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Optical Fibre Sensors

**Fundamentals for Development
of Optimized Devices**

Ignacio Del Villar | Ignacio R. Matias


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Optical Fibre Sensors

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of Optimized Devices

Edited by

*Ignacio Del Villar
Ignacio R. Matias*

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Contents

List of Contributors xv

Acknowledgment xix

About the Editors xxi

- 1 Introduction** 1
Ignacio R. Matias and Ignacio Del Villar
References 14

- 2 Propagation of Light Through Optical Fibre** 17
Ignacio Del Villar
 - 2.1 Geometric Optics 17
 - 2.2 Wave Theory 22
 - 2.2.1 Scalar Analysis 23
 - 2.2.2 Vectorial Analysis 26
 - 2.3 Fibre Losses and Dispersion 32
 - 2.4 Propagation in Microstructured Optical Fibre 35
 - 2.5 Propagation in Specialty Optical Fibres Focused on Sensing 37
 - 2.6 Conclusion 45
References 46

- 3 Optical Fibre Sensor Set-Up Elements** 49
Minghong Yang and Dajuan Lyu
 - 3.1 Introduction 49
 - 3.2 Light Sources 50
 - 3.2.1 Light-Emitting Diodes 52
 - 3.2.1.1 Surface Light-Emitting Diode 52
 - 3.2.1.2 Side Light-Emitting Diode 52
 - 3.2.2 Laser Diode 53
 - 3.2.2.1 Single-Mode Laser Diode Structure 54

3.2.2.2	Quantum Well Laser Diode	56
3.2.3	Superluminescent Diodes (SLD)	56
3.2.4	Amplified Spontaneous Emission Sources	59
3.2.5	Narrow Line Broadband Sweep Source	62
3.2.6	Broadband Sources	62
3.3	Optical Detectors	63
3.3.1	Basic Principles of Optical Detectors	64
3.3.1.1	PN Photodetector	64
3.3.1.2	PIN Photodetector	65
3.3.1.3	Avalanche Photodiode (APD)	66
3.3.2	Main Characteristics of Optical Detectors	66
3.3.2.1	Operating Wavelength Range and Cut-Off Wavelength	66
3.3.2.2	Quantum Efficiency and Responsiveness	67
3.3.2.3	Response Time	68
3.3.2.4	Materials and Structures of Semiconductor Photodiodes	69
3.3.3	Optical Spectrometers	70
3.4	Light Coupling Technology	71
3.4.1	Coupling of Fibre and Light Source	71
3.4.1.1	Coupling of Semiconductor Lasers and Optical Fibres	71
3.4.1.2	Coupling Loss of Semiconductor Light-Emitting Diodes and Optical Fibres	72
3.4.2	Multimode Fibre Coupled Through Lens	72
3.4.3	Direct Coupling of Fibre and Fibre	73
3.5	Fibre-Optic Device	74
3.5.1	Fibre Coupler	74
3.5.2	Optical Isolator	74
3.5.3	Optical Circulator	76
3.5.4	Fibre Attenuator	76
3.5.5	Fibre Polarizer	76
3.5.6	Optical Switch	77
3.6	Optical Modulation and Interrogation of Optical Fibre-Optic Sensors	77
3.6.1	Intensity-Modulated Optical Fibre Sensing Technology	78
3.6.1.1	Reflective Intensity Modulation Sensor	78
3.6.1.2	Transmissive Intensity Modulation Sensor	80
3.6.1.3	Light Mode (Microbend) Intensity Modulation Sensor	80
3.6.1.4	Refractive Index Intensity-Modulated Fibre-Optic Sensor	80
3.6.2	Wavelength Modulation Optical Fibre Sensing Technology	81
3.6.2.1	Direct Demodulation System	81

- 3.6.2.2 NarrowBand Laser Scanning System 82
- 3.6.2.3 Broadband Source Filter Scanning System 83
- 3.6.2.4 Linear Sideband Filtering Method 84
- 3.6.2.5 Interference Demodulation System 84
- 3.6.3 Phase Modulation Optical Fibre Sensing Technology 86
- References 87

4 Basic Detection Techniques 91

Daniele Tosi and Carlo Molardi

- 4.1 Introduction 91
- 4.2 Overview of Interrogation Methods 93
- 4.3 Intensity-Based Sensors 97
 - 4.3.1 Macrobending 97
 - 4.3.2 In-Line Fibre Coupling 99
 - 4.3.3 Bifurcated Fibre Bundle 100
 - 4.3.4 Smartphone Sensors 100
- 4.4 Polarization-Based Sensors 102
 - 4.4.1 Pressure and Force Detection 102
 - 4.4.2 Lossy Mode Resonance for Refractive Index Sensing 104
- 4.5 Fibre-Optic Interferometers 105
 - 4.5.1 Fabry–Pérot Interferometer (FPI)-Based Fibre Sensors 106
 - 4.5.1.1 Extrinsic FPI for Pressure Sensing 107
 - 4.5.1.2 In-Line FPI for Temperature Sensing 108
 - 4.5.2 Mach–Zehnder Interferometer (MZI)-Based Fibre Sensors 109
 - 4.5.3 Single-Multi-Single Mode (SMS) Interferometer-Based Fibre Sensors 109
- 4.6 Grating-Based Sensors 111
 - 4.6.1 Fibre Bragg Grating (FBG) 111
 - 4.6.2 FBG Arrays 113
 - 4.6.3 Tilted and Chirped FBG 115
 - 4.6.4 Long-Period Grating (LPG) 117
 - 4.6.5 FBG Fabrication 118
- 4.7 Conclusions 121
- References 121

5 Structural Health Monitoring Using Distributed Fibre-Optic Sensors 125

Alayn Loayssa

- 5.1 Introduction 125
- 5.2 Fundamentals of Distributed Fibre-Optic Sensors 126

- 5.2.1 Raman DTS 128
- 5.2.2 Brillouin DTSS 129
- 5.3 DFOS in Civil and Geotechnical Engineering 130
 - 5.3.1 Bridges 133
 - 5.3.2 Tunnels 134
 - 5.3.3 Geotechnical Structures 137
- 5.4 DFOS in Hydraulic Structures 141
- 5.5 DFOS in the Electric Grid 143
- 5.6 Conclusions 145
 - References 146

- 6 Distributed Sensors in the Oil and Gas Industry 151**
Arthur H. Hartog
 - 6.1 The Late Life Cycle of a Hydrocarbon Molecule 153
 - 6.1.1 Upstream 154
 - 6.1.1.1 Exploration 154
 - 6.1.1.2 Well Construction 155
 - 6.1.1.3 Formation and Reservoir Evaluation 157
 - 6.1.1.4 Production 158
 - 6.1.1.5 Production of Methane Hydrates 159
 - 6.1.1.6 Well Abandonment 160
 - 6.1.2 Midstream: Transportation 160
 - 6.1.3 Downstream: Refinery and Distribution 161
 - 6.2 Challenges in the Application of Optical Fibres to the Hydrocarbon 161
 - 6.2.1 Conditions 161
 - 6.2.2 Conveyance Methods 162
 - 6.2.2.1 Temporary Installations (Intervention Services) 163
 - 6.2.2.2 Permanent Fibre Installations 163
 - 6.2.3 Fibre Reliability 165
 - 6.2.4 Fibre Types 166
 - 6.3 Applications and Take-Up 168
 - 6.3.1 Steam-Assisted Recovery; SAGD 168
 - 6.3.2 Flow Allocation: Conventional Wells 171
 - 6.3.3 Injector Monitoring 174
 - 6.3.4 Thermal Tracer Techniques 175
 - 6.3.5 Water Flow Between Wells 176
 - 6.3.6 Gas-Lift Valves 176
 - 6.3.7 Vertical Seismic Profiling (VSP) 177
 - 6.3.8 Hydraulic Fracturing Monitoring (HFM) 184
 - 6.3.9 Sand Production 185

6.4	Summary	186
	References	186
7	Biomechanical Sensors	193
	<i>Cicero Martelli, Jean Carlos Cardozo da Silva, Alessandra Kalinowski, José Rodolfo Galvão, and Talita Paes</i>	
7.1	Optical Fibre Sensors in Biomechanics: Introduction and Review	193
7.2	Optical Fibre Sensors: From Experimental Phantoms to <i>In Vivo</i> Applications	198
7.2.1	Experimental Phantoms and Models	198
7.2.1.1	Joints	199
7.2.1.2	Bones and Muscles	199
7.2.1.3	Teeth, Lower Jaw (Mandible), and Upper Jaw (Maxilla)	200
7.2.1.4	Prosthesis and Extracorporeal Devices	200
7.2.1.5	Sole and Insoles	201
7.2.1.6	Smart Fabrics	201
7.2.1.7	Blood Vessels	202
7.2.1.8	Respiratory Monitoring	203
7.2.2	<i>In Vitro</i>	203
7.2.3	<i>Ex Vivo</i>	204
7.2.3.1	Joints	204
7.2.3.2	Bones and Muscles	205
7.2.3.3	Teeth, Lower Jaw (Mandible), and Upper Jaw (Maxilla)	205
7.2.3.4	Blood Vessels	205
7.2.3.5	Mechanical Properties of Tissues	207
7.2.4	<i>In Vivo</i>	207
7.2.4.1	Joints	207
7.2.4.2	Bones and Muscles	207
7.2.4.3	Teeth, Lower Jaw (Mandible) and Upper Jaw (Maxilla)	208
7.2.4.4	Blood Vessels	208
7.2.4.5	Respiratory Monitoring	208
7.2.5	<i>In Situ</i>	208
7.2.5.1	Joints	209
7.2.5.2	Bones and Muscles	209
7.2.5.3	Prostheses and Extracorporeal Devices	210
7.2.5.4	Soles and Insoles	210
7.2.5.5	Cardiac Monitoring	211
7.2.5.6	Respiratory Monitoring	211
7.3	FBG Sensors Integrated into Mechanical Systems	213
7.3.1	FBG Sensors Glued with Polymer	214

- 7.3.2 Polymer-Integrated FBG Sensor 215
- 7.3.3 Smart Fibre Reinforced Polymer (SFRP) 218
- 7.4 Future Perspective 222
- Acknowledgment 223
- References 224

8 Optical Fibre Chemical Sensors 239

T. Hien Nguyen and Tong Sun

- 8.1 Introduction 239
- 8.2 Principles and Mechanisms of Fibre-Optic-Based Chemical Sensing 240
 - 8.2.1 Principle of Chemical Sensor Response 240
 - 8.2.2 Absorption-Based Sensors 242
 - 8.2.3 Luminescence-Based Sensors 243
 - 8.2.4 Surface Plasmon Resonance (SPR)-Based Sensors 245
- 8.3 Sensor Design and Applications 247
 - 8.3.1 Optical Fibre pH Sensors 247
 - 8.3.1.1 Principle of Fluorescence-Based pH Measurements 248
 - 8.3.1.2 pH Sensor Design 249
 - 8.3.1.3 Set-Up of a pH Sensor System 253
 - 8.3.1.4 Evaluation of the pH Sensor Systems 254
 - 8.3.1.5 Comments 260
 - 8.3.2 Optical Fibre Mercury Sensor 261
 - 8.3.2.1 Sensor Design and Mechanism 262
 - 8.3.2.2 Evaluation of the Mercury Sensor System 265
 - 8.3.2.3 Comments 271
 - 8.3.3 Optical Fibre Cocaine Sensor 271
 - 8.3.3.1 Sensing Methodology 272
 - 8.3.3.2 Design and Fabrication of a Cocaine Sensor System 273
 - 8.3.3.3 Evaluation of the Cocaine Sensor System 275
 - 8.3.3.4 Comments 280
- 8.4 Conclusions and Future Outlook 281
- Acknowledgements 282
- References 282

9 Application of Nanotechnology to Optical Fibre Sensors: Recent Advancements and New Trends 289

Armando Ricciardi, Marco Consales, Marco Pisco, and Andrea Cusano

- 9.1 Introduction 289
- 9.2 A View Back 292

9.3	Nanofabrication Techniques on the Fibre Tip for Biochemical Applications	293
9.3.1	Direct Approaches	294
9.3.2	Indirect Approaches	301
9.3.3	Self-Assembly	305
9.3.4	Smart Materials Integration	307
9.4	Nanofabrication Techniques on the Fibre Tip for Optomechanical Applications	309
9.5	Conclusions	317
	References	320
10	From Refractometry to Biosensing with Optical Fibres	331
	<i>Francesco Chiavaioli, Ambra Giannetti, and Francesco Baldini</i>	
10.1	Basic Sensing Concepts and Parameters for OFSs	332
10.1.1	Parameters of General Interest	335
10.1.1.1	Uncertainty	335
10.1.1.2	Accuracy and Precision	335
10.1.1.3	Sensor Drift and Fluctuations	336
10.1.1.4	Repeatability	336
10.1.1.5	Reproducibility	336
10.1.1.6	Response Time	336
10.1.2	Parameters Related to Volume RI Sensing	337
10.1.2.1	Refractive Index Sensitivity	337
10.1.2.2	Resolution	338
10.1.2.3	Figure of Merit (FOM)	339
10.1.3	Parameters Related to Surface RI Sensing	339
10.1.3.1	Sensorgram and Calibration Curve	340
10.1.3.2	Limit of Detection (LOD) and Limit of Quantification (LOQ)	341
10.1.3.3	Specificity (or Selectivity)	345
10.1.3.4	Regeneration (or Reusability)	345
10.2	Optical Fibre Refractometers	347
10.2.1	Optical Interferometers	348
10.2.2	Grating-Based Structures	348
10.2.3	Other Resonance-Based Structures	350
10.3	Optical Fibre Biosensors	352
10.3.1	Immuno-Based Biosensors	353
10.3.2	Oligonucleotide-Based Biosensors	354
10.3.3	Whole Cell/Microorganism-Based Biosensors	357
10.4	Fibre Optics Towards Advanced Diagnostics and Future Perspectives	360
	References	361

- 11 Humidity, Gas, and Volatile Organic Compound Sensors 367**
Diego Lopez-Torres and César Elosua
- 11.1 Introduction 367
 - 11.2 Optical Fibre Sensor Specific Features for Gas and VOC Detection 368
 - 11.3 Sensing Materials 370
 - 11.3.1 Organic Chemical Dyes 370
 - 11.3.2 Metal–Organic Framework (MOF) Materials 372
 - 11.3.3 Metallic Oxides 374
 - 11.3.4 Graphene 378
 - 11.4 Detection of Single Gases 379
 - 11.5 Relative Humidity Measurement 383
 - 11.6 Devices for VOC Sensing and Identification 384
 - 11.7 Artificial Systems for Complex Mixtures of VOCs: Optoelectronic Noses 387
 - 11.8 Conclusions 391
References 392
- 12 Interaction of Light with Matter in Optical Fibre Sensors:
A Biomedical Engineering Perspective 399**
Sillas Hadjiloucas
- 12.1 Introduction 399
 - 12.2 Energy Content in Light and Its Effect in Chemical Processes 399
 - 12.3 Relevance of Wien’s Law to Physicochemical Processes 402
 - 12.4 Absorption of Light Molecules 403
 - 12.5 The Role of Electron Spin and State Multiplicity in Spectroscopy 404
 - 12.6 Molecular Orbitals, Bond Conjugation, and Photoisomerization 406
 - 12.7 De-excitation Processes Through Competing Pathways: Their Effect on Lifetimes and Quantum Yield 407
 - 12.8 Energy Level Diagrams and Vibrational Sublevels 412
 - 12.9 Distinction Between Absorption and Action Spectra 413
 - 12.10 Light Scattering Processes 414
 - 12.10.1 Elastic Scattering 414
 - 12.10.2 Inelastic Scattering 416
 - 12.11 Induction of Non-linear Optical Processes 418
 - 12.12 Concentrating Fields to Maximize Energy Exchange in the Measurement Process Using Slow Light 419
 - 12.12.1 Slow Light Using Atomic Resonances and Electromagnetically Induced Transparency 419
 - 12.12.2 Slow Light Using Photonic Resonances 424
 - 12.13 Field Enhancement and Improved Sensitivity Through Whispering Gallery Mode Structures 427

- 12.14 Emergent Technological Trends Facilitating Multi-parametric Interactions of Light with Matter 429
- 12.14.1 Integration of Optical Fibres with Microfluidic Devices and MEMS 429
- 12.14.2 Pump–Probe Spectroscopy 430
- 12.15 Prospects of Molecular Control Using Femtosecond Fibre Lasers 430
- 12.15.1 Femtosecond Pulse Shaping 430
- 12.15.2 New Opportunities for Coherent Control of Molecular Processes 432
- 12.15.3 Developments in Evolutionary Algorithms for Molecular Control 434
- References 436
- 13 Detection in Harsh Environments 441**
Kamil Kosiel and Mateusz Śmietana
- 13.1 Introduction 441
- 13.2 Optical Fibre Sensors for Harsh Environments 442
- 13.3 Need for Harsh Environment Sensing Based on Optical Fibres 443
- 13.4 General Requirements for Harsh Environment OFSs 449
- 13.5 Silica Glass Optical Fibres for Harsh Environment Sensing 451
- 13.6 Polymer Optical Fibres for Harsh Environment Sensing 461
- 13.7 Chalcogenide Glass and Polycrystalline Silver Halide Optical Fibres for Harsh Environment Sensing 464
- 13.8 Monocrystalline Sapphire Optical Fibres for Harsh Environment Sensing 467
- 13.9 Future Trends in Optical Fibre Sensing 469
- References 470
- 14 Fibre-Optic Sensing: Past Reflections and Future Prospects 477**
Brian Culshaw and Marco N. Petrovich
- 14.1 Introductory Comments 477
- 14.2 Reflections on Achievements to Date 478
- 14.3 Photonics: How Is It Changing? 484
- 14.4 Some Future Speculation 486
- 14.4.1 Photonic Integrated and Plasmonic Circuits 487
- 14.4.2 Metamaterials in Sensing 490
- 14.4.3 More Variations on the Nano Story 492
- 14.4.4 Improving the Signal-to-Noise Ratio 493
- 14.4.5 Quantum Sensing, Entanglement, and the Like 494
- 14.4.6 The Many Prospects in Fibre Design and Fabrication 495
- 14.4.7 Technologies Other than Photonics 500
- 14.4.8 Societal Aspirations in Sensor Technology 501
- 14.4.9 The Future and a Quick Look at the Sensing Alternatives 501

14.4.10 So What Has Fibre Sensing Achieved to Date 503

14.5 Concluding Observations 504

References 504

Index 511

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1

Introduction

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The optical telegraph, invented in 1791 by Claude Chappe, consisted of a network of stations that allowed the transmission of information at a speed of one symbol in two minutes between Paris and Lille (i.e. 230 km) [1]. Each station monitored, with the aid of a telescope, the character that was represented with a wooden semaphore in the previous station. This system was widely used for about 50 years because it was much faster than sending messages by letter, but it required direct vision between each couple of consecutive stations. Consequently, bad weather, or simply the night, prevented its utilization. These are the main reasons why with the invention of the electrical telegraph, a system based on a guided electrical signal, the utilization of the optical telegraph came soon to an end.

However, in parallel to the invention of the electrical telegraph, in 1841, the path towards optical guiding was started with an important discovery by two French researchers, Jean Daniel Colladon and Jacques Babinet, who independently demonstrated that it was possible to guide light in a curved waveguide [2]. Colladon proved this with light rays trapped in a water jet by total internal reflection, whereas Babinet did the same in a bent glass rod.

Another breakthrough occurred in 1966, when Charles Kao (he received the Nobel Prize in Physics in 2009) and George Hockham published a work demonstrating that the attenuation in optical fibres available at the time was caused by impurities, rather than fundamental physical effects such as scattering. They

pointed out that fibres with low loss could be manufactured by using high-purity glass [3, 4]. This idea was proved in the North American company Corning in 1970, with the development of an optical fibre with losses lower than 20 dB/km. Soon afterwards, in 1977, losses were reduced to such a point that General Telephone and Electronics could carry live telephone traffic, 6 Mbit/s, in Long Beach, California, whereas the Bell System could transmit a 45 Mbit/s fibre link in the downtown Chicago phone system. Since that year optical fibre has become the most widely used guided medium in the twentieth century, mainly thanks to the huge bandwidth it presents compared with other guided communication media such as twisted pair and coaxial cable.

Optical communication is the main application of optical fibre. However, there is a second domain where this structure can be used: sensors. Despite the impact of optical fibre in the domain of sensors not being as big as in communications, their presence in the global market cannot be neglected. Indeed, it is the natural and ideal platform in terms of integrating the sensor in the communication system.

Optical fibre sensors (OFSs) can be classified in many different ways. The main classification concerns to the location where the light is modulated, existing in two groups: extrinsic and intrinsic OFSs. In both cases there is a parameter (physical, chemical, biological, etc.) that modulates light. However, the difference is that in an extrinsic OFSs light is guided to the interaction region, extrinsic to the optical fibre, where light is modulated, and after this modulation light is collected again in the optical waveguide, whereas in an intrinsic OFS light is always guided by the optical fibre. In Figure 1.1 the difference between an intrinsic and an extrinsic OFS

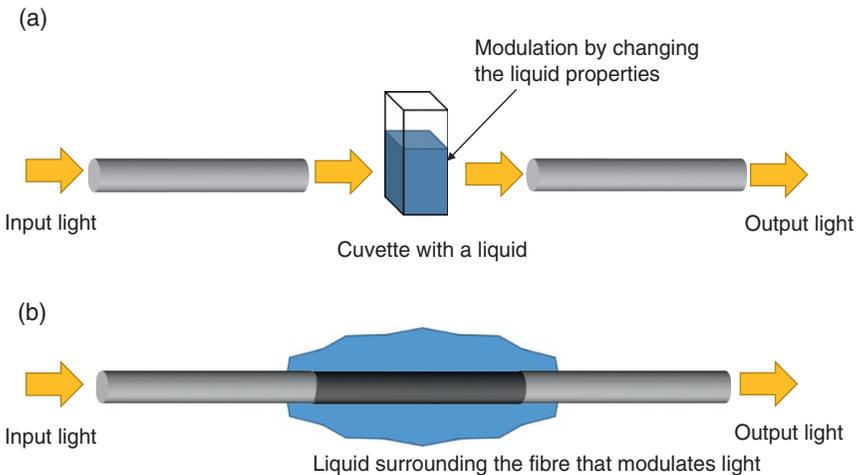


Figure 1.1 (a) Extrinsic sensor: light is modulated outside of the fibre. (b) Intrinsic sensor: light is modulated while it is transmitted through the fibre.

is shown. In the case of an extrinsic sensor, light is modulated outside of the fibre by a liquid (its properties may change as a function of temperature, for instance), whereas in the case of the intrinsic sensor, a fibre has been spliced to two other fibres (one input and one output fibre), which allows an enhanced interaction with the outer medium. In this case, a liquid modulates the light at the same time it is being transmitted through the fibre.

Probably the first OFS was the fibroscope. In 1930 Heinrich Lamm, a German medical student, assembled a bundle of optical fibres to carry an image. His purpose was to use the device for obtaining images of inaccessible parts of the body. He tried to patent the device, but John Logie Baird and Clarence W. Hansell had patented a similar idea some years before. The quality of the images that Lamm obtained was not good, but he is the first researcher that experimentally achieved this breakthrough in the history of optical sensors. Afterwards, in 1954, the Englishman Harold H. Hopkins and the Indian Narinder S. Kapany presented results of better quality on the same principle [5].

Some years later, in 1967, the first effective demonstration of a fibre-optic sensor, the Fotonic sensor, was published [6]. The device was also based on a fibre bundle. However, this time the arrangement was different. Some of the fibres emitted light, and some others did not. The fibre bundle illuminated a surface in front of the fibre, and some part of light was coupled to the fibres that did not transmit light. The amount of light reflected back depended on the distance between the fibre bundle end and the surface. Consequently, the device could be used as a displacement sensor (Figure 1.2).

This type of sensor was the basis for the commercialization of the MTI Fotonic sensor. In the 1980s, the MTI 2000 version allowed monitoring vibration and displacement. Nowadays it is still sold under the version MTI 2100, which is the same concept but with improved characteristics such as the ability to operate in cryogenic, vacuum, high pressure, or in high magnetic field and harsh environments. The resolution has also been improved from 1 nm in the MTI 2000 to 0.25 nm with the MTI 2100 and frequency response from direct-coupled (dc) to 150 kHz in the MTI 2000 up to dc-500 kHz in the MTI 2100.

The concept used in the Fotonic sensor was also the basis for detection of intracranial pressure by using a surface that is a diaphragm that can be deformed by the action of pressure. Depending on the pressure, the surface is deformed, and in this way, the light coupled back to the receiving fibre is modulated. The commercialized device was called Camino ICP Monitor.

Interferometric fibre sensors emerged in the 1970s, the most successful one among them being the optical fibre gyroscope (OFG) (see Figure 1.3). The basic principle was very simple. Light from a laser is split by a beam splitter and enters the fibre on both ends. Both beams go out of the fibre and a photodetector receives them. Thanks to the Sagnac effect, both beams interfere constructively and

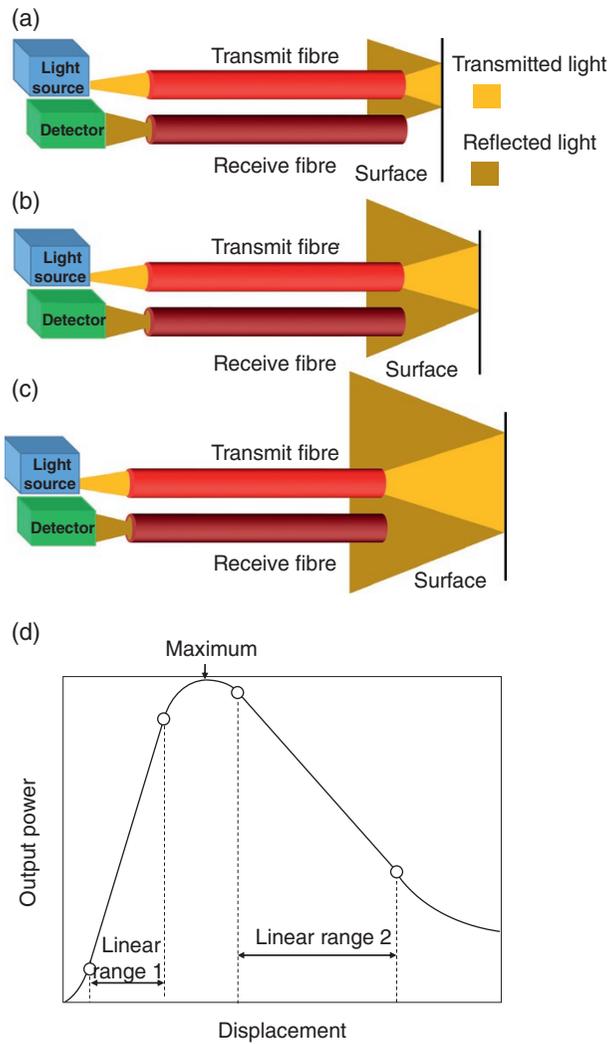


Figure 1.2 (a–c) Photonic sensor setup with a fibre bundle composed of one transmitting and one receiving fibre: (a) with the surface too close and hence only a small part is coupled back to the receiving fibre; (b) with the surface at the optimal position for a highest coupling; and (c) with the surface too far and hence a great part of light is lost and not coupled to the receiving fibre. (d) MTI 2100 diagram showing the power detected as a function of the distance (the maximum is obtained when the distance is neither too big nor too small).

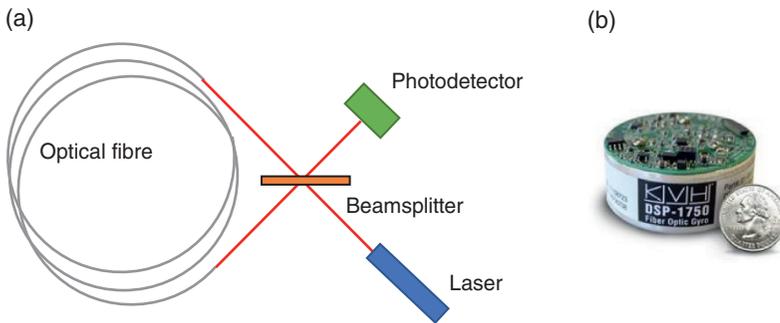


Figure 1.3 (a) Simplified setup: light from a laser is split by a beam splitter and enters the fibre on both ends. The two beams go out of the fibre and the photodetector receives them. Due to the Sagnac effect, both beams interfere constructively and destructively depending on the rotation speed of the device. (b) Commercial optical fibre gyro with a size comparable to a coin (from KVH website).

destructively depending on the rotation speed of the device. The first publication dates from the year 1976 [7]. Since that moment the device has been improved with additional elements such as polarization control, but the initial concept is still maintained. The true benefit of the OFG over traditional spinning-mass gyros is that it has no moving parts. As a result, OFGs are faster, tougher, more reliable and demand far less maintenance. That is why they have become an essential component in platform stabilizing systems, for example, for large satellite antennas, in missile guidance, in subsea navigation, and in aircraft stabilization and navigation, and a host of other applications [8]. It moves about 1000 million US\$ per year according to MarketsandMarkets: Fibre Optics Gyroscope Market by Sensing Axis (1, 2, and 3), Device (Gyrocompass, Inertial Measurement Unit, Inertial Navigation System, and Attitude Heading Reference System), Application, and Geography – Global Forecast to 2022.

Based on the acousto-optic effect, it was possible also to develop hydrophones, OFSs that could detect acoustic waves when immersed in water. One of the first approaches was based on interferometry [9], by combining the signals transmitted by an optical fibre that was not immersed in water with the signal reflected at the end facet of another optical fibre immersed in water. By exciting an acoustic wave in front of the fibre immersed in water, it was possible to observe variations in the detected signal. Though it has not been a commercial success like OFG, this application still attracts interest, and the utilization of a Fabry–Pérot cavity (i.e. a coating on the end facet of the optical fibre immersed in water) allows avoiding the use of the reference fibre because in this way an interferometric pattern in the optical spectrum is generated. The setup is depicted in Figure 1.4, and a commercial device is available at the company Precision Acoustics. Its immunity from

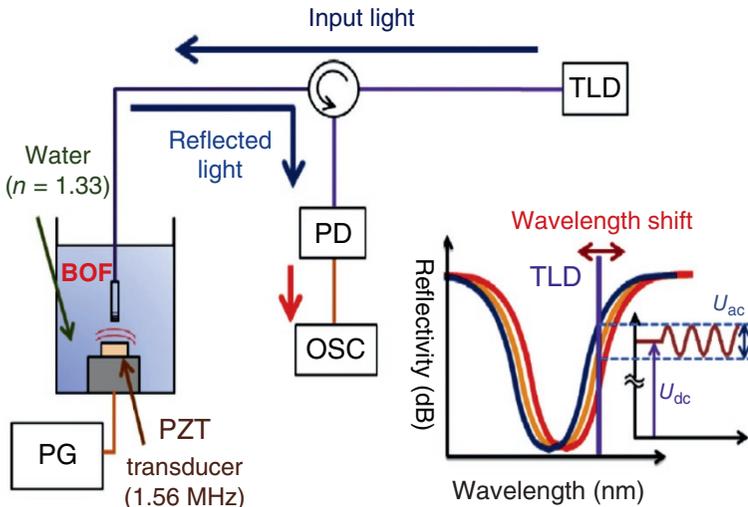


Figure 1.4 Optical setup for a Fabry-Pérot hydrophone [10]. OSC is oscilloscope, PD photodiode, PG pulse generator, PZT piezoelectric transducer, and TLD tunable laser diode. *Source:* Reproduced with permission of Elsevier.

electromagnetic radiation makes it particularly suited for high-frequency measurements in hostile fields.

As we can see, this property was also included in the Fotonic sensor and is one of the key advantages of optical fibres in general. However, in order to make a fibre optical sensor the first option of an end user, more advantages are required compared with the rest of sensors in the market. In the case of the OFG, the key property was that it was not necessary to use moving parts, which means long duration and fast response.

A second OFS success was the measurement of current and voltage with the aid of the Faraday effect [11, 12]. As an example, ABB has developed a commercial device called fibre-optic current sensor (FOCS), which can be used instead of magnetic systems due to its exceptional accuracy and reliability. It can measure uni- or bidirectional DC currents of up to 600 kA with an accuracy of $\pm 0.1\%$ of the measured value (Figure 1.5).

Strain gauges are another well-known application where optical fibres can be used. The first work was published in 1978 [13]. SOFO, from the company Smartec, is a commercial example that can be used for surface mounting or embedding in concrete and mortars. It is ideal for long-term structural deformation monitoring and presents a 20-year track record in field applications.