsored by a number of organizations including EPSRC, the EU, DERA, private industry and BTG, with whom a joint patent for systems for monitoring in the water industry is held. He is the author and co-author of over five hundred publications in major international journals and at conferences and is the co-editor (with Professor B T Meggitt) of a five volume topical series on Optical Fiber Sensor Technology. He is also Dean of the School of Informatics.

Prof. Grattan is extensively involved with the work of the professional bodies having been Chairman of the Science, Education and Technology of the Institution of Electrical Engineers, the Applied Optics Division of the Institute of Physics and he was President of the Institute of Measurement and Control during the year 2000. He was awarded the Callendar Medal of the Institute of Measurement and Control in 1992, and the Honeywell Prize for work published in the Institute's journal. Professor Grattan has been Deputy Editor of the *Journal Measurement Science and Technology* for several years and currently serves on the Editorial Board of several major journals in his field in the USA and Europe. In January 2001 he was appointed Editor of the IMEKO Journal "*Measurement*" and also serves on their General Council.

W. Margulis, biography not available at the time of publication.

P. Fonjallaz, biography not available at the time of publication.