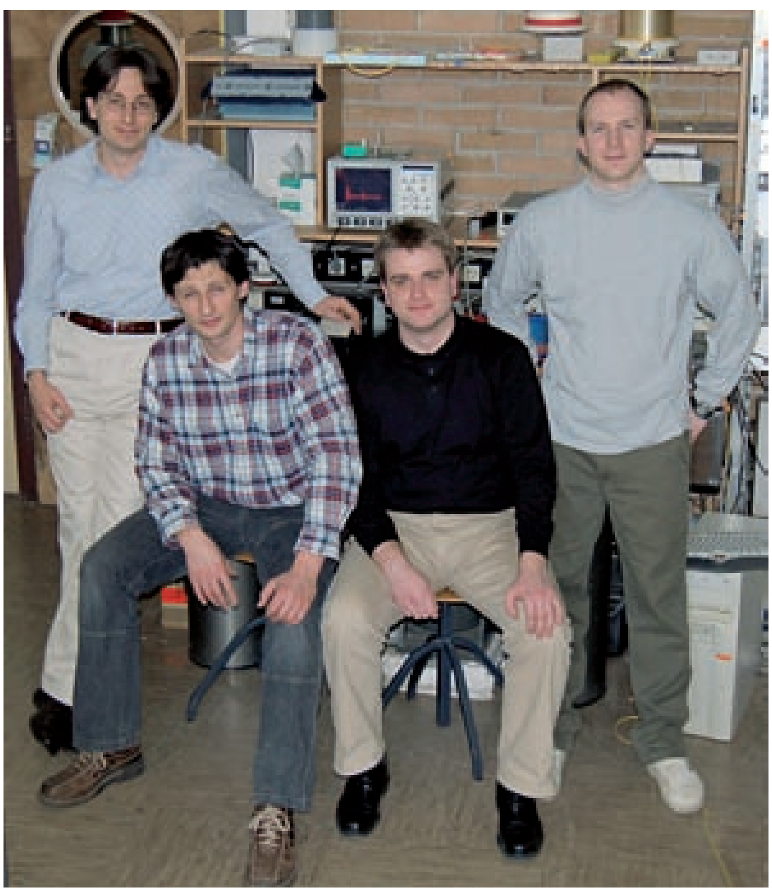
Fibre Optic Sensors: State-of-the-Art Technology Becomes an Emerging Industrial Reality

By Denis Đ onlagić

Introduction

Back in the seventies, only a few years after the invention of low-loss optical fibre, it became apparent that optical fibre can not only reliably transmit data, but also provide remarkable sensing capabilities. These sensing capabilities combined with unique properties offered by optical fibres, such as total dielectric design, complete immunity to electromagnetic interference, small size, capability for distributed sensing, explosion safety and good bio-compatibility attracted significant attention in both industry and academia. Over the past two decades, fibre optic sensors have evolved from first demonstrations to practical applications. For instance, a fibre gyroscope has penetrated firmly into the commercial aerospace market, demanding civil engineering applications have started to rely on data collected by distributed fibre optic sensors, and there is an emerging market for fibre optic biomedical devices, etc. For over a decade, fibre optic sensors have been the subject of intense research at the Laboratory for Electro-Optics and Sensor Systems (LEOSS) at the Faculty of Electrical Engineering and Computer Science at the University of Maribor. We have developed various innovative fibre optic sensing concepts that are advancing towards industrial products through collaboration with domestic and foreign industrial partners. This article briefly describes some of the Laboratory's recent activities and efforts towards industrialization of our research results.



The LEOSS team (left to the right): Assoc Prof Dr Denis Đ onlagić, head of LEOSS; Dr Edvard Cibula; Dipl Ing Matjaž Linec; and Dipl Ing Marko Kežmah

Faculty of Electrical Engineering and Computer Science

The Faculty of Electrical Engineering and Computer Science is part of the University of Maribor, Slovenia

Within the Faculty, academic studies and research are carried out at the following institutes:

- Institute for Automation
- Institute for Electronics
- Institute for Information Systems
- Institute for Mathematics and Physics
- Institute for Media Communications
- Institute for Power Engineering
- Institute for Computer Science
- Institute for Robotics
- Institute for Telecommunications.

Teaching and research activities at the Faculty are the province of 21 professors, 20 associate professors, 16 assistant professors, 11 senior lecturers, 74 teaching assistants, 43 researchers, and 76 technical and administrative staff members.
We offer two separate directions in our undergraduate study pro-

grammes, each leading to a different type of degree: academic and professional. Five undergraduate study programmes lead to academic degrees (Electrical Engineering, Computer and Information Science, Telecommunications, Media Communications and Industrial Engineering – Electrical Engineering option), while two additional study programmes lead to professionally oriented degrees (Electrical Engineering and Computer and Information Science). In the academic year 2005/2006 we enrolled 2,714 students, of whom 2,013 are full-time and 701 are part-time students.

Two postgraduate programmes are currently being offered: Electrical Engineering and Computer and Information Science. We have 317 postgraduate students for the academic year 2005/2006.

Research plays a vital role in the activities of the Faculty of Electrical Engineering and Computer Science. The Faculty offers a wide variety of different and developing fields, and as such, the only possible way to be successful is to build on the solid foundation and strength of the scientific research work of our professors, assistants and researchers. That is why one of the most important aspects of our current pedagogical activity is keeping abreast of the latest scientific advances in the world and being creative and collaborative in the development of our own research work.

The Faculty has also a strong tradition of applied research for industry. On average, about 100 industrial projects are realised at the Faculty each year. Students are actively involved in many of these projects, which gives them the necessary experience for success in their future careers.

Other evidence of the Faculty's stimulating environment is also the record of excellent results in various student competitions. In 2005 a group of 4 computer science students won the MS Imagine Cup for Eastern Europe (the competition took place in Greece) and ranked 6th at a world competition in Japan.

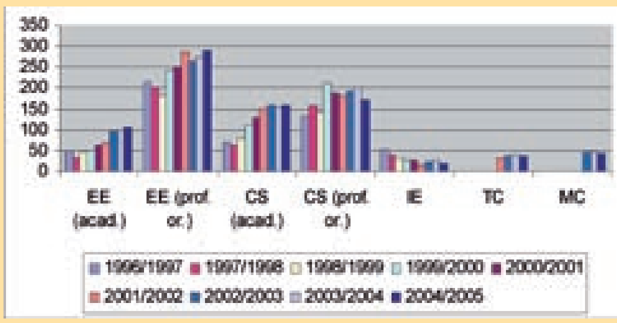
At our Faculty we have also participated in a variety of international projects and have published important research findings in the most prestigious scientific publications. Our work has been well recognized by foreign scientists, and many of our ideas are protected by international patents. Our researchers have also been educated at various renowned foreign universities and institutes.

Our 7 programme units, registered with the Slovenian Research Agency, are Telematics, Control of Electromechanical Systems, Mechatronic Systems, Advanced Methods of Interaction in Telecommunications, Information Systems, Applied Electromagnetics and Computer Systems, and Methodologies and Intelligent Services. The work in these programme units represents the basis of fundamental research at our faculty and includes the majority of our researchers.

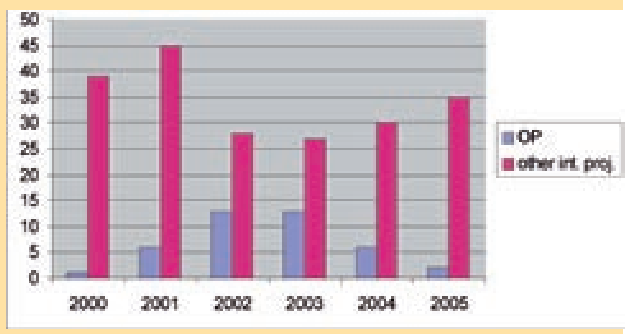
The Faculty of Electrical Engineering and Computer Science has been actively involved in many bilateral R&D projects with numerous countries throughout the world, especially in Europe, with participation in many EU projects and programmes (FP5, FP6 and other EU projects).

Dean Prof Dr Igor Tičar

Number of full-time students in the 1st year



International projects



National projects

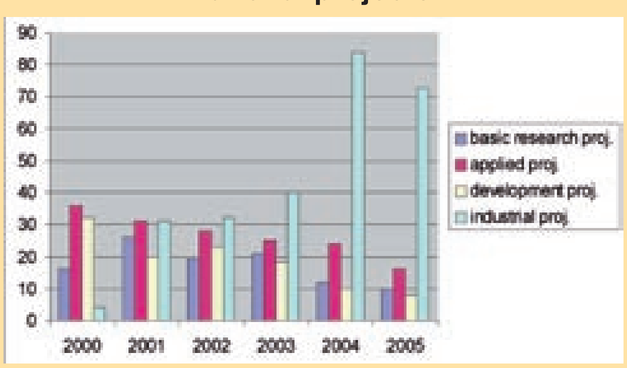


Fig 1: Live road installation of an experimental fibre optic axle detector near Sp. Polskava.

Putting fibre optic sensor on duty in extreme environments: Vehicle axle detectors for roadways

Increasing road traffic requires a more efficient system for the monitoring and intelligent control of road management systems. Vehicle axle detectors are sensor devices that are useful in a variety of transportation applications ranging from traffic monitoring, automatic tooling, automatic vehicle classification, etc. Current vehicle axle detectors mostly rely on piezoelectric arrays, which have proved to be expensive, difficult to install and not sufficiently robust to operate in extremely harsh environments such as the upper asphalt layer of road surfaces. In 1999, Mikrobit d.o.o., a small Slovenian enterprise located in Murska Sobota, and LEOSS began to developed a reliable vehicle axle detector for roadways. After preliminary testing we started a formal three-year project in 2003 that resulted in a robust, cost-effective and easy way to install vehicle axle detectors. The prototype is now being developed into a commercial product.

Optical fibre has two important properties that make it a likely candidate for the design of vehicle axle sensors: it is made of fused silica, which is one of the most elastic inorganic materials known and which allows for the design of long-gauge sensors. The first property allows installation of the fibre into the upper layer of road asphalt, where shifts and drifts of the layer geometry over the expected lifetime of the sensors can be expected. Second, the axle detector is in essence a long-gauge sensor, i.e. the length of the sensitive area can span the entire road lane to provide reliable detection of vehicle axles.

We investigated a variety of different approaches. For this purpose we established a test polygon in a section of unused freeway in Hoče near Maribor. Various concepts and sensor designs were tested, ranging from Michelson and Sagnac interferometers, microbend and some other fibre sensing concepts. Several designs were then installed in live roadways. A few of those designs were developed into practical prototypes. Figure 1 shows the installation of a fibre optic axle detector in a live roadway located in Sp. Polskava. Figure 2 shows the typical sensor response during passage of a heavy vehicle. Further development has been carried out to improve cost effectiveness and sensor lifespan. Part of this work was published and received an IEEE Vehicular Technology Society Award for the best land transportation paper published in 2003.

Fig. 2: Typical sensor response to passage of a 5-axle truck at Lipovci near Murska Sobota.

Micromachining the fibre tip: A method for creating cost-effective, ultra-miniature, all-silica fibre sensors

Intensive research efforts have been directed into the development of advanced micro-opto-electromechanical systems (MOEMS). At LEOSS, we developed a special method that allows for quick and cost-effective micromachining of the fibre tip. The method is suitable for low-cost mass production; it does not require lithographic masks and can be performed in large batches. Essentially, the technique is based on the fact that the doped silica glass etching rate in HF or buffered HF depends on the local dopand concentrations. Fibre with an appropriate dopand distribution is produced by one of the well-established fibre manufacturing techniques (such as MCVD). The fibre is then cleaved and appropriately etched (in batches when desired). Typical examples of structures created on the tip of the fibre are shown in Figure 3.

By splicing these structures with ordinary fibres or one to another, a variety of interesting optical sensors or other miniature devices can be created. Figure 4 shows examples of a microlens and an in-fibre strain sensor. The microlens is attached to the tip of the fibre and measures about 65 µm in diameter. The strain sensor measures only 125 µm in diameter. Figure 4 also provides a comparison of strain sensor response to the reference conventional resistive strain gauge.

Further development of this technology allowed for design and production of one of the smallest pressure sensors ever made, as shown in Figure 5. The sensor is only 125 µm in diameter and features an all-silica design. Since the sensor is fully fusion spliced and does not contain any adhesives or bonding materials, it therefore exhibits a broad temperature range (more than 500 °C) and excellent temperature stability.

Fig. 3: Various structures formed at the tip of an optical fibre.

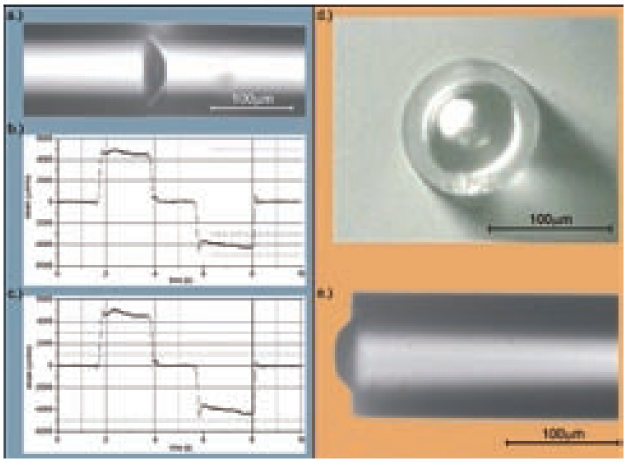


Fig. 4: a) In-fibre strain sensor; b) string gauge response; c) fibre strain sensor response; d) and e) microlens at the tip of an optical fibre.

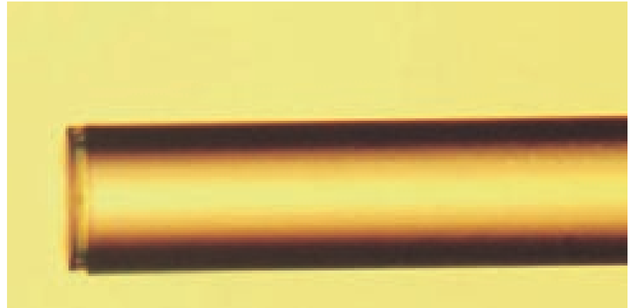


Fig. 5: Miniature all silica pressure sensor.

A special technique for production of a very thin diaphragm was developed that uses on-line control of the diaphragm thickness during the manufacturing process. This allowed us to achieve the high sensitivity that makes this sensor suitable for measurements of low pressures such as those encountered in biomedical applications. In 2005 LEOSS established long-term collaboration with one of the major fibre optic sensor suppliers, FISO Technologies Inc., Canada, to further develop and commercialize this technology. In 2005 LEOSS and FISO jointly filed three international patent applications.

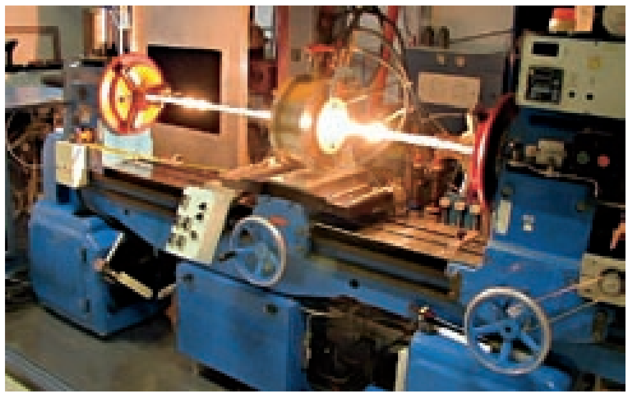


Fig. 6: Specialty fibre production at Optacore.

Specialty optical fibres: A way to make optical sensing technology more cost effective

LEOSS has been actively involved in the research and development of specialty optical fibres. This effort started in 1996 when we developed the first special fibres for distributed sensing. This work was done in collaboration with Fotona d.d. Unfortunately, Fotona discontinued fibre production a few years later; however, LEOSS actively continued specialty fibre research work that resulted in special fibres that are extremely resistant to bend-induced losses. Some of this work was later acquired by Corning Inc., the largest optical fibre manufacturer in the world. Recently, specialty fibre production was re-established in Slovenia. Figure 7 shows the typical performance of the patented bend resistive fibre system compared to conventional and other special bend restive fibre. LEOSS closely collaborates with Optacore d.o.o., a small enterprise dedicated to MCVD fibre manufacturing technology. In collaboration with Optacore and FISO Technologies we recently developed a variety of specialty fibres that further advanced our MOEMS sensors. The fibres developed allow for a more cost-effective sensor production process. Other current activities in fibre design and manufacturing are directed towards the development of new optical fibres for distributed sensing, high temperature fibres, special bend sensitive/insensitive fibre profiles and fibres for specialty telecommunications applications.

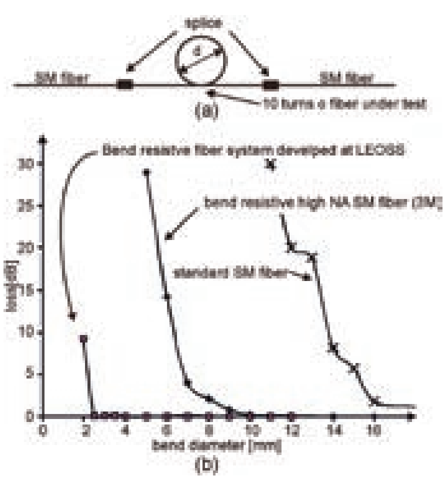


Fig. 7: Bend resistive optical fibre: a comparison of by LEOSS developed system to standard single-mode fibre and special bend resistive fibre produced by 3M.

Searching for further industrial opportunities for optical fibre sensors

While conducting basic research to improve the understanding of waveguide properties of optical fibre sensing devices, LEOSS continues its state-of-the-art industrial research. We have been researching and developing new cost-effective industrial sensing concepts and applications. An example of such recent work is shown in Figure 8, where we were looking into the possibilities of introducing fibre sensing technology into cost-driven applications such as the automotive sensor sector. We developed a special quasi-distributed anti-squeeze sensor that prevents accidental closure of a car window when an object (like a human hand) is in the way, as required by new EU car safety directives. The sensor we developed relies on the application of plastic optical fibre and opto-electronic components that are already in use in the automotive market.

Fig. 8: Low-cost distributed fibre optic anti-squeeze sensors: effective protection against injuries caused by electric car windows.