OPTICALLY POWERED FIBER OPTIC SENSORS

[*]Ján TURÁN, [*]Ľuboš OVSENÍK, [**]Ján TURÁN, Jr.
[*]Department of Electronics and Multimedia Communications, Faculty of Electrical Engineering and Informatics,
Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, tel. 055/602 2943, E-mail: jan.turan@tuke.sk
[**]3D People gmbh, Kaiser Passage 6, D-72766 Reutlingen, Germany

SUMMARY

In this paper a review of optically powered fiber optic sensors is presented. The basic properties, key elements (photovoltaic power converters) and possible generalized sensory system architectures are discussed. A brief outlook on recent developments and industrial applications is presented.

Keywords: *fiber optic sensor, optically powered fiber optic sensor, optical fiber power-delivery system*

1. INDRODUCTION

Optically **P**owered **F**iber **O**ptic **S**ensors (**OPFOS**) combine the advantages of fiber optic and microelectronic technologies [1-12]. Fiber optic and partially **F**iber **O**ptic **S**ensors (**FOS**) offer advantages that are significant in the field of variety of industrial, military and medical applications. **FOS** are immune to **e**lectro**m**agnetic **i**nterference (**EMI**), they have low thermal and mechanical inertia, and they are often more sensitive that other sensors [8,9,11,12]. **FOS** are advantageous in electrically noisy, corrosive, explosive, high-voltage, high-current, or high-temperature environments. In addition the use of fiber optic telemetry systems exhibit some advantages of fiber optic communication systems, providing telemetry over long distances and the possibility of control, interrogate or multiplexing many sensors or sensors for different measured into a single system [1,2,3,13]. Microelectronics and partially microelectronic sensors have many advantages too [1,2,3]. The most important advantages are the simplicity of implementation (well understood techniques), simple construction, easy and low powering, low cost, high accuracy (with possible embedded data processing, intelligence), the possibility of miniaturization and integration. The output signal is easy to evaluate (frequency, digital outputs). The output information can be simply evaluated by microcomputer or signal processor. On the other hand the main disadvantage of pure microelectronic sensory systems is caused by electrical transmission of information and powering, i.e. they are not tolerant to **EMI** and the transmission rate is very low, too. They also cannot be used in explosive, corrosive, high-voltage or high-current environment. That is the reason why such a systems cannot be used for sensing in gasoline, mining or electrical power industry.

OPFOS can solve these disadvantages [1-12], by hybridization of fiber optic and microelectronic technologies. The basic principle of this sensory systems is using optical fibers for transmission of control and measurement information, as well as for optically powering of remote microelectronic sensory system [3,5,8,9,10,12]. **OPFOS** join the advantages of fiber optics and microelectronics sensors (i.e. high sensitivity, flexibility and low cost of electronic sensors with galvanic insulation between two ends (sensory and control), lack of **EMI**, no need of batteries or main socket for powering, saving the weight, etc.). These properties make it possible to use **OPFOS** in applications such as measurement of high-voltage, high-current, temperature, pressure, humidity, gas monitoring, etc. in various industrial, medical and military applications in high-voltage, hazardous, explosive, noisy, etc. environment [1-45].

In this paper a review of **OPFOS** is presented. First the basic properties and the key elements of **OPFOS** are taking into account. Then **OPFOS** generalized architectures are discussed. Next the various industrial applications are presented. The paper is closed with short outlook on future trends.

2. BASIC PROPERTIES AND KEY ELEMENTS

Basic structure of a general **OPFOS** system is on Fig.1. The system consists from three parts: **L**ocal **M**odule (**LM**), **R**emote **M**odule (**RM**) and **L**ow-**P**ower **M**icroelectronic **S**ensory **S**ystem (**L-PMSS**).

From the functional point of view the **OPFOS** system (Fig. 1) may be divided in three sub-systems:
1. **L**ow-**P**ower **M**icroelectronic **S**ensory **S**ystem uses conventional electronics for the measurement of desired physical parameters (temperature, pressure, voltage, current, high-frequency electromagnetic field, humidity, strange, position, angle, etc.). The power consumption of such a sensory system depends on the IC technology (GaAs) used, sampling rate (< 1kHz, up to several 100 kHz) in a wide range (< 100μW up to 25mW) [1-46].
2. **F**iber **O**ptic **D**ata / **C**ontrol **T**ransmission **S**ystem is a dedicated fiber optic digital transmission system used for transmission of measured data and control information between Remote and Local Module. In Remote Module two main parts of this system are indicated. Low-Power Microcontroller is used for data format conversion (ADC), interrogation and multiplexing of the sensors. Low-Power Optical

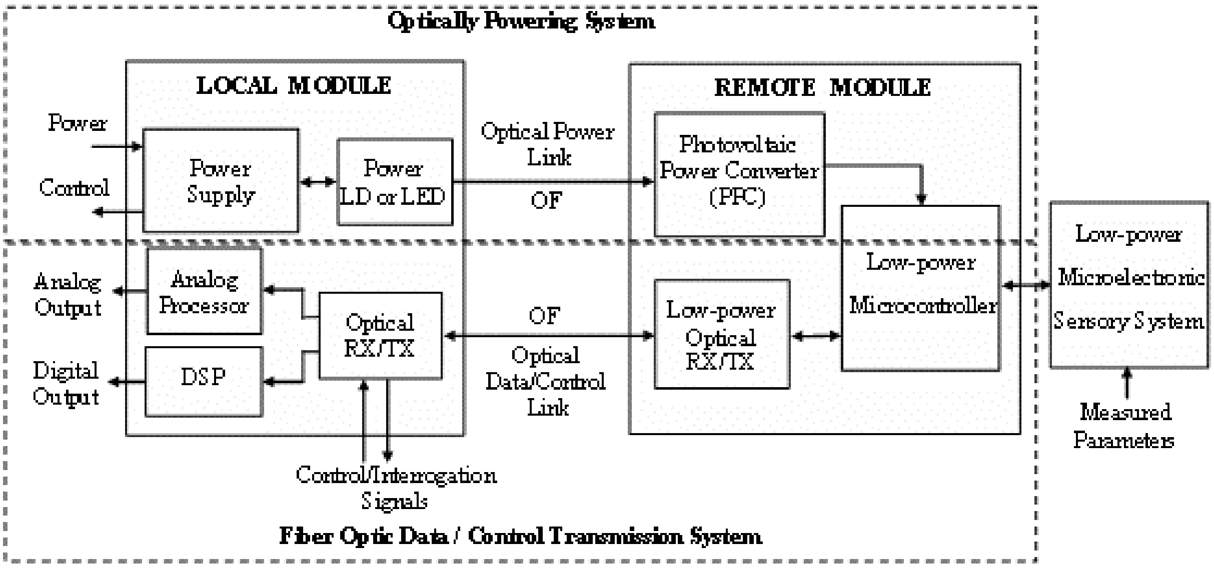
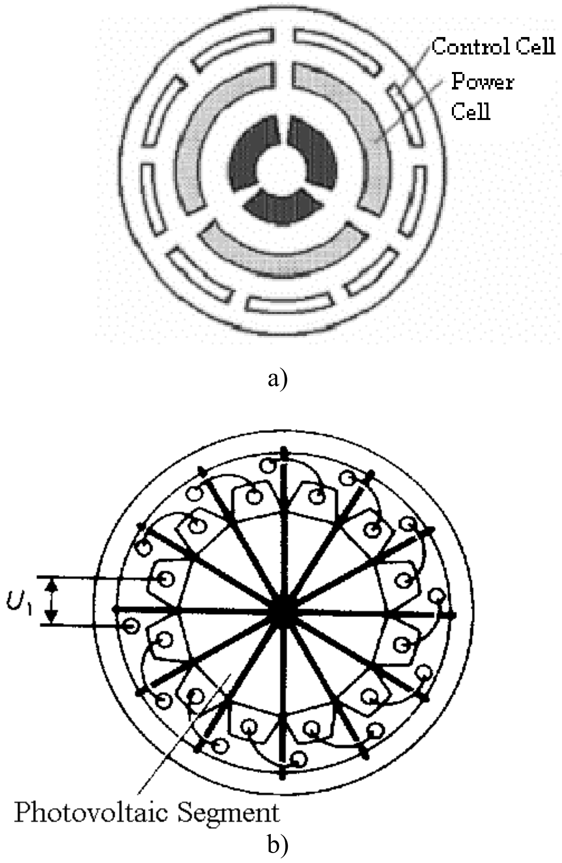


Fig. 1 Nativity Symbols used in experiments

Receiver / **T**ransmitter (**RX/TX**) provide the optical sending and receiving of measurement and control data (LD, LED and PIN, APD key elements, with trans-impedance preamplifier are often used). As **O**ptical **F**iber (**OF**) low-cost **M**ulti **M**ode (**MM**) optical fibers are used. There is possibility using several multiplexing techniques in electronic (frequency, time, PWM, etc.) or optical (WDM) domain [1,2,3,13,14]. Local Module houses similar Optical RX/TX, Analog and **D**igital **S**ignal **P**rocessor (**DSP**). The analog output channel is usually provided with a bandwidth up to 16kHz (sample rate 33.3 kSample/s, 12 bit resolution and output current 4 - 20mA). Digital output is designed according to normalized measurement interface protocols.

3. **O**ptically **P**owering **S**ystem provides driving electrical power for the Remote Module. The light power for the system is delivered by a **L**aser **D**iode (**LD**) (in some simple and short distance applications LED, special small incandescent lamps or other miniature laser sources can be also used) housed in a passively cooled enclosure placed in Local Module (a controlled environment at ground potencial). AlGaAs LD emitting light at wavelength λ=850nm, and output optical power up to P_o=500mW are commercially available. For optical power transfer wide core (200μm) SI MM **OF** is used typical attenuation d_{fc}=2dB.km^{-1}. For simple systems other type low-cost **OF** and fiber optical bundles may be also used. The operation distance is up to several km depending on the power consumption of the Remote Module and **P**hotovoltaic **P**ower **C**onvert (**PPC**) used. The most critical and enabling device in the **OPFOS** is the **PPC**, which is essentially a specially developed solar cell (Fig. 2) divided into sections with radial symmetry (light radiated from the **OF** output have it self radial symmetry). In previous developments there was low power ~100μW, 10nW and efficiency of the **O**ptically **P**owering **S**ystem (**OPS**) [5,10,12]. New research developments based on the use new materials (InGa(Al)As **LD** and GaAs based **PPC**) with Optically Powering System optimization increase the power level up-to 200mW (with 27% efficiency) {15,16,17,18]. Nowadays the



a)

b)

Fig. 2 PPC array O/E converter

wide scale of several type of optimized Optically Powering System can be commercially available (typical **LD** power is set at 500mW and **PPC** capable of converting over 40% of incident light in the wavelength rang λ=780-820nm into output electrical power at 6V)[19] in operating temperature range (- 40 to + 70 ºC). **PPC** optimized for the wavelength range λ=1300-1500nm designed to convert light to electrical power up-to 4V, with output power from a few mW to 100mW have been also commercially available.

3. GENERALIZED ARCHITECTURES

Possible architectures of **OPFOS** can be classified according to the number of **OF** used [20,21].

3.1. OPFOS with three OF

The **OPFOS** (Fig. 3) consists of three sections:
1. Decoding and Control Section: realized by Local Module, Control PC and Analog or Digital I/O circuits. Local Module consists from Powering Module, Control Transmission Module, Measuring Receiver Module, Operative Microcontroller and Power Supply.
2. Transmission Section: realized with fiber optic power delivery system (consist from a high power **LD**), **OF PPC**, fiber optic control signal transmission system and fiber optic measuring information transmission system.
3. Sensor Section: realized with Remote Module and Sensory Modules with Sensors. Remote Module consists from: Optical Power Supply, Control Receiver Module, Measuring Transmission Module and Sensor Microcontroller.

The two optical data transmission lines (Fig. 3) incorporated into the **OPFOS** architecture are entitled to delivery control and measuring signals between Local and Remote Module. The control signals are usually digital, but PWM technology may be also used. The measuring signal (data) delivery systems are in simple systems often (to compatibility with classical technology) an analog channel. The flexibility of digital measuring signal (data) delivery system is more adjustable to various kinds of commercially available components and microelectronics sensors with frequency output. As **OF** commercially available cheap MM-SI or MM-GI **OF** are used.

3.2. OPFOS with two OF

Using commercially available multiplexing and demultiplexing devices from data transmission WDM technology it is possible to integrate the control and measuring signal (data) transmission systems to one **OF** (Fig. 4). The advantage of such a system may be in decreasing complexity.

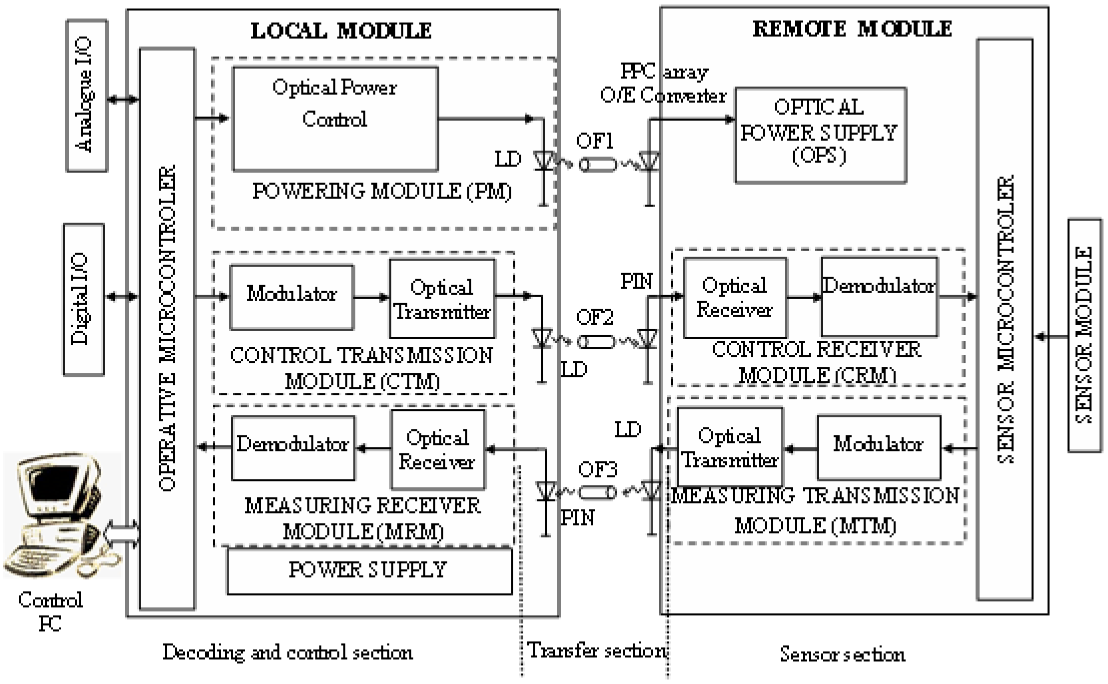


Fig. 3 OPFOS with three OF

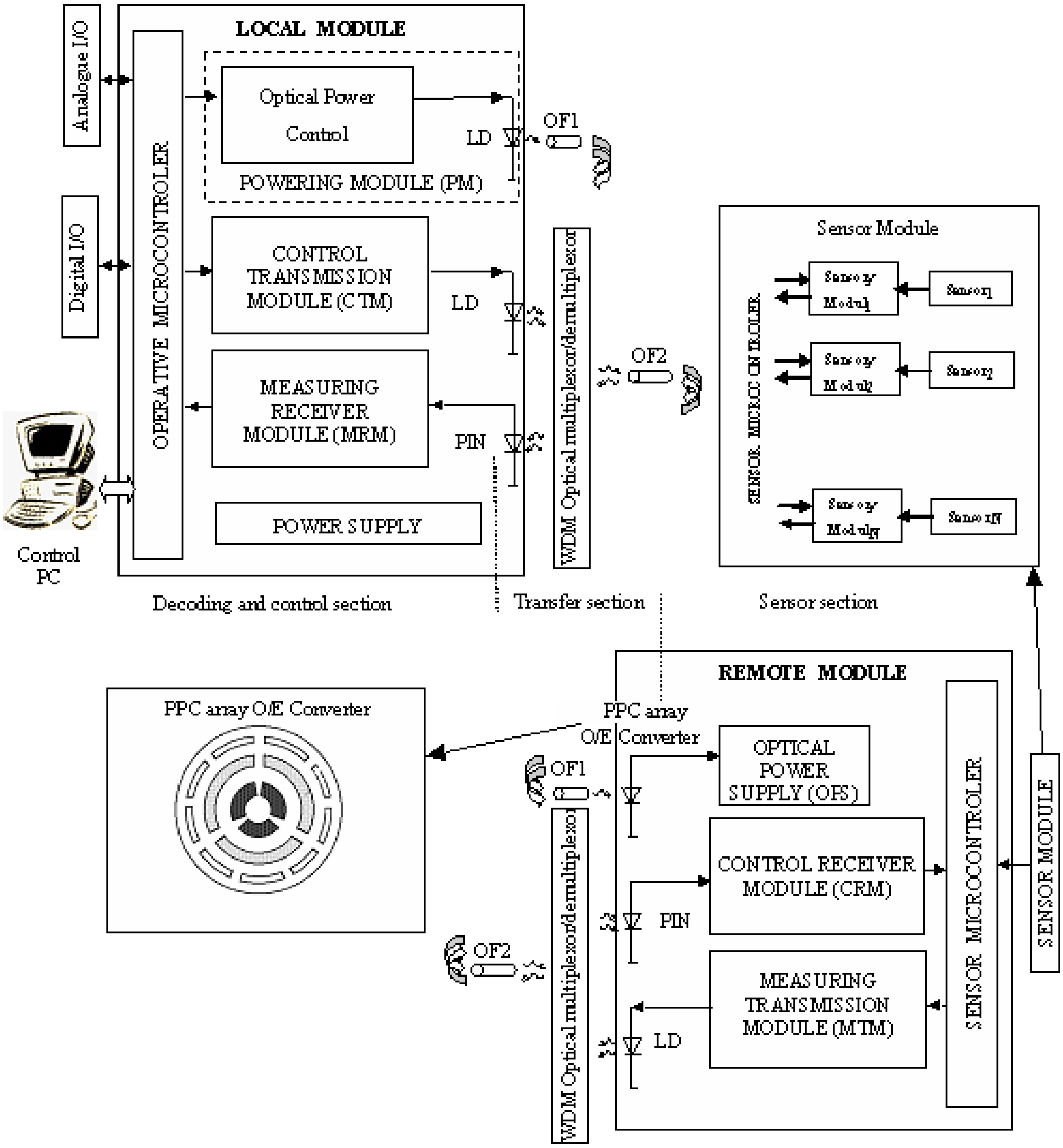


Fig. 4 OPFOS with two OF

3.3. OPFOS with one OF

Using appropriate WDM multiplexing and demultiplexing technology to accommodate also the power delivery system to one **OF** with control and measuring signals transmission systems we obtain more compact solution (Fig.5), however with the advantages to such a system (decreasing complexity) there may be a disadvantage of decreasing power delivery efficiency through to influence of optical attenuation in used WDM multiplexing /demultiplexing devices and coupling loss.

4. INDUSTRIAL APPLICATIONS

In open scientific literature several **OPFOS** have been described at the level of basic technical design and tests (also some field applications). So far, tests and operation of **OPFOS** indicate their usefulness for monitoring, control and metering in various industrial applications [1-46]:

<u>1. Temperature Sensors:</u> [22-27,46] various designs cover the range over -50°C to +130°C they can operate in high humidity and voltage levels (up to 750kV), or in presence of high frequency electromagnetic fields, and free of ground loops. The main applications are in electric power stations, high current transformer monitoring, medicine (tiny sized pigtail sensor; heeds allow direct penetration to internal organs including blood vessels) and other industrial applications.

<u>2. **H**igh-**v**oltage and **H**igh-**c**urrent Sensors</u> [19,28,29,46] according to excellent isolation and resistance to **EMI** are dedicated to use in high

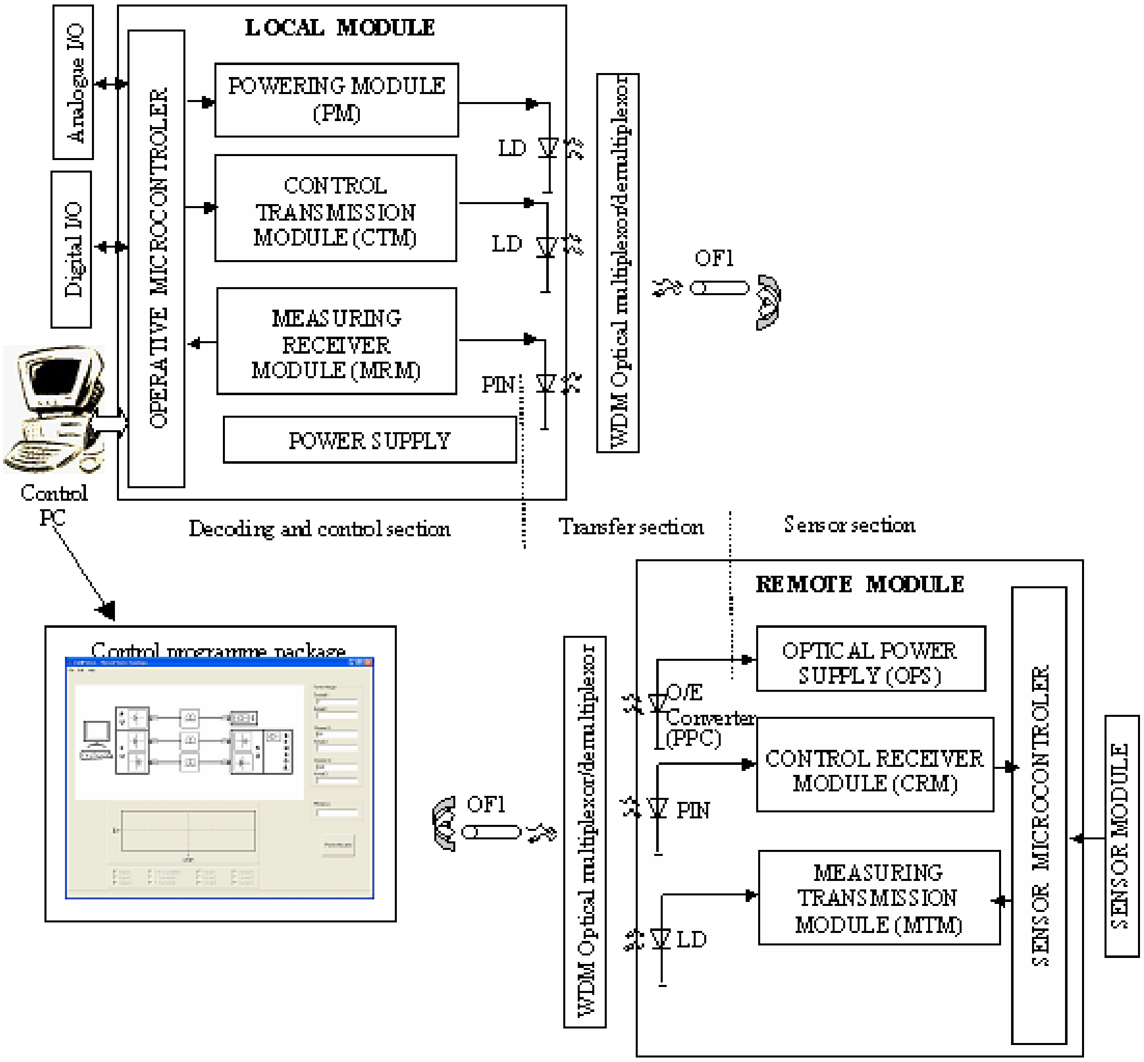


Fig. 5 OPFOS with one OF

voltage technology and power electronics to create a new **H**ybrid **O**ptical **F**iber **C**urrent **T**ransformer (**HOFCT**) to replace conventional accurate current transformers and Rogowski coils.

3. Sensors of Mechanical Variables (position, angle, velocity strange, pressure, force, vibrations, proximity, etc.) [19,30-37] are according to the good electrical isolation, immunity to noise, **EMI** and harsh environment used in control engineering, mechatronics, electrical encoders–tachometers, machine control, power electronics (rotating machinery), civil engineering (non–destructive evaluation of structural systems buildings, bridges), avionic and aerospace (position, rotation control), robotics, etc.

4. Oil Tank Liquid Level Sensors [38-40] give a accurate and safe solution in petrochemical industry for monitoring fuel tanks, fuel leakage, etc.

5. High Frequency Electromagnetic Field Sensors (**E** and **H**) [41-43] demonstrate high spatial resolution and high sensitivity for many technical and medical applications, such as **e**lectro**m**agnetic **c**ompativity (**EMC**) and antenna measurements (in wide frequency range from 10MHz up to 6GHz) with sensitivity of 0.1V/m and very small dimensions of sensor head (several mm).

6. Remote Gas and Coal Mines Monitoring Sensors [44,45] use immunity of all-optical networks to **EMI**, safe applications in explosive environments (CH_4), electrical isolation for remote monitoring of several microelectronics toxic gas sensors (NO_2, SO_2, CO, etc.) in mines, petrochemical industry, environmental control, etc.

7. Home Automation Sensors (temperature, humidity, pressure, illumination and obtrusive detection) [15,17] using low-consumption simple electronic IC have been demonstrated.

5. OUTLOOK ON THE FUTURE TRENDS

The benefits of **OPFOS** are now evident. Key elements of such a systems (high-power LD and efficient PPC) are now commercially available and the price of optimized **O**ptical **P**ower **L**inks (**OPL**) is moderate and is expected to decrease in the near future. The available wide range of fiber optic communication solutions and relatively cheap low-power microelectronic sensors of different measured promote elegant and sophisticated solutions for many industrial applications. At presented days the main application areas of **OPFOS** are in: high voltage technology, medicine, and power electronics, military, avionic and aerospace systems. In the near future the applications of **OPFOS** and more generally the fiber optically powering technology will be spread in the wide range of commertial applications in: **EMC**, nanotechnology, communications, robotics, intelligent manufacturing systems, automotive industry, surveillance system, etc.

6. CONCLUSION

The paper presents a short review of **OPFOS** technology. The basic properties and key elements of **OPFOS** are discussed. Possible generalized sensory system architectures are introduced. A brief outlook on recent developments and industrial applications indicate that the **OPFOS** technology is able to provide simple and economic solutions for monitoring, control and metering problems which are immune to electromagnetic interference, have low thermal and mechanical inertia, are immune to electrical noise, corrosive, explosive, high-voltage, high-current or high-temperature environment and are often more sensitive that other sensors.

ACKNOWLEDGEMENTS

This work was supported from the grant to the projects VEGA grant No. 1/0381/03 and Inst. Sci. Project of FEI TU Košice.

REFERENCES

[1] Culshav, B. – Dakin, J.: Optical Fiber Sensors. Vol.3 and Vol.4, Artech House, Norwood, 1997.

[2] Turán, J. – Petrík, S.: Optical Fiber Sensors. Alfa, Bratislava, Slovakia, 1990.

[3] UDD, E.: Fiber Optic Sensors – an Introduction for Engineers and Scientists. J. Wiley, New York, 1991.

[4] Neiuwkoop, E. – Kapsenberg, T. – Steenvoorden, G. K. – Bruinsma, A. J. A.: Optically Powered Sensor System Using Conventional Electrical Sensors. Proc. SPIE, Vol.1511, 1991, 255-263.

[5] Culshaw, B.: Optical Fiber Sensing and Signal Processing. Peter Peregrinus, London, 1984.

[6] Bjork, P. – Lenz, J. – Fujiwara, K.: Optically Powered Sensors. Optical Fiber Sensors, Washington, USA, Vol.2, 1988, 336-339.

[7] Lenz, J. – Bjork, P.: Optically Powered Sensors: a System Approach to Fiber Optic Sensors. Proc. SPIE, Vol.961, 1988, 8-25.

[8] Turán, J. – Petrík, S.: Optické vláknové sensory (Optical Fiber Sensors). Alfa, Bratislava, 1990.

[9] Ross, J. N.: Optical Power for Sensor Interface. Measurement Sci. Technol., No.3, 1992, 651-655.

[10] Gros, W.: Fiber – Optic Hybrid Sensors with Optically Powered Supply. Siemens Forschungs – und Entwickungsbericht, B.d. 17, 1988.

[11] Johnson, M.: Self – Powered Fiber Optical Sensors. Proc. SPIE, Vol.1011, 1988, 203-207.

[12] Turán, J.: Fiber Optic Sensors in Technical Practice. Journal on Communications, Vol.XLII, 1991, 12-16.

[13] Turán, J. – Mihok, M.: Multiplex in Optically Powered Sensor Telemetry System. . Journal of El. Engineering, Vol.49, No.1-2, 1998, 37-40.

[14] Turán, J. – Probstner, R.: Principles of WDM Optical Sensor Systems and Their Design. Journal of El. Engineering, Vol.47, No.9-10, 1996, 242-247.

[15] Pena,R.-Algora,C.-Matias,I.R.-Lopez-Amo,M.: Fiber-Based 205mW (27% Efficiency) Power-Delivery System for an All-Fiber Network with Optoelectronic Sensor Unit. Applied Optics, Vol.38, No.12, 1999, 2463-2466.

[16] Algora, C. – Diaz, V.: Design and Optimization of Very High Power Density Monochromatic GaAs Photovoltaic Cells. IEEE Trans. El. Dev., Vol.45, 1998, 2047-2054.

[17] Pena, R. – Matias, I. R. – Algora, C. – Lopez–Amo, M.: Optical Fiber Based Power Delivery System for Optoelectronic Sensor Modules. LEOS'98, Piscataway, USA, Vol.2, 1998, 75-76.

[18] Landry, M. J. – Rupert, J. W. – Mittas, A.: Photovoltaic Array GaAs Cells Response Driven by High Power Laser Diodes. Sol. Cells, Vol.29, 1990, 283-301.

[19] Photonic Power System:
www. photopnicpower.com

[20] Turán, J. – Ovseník, Ľ. – Adam, T.: Zapojenia opticky napájaného senzorového systému. Optické Komunikace OK 2004, Praha, Czech republic, October 21-22, 2004, 127-136.

[21] Turán, J. – Ovseník, Ľ. – Adam, T. – Amadou, K.: Optically Powered Fiber Optic Sensor System Architectures. MicroCAD, Miskolc, Hungary, 2005 (in Press).

[22] Datta, P. – Matias, I. R. – Aramburn, C. – Bakas, A. – Oton, J. M. – Lopez – Amo, M.: Tapered Optical-Fiber Temperature Sensor. Microwave Opt. Technol. Lett., Vol.11, 1996, 93-95.

[23] Werthen, J. G. – Anderson, A. G.: Optically Powered Sensors and Transmitters for Industrial Applications. Proc. Sensors Expo, Peterborough, USA, 1996, 207-2014.

[24] Travica, S. – Tomic, M. – Aleksic, O. – Sreckovic, M. – Pantetic, S.: Optically Powered Fiber – Optic Temperature Thick Film NTC Sensor. LASERS'98, McLean, USA, 1999, 562-567.

[25] Werthen, J. G. – Anderson, A. G. – Wu, T. C.: Optically Powered Sensors: Are they Really Fiber Optic Sensors? Proc. SPIE, Vol.2872, 1996, 131-138.

[26] Sai, Y.: Optimization of Optically Powered

sensors. IECON'91, Kobe, Japan, Vol.3, 1991, 2439-2443.

[27] Spooner, R. C. – Jones, B. E. – Ohba, R.: Pulse Modulated Optical Fiber Quartz Temperature Sensor. 4th ISOO-87, Appl. Sci. and Eng., 1987, 25-27.

[28] Weiss, S. – Werthen, J. G. – Anderson: Optically Powered Sensor Technology. ISA'97, Orlando, USA, May 4-8, 1997.

[29] Quinteng, S. – Yincheng, Q. – Zhiynan, X. – Bo, Ch. – Yihan, Y.: Hybrid Optical Fiber Current Transformer Based on DSP and Ultra–low–power Consumption Micro-controller. Power Conference 2002, Piscataway, USA, Vol.2, 2002, 1137-1147.

[30] Feng, M. Q.: An Experimental Study of an Electro-Optical Displacement Sensor. Nondestructive Testing and Evaluation, Vol.13, No.1, 1996, 5-14.

[31] Yutian, W. – Yudong, H. – Jinshan, S. – Xiaogun, Z.: An Optically-Powered Optical Fiber Pressure Sensor of Diffused Silicon. Sensor 95, Wunstorf – Steinhude, Germany, 1995, 63-66.

[32] Spillman, W. B. Jr. – Crowne,D.H.-Woodward, D. W.: Optically Powered and Interrogated Rotary Position Sensor for Aircraft Engine Control Applications. Optics and Lasers in Engineering, Vol.16, No.2-3, 1992, 105-118.

[33] Glomb, W. L. Jr.: Fiber-Optic Position Transducers for Aircraft Controls. Proc. SPIE, Vol.1367, 1991, 162-164.

[34] Grattan, K. T. V. – Palmer, A. W. –Samaan, N. D. – Abdullah, F.: Mathematical Analysis of Optically Powered Quartz Resonator Structures in Sensor Applications. Journal of Lightwave Technology, Vol.7, No.1, 1989, 202-208.

[35] Trisno, Y. – Wobschall, D.: Optically Powered Fiber Optic Echo Transmitter. SENSORS EXPO, Peterborough, USA, 1987, 245-251.

[36] Schweizer, P. – Neveux, L. – Ostrowsky, D.B.: Optical Fiber Powered Pressure Sensor. Proc. SPIE, Vol.798, 1987, 82-85.

[37] Spillman, B. – Crowne, D. H.: Optically Powered and Interrogated Rotary Position Sensor for Aircraft Engine Control Applications. Opt. Laser Eng., Vol.16, 1992, 105-118.

[38] Wany, Y. – Cui, J.: Micro-Power Consumption Handy Oil Tank Liquid Level Detection System with Optical Fiber Link. Proc. SPIE, Vol.4920, 2002, 247-250.

[39] Pember, S. J. – France, C. M. – Jones, B. E.: A Multiplexed Network of Optically Powered, Addressed and Interrogated Hybrid Resonant Sensors. Sensors and Actuators, Vol.46-47, 1995, 474-477.

[40] Litian, W. – Yutian, W. – Jinshan, S. – Longijang, Z.: Optically Powered Hydrostatic Tank Gauging System with Optical Fiber Link. Proc. SPIE, Vol.3555, 1998, 277-284.

[41] Heinzelmann, R. – Stohr, A. – Kalinowski, D. – Joger, D.: Miniaturized Fiber Coupled RF E-field Sensor with High Sensitivity. LEOS2000, Piscataway, USA, Vol.2, 2000, 525-526.

[42] Stohr, A. – Et. Al.: Optically Powered Integrated Optical E-field Sensor. 12th International Conference on Optical Fiber Sensors, Washington, USA, 1997, 261-264.

[43] Petrík, S. – Turán, J.: An Analysis of Fiber Optic Sensor of High Frequency Magnetic Field. Journal of El. Engineering, Vol.41, No.2, 1990, 84-96.

[44] Zientkiewicz, J. K.: All-optical Fibre Networks for Coal Mines. Proc. SPIE, Vol.734, 87, 47-54.

[45] Dubaniewicz, T. H. Jr. – Chilton, J. E.: Optically Powered Remote Gas Monitor. www.cdc.gov/ niosh/mining/pubs/pdfs/ri9558.pdf

[46] Tamura, T. – Togava, T. – Oberg, P. A.: Fiber-Optic Power-Feed System for Temperature Measurement. Sensor and Actuators, Vol.34, 1992, 155-159.

BIOGRAPHY

Ján Turán (Prof, Ing, RNDr, DrSc) was born in Šahy, Slovakia. He received Ing (MSc) degree in physical engineering with honours from the Czech Technical University, Prague, Czech Republic, in 1974, and RNDr (MSc) degree in experimental physics with honours from Charles University, Prague, Czech Republic, in 1980. He received a CSc (PhD) and DrSc degrees in radioelectronics from University of Technology, Košice, Slovakia, in 1983, and 1992, respectively. Since March 1979, he has been at the University of Technology, Košice as Professor for electronics and information technology. His research interests include digital signal processing and fiber optics, communication and sensing.

Ľuboš Ovseník (Ing, PhD.) was born in Považská Bystrica, Slovakia, in 1965. He received his Ing. (MSc.) degree in 1990 from the Faculty of Electrical Engineering and Informatics of University of Technology in Košice. He received PhD. degree in electronics from University of Technology, Košice, Slovakia, in 2002. Since February 1997, he has been at the University of Technology, Košice as Assistant professor for electronics and information technology. His general research interests include optoelectronic, digital signal processing, photonics, fiber optic communications and fiber optic sensors.

Ján Turán, Jr. (Ing) was born in Košice, Slovakia. He received his Ing. (MSc.) degree in computer engineering in 1999 from the Faculty of Electrical Engineering and Informatics of University of Technology in Košice. He works in 3D People gmbh as research manager. His research interests include digital signal and image processing and computer games design.