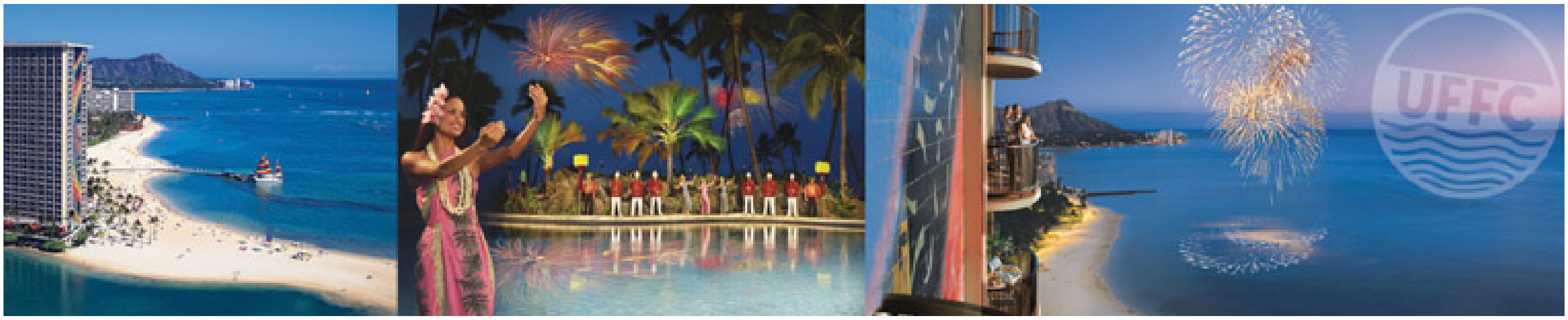

2008 IEEE International Frequency Control Symposium

Tutorials 18 May 2008, Symposium 19-21 May 2008
Hilton Hawaiian Village Hotel, Honolulu, Hawaii, USA

2008 Frequency Control Symposium Short Courses
Sunday, May 18

Time	Session A - Honolulu 1	Session B - Honolulu 2	Session C - Honolulu 3
Session 1 8:15-10:15	**Phase and Amplitude Modulation Noise Metrology** *Craig Nelson* *NIST, USA*	**Traceability in Time and Frequency Metrology** *Michael A. Lombardi* *NIST, USA*	**Resonant Piezoelectric Devices for Physical and Chemical Sensors** *Fabien J. Josse* *Marquette University, USA*
10:15-10:30	***Break***		
Session 2 10:30-12:30	**Microwave Frequency Synthesizers: Architectures and New Developments** *Alexander Chenakin* *Phase Matrix, USA*	**Transmitting Time and Frequency Information** *Judah Levine* *NIST Boulder, USA*	**Surface Acoustic Wave ID-Tags and Wireless Passive Resonant Sensors** *L. M. Reindl* *University of Freiburg, Germany*
12:30-1:30	***Lunch - Tapa 3***		
Session 3 1:30-3:30	**Chip-Scale Atomic Clocks** *Robert Lutwak* *Symmetricom, USA*	**IEEE 1588: The Precise Time Protocol** *Doug Arnold* *Symmetricom, USA*	**Wireless and Mobile Acoustic Sensor Interrogation for (Bio) Chemical Sensing and Industrial Control** *J.-M. Friedt* *FEMTO-ST, France*
3:30-3:45	***Break***		
Session 4 3:45-5:45	**Chip-Scale Atomic Magnetometers** *Svenja Knappe* *NIST Boulder, USA*	**An Introduction to Atomic and Quartz Clock Hardware for Space Applications** *Leo A. Mallette* *The Boeing Company, USA*	**Piezoelectric Biosensors: Recent Advances and Applications** *Ryszard M. Lec* *Drexel University, USA*

On Sunday, 18 May 2008, there will be a series of tutorials covering a wide range of related topics. The tutorials include both the fundamental topics of frequency and timing at a level suitable for practitioners new to the field, and more advanced and specialized topics related to specific areas. As such, the tutorials aim to provide useful knowledge to the beginners in the community, as well

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as those with extensive experience. Previously presented tutorial topics may be found at http://www.ieee-uffc.org/fc.

Tutorials

- Chip-Scale Atomic Clocks
- Traceability in Time and Frequency Metrology
- Surface Acoustic Wave ID-Tags and Wireless Passive Resonant Sensors
- Chip-Scale Atomic Magnetometers
- Microwave Frequency Synthesizers: Architectures and New Developments
- Phase and Amplitude Modulation Noise Metrology
- IEEE 1588: The Precise Time Protocol
- Resonant Piezoelectric Devices for Physical and Chemical Sensors
- Wireless and Mobile Acoustic Sensor Interrogation for (Bio)Chemical Sensing and Industrial Control
- Transmitting Time and Frequency Information
- An Introduction to Atomic and Quartz Clock Hardware for Space Applications
- Piezoelectric Biosensors: Recent Advances and Applications

Additional information, including abstracts of the tutorial presentations along with a biography of each presenter is listed below.

CHIP-SCALE ATOMIC CLOCKS

Robert Lutwak
Symmetricom Technology Realization Center

Recent developments in micro-electronic mechanical systems (MEMS), as well as ultra-low power digital and microwave electronics, have enabled the development of a new class of low-power atomic clocks. The so-called "Chip-Scale Atomic Clock (CSAC)" provides the long-term stability of a conventional rubidium oscillator, with >100X reduced size and power than any existing atomic clock technology.

The advent of CSAC technology opens the possibility of providing atomic timing accuracy in portable, battery-powered instruments, thus enabling a variety of new applications in secure communications, advanced navigation systems, and remote sensing and data logging.

The possibility of a functional CSAC was first suggested by NIST at the 2002 IEEE FCS.[1] Since that time, and with a concerted funding effort from the Defense Advanced Research Projects Agency, prototype CSACs have been demonstrated by NIST, as well as by several manufacturing organizations, including (at least) Symmetricom, Honeywell, Teledyne Scientific, and Sarnoff Corporation. Employing a variety of technical approaches, CSACs have recently been demonstrated with total volume <1 cm^3, power consumption of <30 mW, and short-term stability of $\sigma_y(\tau)<6\times10^{-10}\ \tau^{-1/2}$. These achievements reflect significant innovations from several organizations in physics, electronics, and packaging technology.

This tutorial will review the fundamental physics, engineering, and limitations to CSAC technology. Wherever possible, I will include a survey of alternative approaches to the technical challenges, though the tutorial will necessarily and conveniently draw extensively from my own experience in the field.

Robert Lutwak is a senior scientist at Symmetricom's Technology Realization Center. Dr. Lutwak has been involved in CSAC development since 2002 and has been a Principal Investigator in the

DARPA CSAC program since 2003. Dr. Lutwak has authored numerous publications on CSAC technology, including presentations at the 2002, 2003, 2004, and 2007 Precise Time and Time Interval Systems and Applications Meetings (PTTI), and the 2005 and 2007 IEEE Frequency Control Symposia.[2]

[1] J. Kitching, S. Knappe, and L. Hollberg, "Performance of small-scale frequency references," Proceedings of the IEEE International Frequency Control Symposium, New Orleans, LA, 2002.

[2] Collected preprints at: http://www.symmttm.com/info_center_white_papers.asp#acd

TRACEABILITY IN TIME AND FREQUENCY METROLOGY

Michael A. Lombardi
NIST

Abstract: An overview of how traceability to the International System (SI) units is established in time and frequency metrology. This tutorial discusses the definition of traceability, and briefly examines calibration methods, uncertainty analysis, and legal and technical measurement requirements. It describes how broadcast reference signals from satellite and ground-based signals can be used to satisfy traceability requirements, and discusses the remote time and frequency calibration services offered by NIST.

Michael Lombardi has been with the Time and Frequency division of NIST since 1981. He has worked closely with calibration and testing laboratories for a number of years, and is the project manager for two remote calibration services operated by NIST, the Frequency Measurement and Analysis Service (FMAS) and the Time Measurement and Analysis Service (TMAS). He received the NIST Condon Award in 2005 for publications related to the NIST quality system, and the Bronze Medal in 2007 for the development of a real-time common-view GPS network that serves North, Central, and South America as part of the Interamerican Metrology System (SIM). Mr. Lombardi is a member of IEEE, a member delegate of the National Conference of Standards Laboratories (NCSLI), and an associate editor for *Measure: The Journal of Measurement Science*. He has over 70 publications related to time and frequency metrology.

SURFACE ACOUSTIC WAVE ID-TAGS AND WIRELESS PASSIVE RESONANT SENSORS

L. M. Reindl
Institute of Microsystems Technology (IMTEK),
University of Freiburg, Germany

In the recent years unwired SAW sensors and identification tags have come under notice with a growing number of publications and applications. In this presentation the operating principles of wireless passive, mostly SAW based identification marks and sensors are shown. The whole radio based sensor system consists of a read-out unit, comparable to an RADAR device, and a passive transponder, consisting of a surface acoustic wave (SAW) device wired to an antenna. The surface acoustic wave stores the read-out signal for a predefined period of time to suppress all environmental echo interferences. Physical or chemical effects may influence the propagation characteristics of the surface acoustic wave. Two fundamental devices allow storing and modulating of surface acoustic waves: the resonator, and the uniform or chirped delay line. In this presentation, the transponder setup using a reflective delay line, resonator, or impedance sensor is discussed in detail, as well as the setup of the read out unit using a pulse or FMCW radar. Special emphasis is set on the achievable accuracy and on the sensitivity range. Several applications of such sensor systems and their state-of-the-art performance is presented by way of

examples which include identification marks and wireless measurements of temperature, pressure, torque, acceleration, tire-road friction, magnetic field, and water content of soil. A discussion of other resonant structures which also could be used in a passive transponder system will close the presentation.

Leonhard Reindl received his Diploma in Physics from Technical University of Munich, Germany, in 1985 and his Dr. sc.techn. from the University of Technology Vienna, Austria, in 1997. In April 1985 Dr. Reindl joined the surface acoustic wave group of the Siemens Corporate Technology Division, Munich, Germany. At Siemens Dr. Reindl contributed to the development of SAW convolvers, dispersive, tapped, and reflective delay lines. His primary interest was in the development and application of SAW ID-tag and wireless passive SAW sensor systems. In April 1999 Dr. Reindl joined the Institute of Electrical Information Technology, Clausthal University of Technology, where he became professor of communications and microwave techniques. In May 2003 he accepted a full professor position as the chair for Electrical Instrumentation at the Institute for Microsystem Technology (IMTEK) at the University of Freiburg, Germany. Dr. Reindl is member of the IEEE, of the TPC of the IEEE Frequency Control Symposium, and of the German biannual Symposium Sensoren und Messsysteme. He has been elected member of the AdCom of the IEEE UFFC society in 2005 to 2007. He holds more than 30 patents on SAW devices and wireless passive sensors and has authored or co-authored more than 100 papers in this field.

CHIP-SCALE ATOMIC MAGNETOMETERS

Svenja Knappe,
Time and Frequency Division, NIST Boulder

High-resolution laser spectroscopy enables the precise measurements of many physical quantities such as time, magnetic field, rotation, acceleration, temperature, and pressure. Despite their good performance, atomic sensors have been excluded form many everyday applications due to their large size and weight, high power consumption, or expensive price. Combining laser and atomic physics with Micro-Electromechanical Systems (MEMS) could benefit such applications. Enhanced precision or accuracy of atomic stabilization could be combined with wafer-level fabrication processes to reduce size, cost, and power consumption.

Rapid advancements in the field of atomic magnetometry have made these sensors competitive with superconducting quantum-interference devices (SQUIDs). The operating principles of atomic magnetometers depend largely on the requirements of the specific application. This tutorial will give an introduction into atomic magnetometry. Different excitation schemes, transitions, and modes of operation will be discussed. Magnetic sensitivity, bandwidth, and operating range are important factors in the choice of the sensor. Fabrication of chip-scale atomic magnetometers will be outlined. Applications can range from geophysical surveys to medical imaging. Issues involving the miniaturization of such sensors specific to the applications will be illustrated. Finally, other chip-scale atomic sensors will be introduced briefly.

Svenja Knappe received her diploma in physics from the University of Bonn, Germany in 1998. The topic of her diploma thesis was the investigation of single cesium atoms in a magneto-optical trap. She obtained her PhD from the University of Bonn in 2001, with a thesis on "Dark resonance magnetometers and atomic clocks". Since 2001, she has been pursuing research in the Time and Frequency Division at NIST, Boulder. Her research interests include precision laser spectroscopy, atomic clocks and atomic magnetometers, laser cooling, alkali vapor cell technology, applications of semiconductor lasers to problems in atomic physics and frequency control, miniaturization of atomic spectroscopy, and chip-scale atomic devices.

MICROWAVE FREQUENCY SYNTHESIZERS: ARCHITECTURES AND NEW DEVELOPMENTS

Alexander Chenakin,
Phase Matrix, Inc.

This tutorial presents an overview of today's microwave frequency synthesizer technologies. It begins with basic requirements and specifications followed by a detailed survey of various synthesizer techniques, which are compared in terms of performance, circuit complexity, and cost impact. Included are direct analog, direct digital and indirect synthesizer architectures along with their main characteristics and performance trade-offs. The latest frequency synthesizer developments, new market demands, design challenges, and various solutions are discussed.

Dr. Alexander Chenakin is the Director of the Frequency Synthesis Group at Phase Matrix, Inc., www.phasematrix.com. He earned his degree from Kiev Polytechnic Institute and has worked in a variety of technical and managerial positions around the world. He also founded Critical Design Company, LLC, focusing on the research and development of low phase noise microwave oscillators and frequency synthesizers. In 2005 Dr. Chenakin joined Phase Matrix, Inc. where he leads the development of advanced frequency synthesizer products for test & measurement applications. Dr. Chenakin can be reached by phone at 408-954-6409 or by e-mail at achenakin@phasematrix.com.

PHASE AND AMPLITUDE MODULATION NOISE METROLOGY

Craig Nelson,
NIST

Noise is everywhere. Its ubiquitous nature interferes with or masks desired signals and fundamentally limits all electronic measurements. Noise in the presence of a carrier is experienced as amplitude and phase modulation noise. Modulation noise will be covered from its theory, to its origins and consequences. The effects of signal manipulation such as amplification, frequency translation and multiplication on spectral purity are examined. Practical techniques for measuring AM and PM noise, from the simple to complex will be discussed. Calibration of measurements and common problems and pitfall will also be covered.

Craig Nelson is an electrical engineer at the Time and Frequency Division of the National Institute of Standards and Technology. He received his BSEE from the University of Colorado in Boulder in 1990. After co-founding SpectraDynamics, he joined the staff at the NIST. He has worked on the synthesis and control electronics, as well as software for both the NIST-7 and F1 primary frequency standards. He is presently involved in research and development of ultra-stable synthesizers, low phase noise electronics, and phase noise metrology. Current areas of research include optical oscillators, high-speed pulsed phase noise measurements and phase noise metrology in the 100 GHz range. He has published over 35 papers and teaches classes, tutorials, and workshops at NIST, the IEEE Frequency Control Symposium, and several sponsoring agencies on the practical aspects of high-resolution phase noise metrology.

IEEE 1588: THE PRECISE TIME PROTOCOL

Doug Arnold,
Symmetricom

The Precise Time Protocol, or PTP, defined by the IEEE 1588 standard, allows for sub-microsecond precision time transfer in shared data networks. This allows system integrators to synchronize equipment without the need of a dedicated timing network. Such a fundamental cost reduction is expected to drive wide scale adoption of PTP in numerous application spaces including Industrial automation, power utilities, automated test systems, military and aerospace systems, telecommunications, and audio/visual technology. Transferring time over networks, which are also used for other data, creates a new set of challenges, however, which have to be overcome. In this tutorial I will describe:

- How PTP works
- Types of PTP devices
- Changes in the new version of the standard
- Implementation challenges and solutions
- PTP "Profiles" for different applications
- The PTP commercial eco-system

Dr. Arnold joined TrueTime in 1998, and became the Chief Scientist. When Symmetricom acquired TrueTime in 2001, Dr. Arnold became the Chief Scientist of the Timing Test and Measurement Division of TrueTime. In this role he manages new technology development projects for the division, contributes to marketing, engineering management and corporate strategy development. Dr. Arnold served on the IEEE 1588 version 2 standards committee.

From 1995 to 1998 he served as Sr. Project Engineer at Summit Industries in Chicago, leading a medical imaging equipment design team. Prior to that he was an assistant professor at the University of Illinois at Chicago, worked as a scientist at IBM TJ Watson Research Center in New York, and the Naval Research Laboratory in Washington D.C. Dr. Arnold has published more then two dozen papers in science and engineering technical journals. He holds Ph.D. and M.S. degrees in Electrical Engineering from the University of Illinois at Urbana-Champaign. He also holds a B.S. in Electrical Engineering from Michigan State University.

RESONANT PIEZOELECTRIC DEVICES FOR PHYSICAL AND CHEMICAL SENSORS

Fabien J. Josse, Ph.D.
Department of Electrical and Computer Engineering
Marquette University, Milwaukee, WI, USA

This tutorial will cover devices based on piezoelectric crystals and used for physical and chemical sensor applications. Various acoustic wave devices used as temperature, mass, pressure, torque, acceleration sensors, for material characterization, and as chemical agents detectors will be presented and described. The course will focus on two types of piezoelectric sensors that have reached some level of maturity - available as commercial products or under development. They are the thickness shear mode (TSM) resonators and surface acoustic wave (SAW) devices (both Rayleigh SAW and shear horizontal-SAW). Chemically sensitive and selective absorptive coatings used for chemical sensors will also be described. Sensor device principles and modeling including second order effects, design parameters, operating characteristics, and key sensing parameters will be covered. Various measurement schemes used with the piezoelectric sensors will be described.

Fabien Josse received the License in Maths and Physics, the M.S. and Ph.D. degrees in electrical engineering in 1976, 1979 and 1982, respectively. He has been with Marquette University, Milwaukee, WI, since 1982 and is currently professor in the Department of Electrical and Computer Engineering, and the Department of Biomedical Engineering, as well as the Director of Graduates Studies. He is also an adjunct professor in the Department of Electrical and Computer Engineering, Laboratory for Surface Science and Technology (LASST), University of Maine, and has been a visiting professor at the University of Heidelberg, Germany, since 1990, and a visiting professor at Laboratoire IMS, University of Bordeaux, France, and the Physical Electronics Laboratory (PEL) at the Swiss Federal Institute of Technology (ETH), Zurich, Switzerland since

2002. His current research interests include solid state and acoustic wave device sensors (bio-chemical sensors), micro-electro-mechanical systems (MEMS) devices (microcantilevers for sensor applications), investigation of novel sensor platforms, and smart sensor systems. Dr. Josse is a senior member of IEEE and a member of Eta Kappa Nu, Sigma Xi, and associate editor of the IEEE Sensors Journal since 2002.

WIRELESS AND MOBILE ACOUSTIC SENSOR INTERROGATION FOR (BIO)CHEMICAL SENSING AND INDUSTRIAL CONTROL

J.-M. Friedt

Surface acoustic wave resonators provide great opportunities for wireless, passive sensing applications: their high quality factor allows for the storage of a large amount of energy and hence greater interrogation ranges than electronics RFID tags or MEMS sensors. The fully passive SAW sensors are compatible with harsh environments. However, probing radio-frequency passive sensors located several meters from the interrogation unit induces design challenges related to radar technology, with the additional constraint of cost reduction and ISM band regulations.

The first part of this presentation will focus on various designs of wireless interrogation systems for probing SAW resonators used as sensors. Two main strategies, wideband and narrowband, will be presented with a focus on the latter requiring less computing power. Practical designs using commercially components will be shown, including measurements results for illustrating the accuracy of the measurement (sub-kHz at 433 MHz), measurement delay (a few ms for sweeping the ISM band) and signal processing strategies for extracting accurate resonance information from coarse measurements. Experimental results concerning wireless temperature, pressure and strain measurements will be presented.

A second class of SAW sensors concerns delay lines. Several approaches for the wireless interrogation of delay lines -- in the time and frequency domains -- will be presented. Delay lines are intrinsically wideband devices which can hardly meet the narrow 433 MHz ISM band regulations: their use is confined to shielded environments (motors for example) in which radio-frequency signals are confined within the device being monitored. However, numerous applications are developed in the ISM band centered at 2.45 GHz thanks to the corresponding bandwidth, allowing for the implementation of reasonably long delays lines, compatible with actual application requirements.

A special focus on delay lines concerns the characterization of biochemical species: in this case, a wideband characterization of the propagation properties of the acoustic waves is suitable to extract multiple parameters of the acoustic wave/adsorbed layer interaction. We will present embedded designs for the wired transmission characterization of delay lines used for viscosity and (bio) chemical adsorption analysis. Experimental results on the detection of electrochemical deposition of metals monitored by SAW delay line will be presented to illustrate these concepts.

J.-M. Friedt obtained his PhD in 2000 from Besancon University (France). He spent 3 years in IMEC (Leuven, Belgium) working on optical and acoustic (quartz crystal resonator and surface acoustic wave) biosensors, focusing on the characterization of the physical properties of the adsorbed layers. He joined the group of S. Ballandras (FEMTO-ST, Besancon, France) in 2004, working on the use of acoustic resonators for the wireless measurement of physical properties (temperature, pressure, strain), including the development of the associated interrogation units.

TRANSMITTING TIME AND FREQUENCY INFORMATION

Judah Levine,

Time and Frequency Division, NIST
Boulder, Colorado 80309
jlevine@boulder.nist.gov

In this tutorial I will discuss the different methods of transmitting time and frequency information. All of the methods that I will discuss are based on 4 fundamental techniques: (1) transmitting signals in one direction between an active transmitter and a passive receiver, (2) two-way transmissions between two active stations, (3) common-view methods in which several passive receivers listen to the signals from one transmitter, and (4) variations on the basic common-view method in which several stations listen to the signals from several transmitters and combine the data using a "melting pot" technique. I will compare the capabilities of these techniques in principle, and I will illustrate these capabilities using examples derived from systems that currently use each of these techniques. I will then turn to a more detailed discussion of the methods that are in common use, including those that use the telephone system, the Internet, radio broadcasts, and both active and passive satellite systems. Finally, I will introduce the various methods of disciplining a local oscillator - that is, what to do with the time information after it has been received. Since this is a very broad topic, I welcome suggestions (sent to jlevine@boulder.nist.gov) on areas of special interest to the attendees, and I will try to address these interests in my presentation.

Judah Levine received his Ph.D. in Physics from New York University in 1966. After post-doctoral work at the Clarendon Laboratory of Oxford University and the Joint Institute for Laboratory Astrophysics in Boulder, he joined the staff of the National Bureau of Standards in 1969. He joined the Time and Frequency Division of NBS in 1972, and has worked on time scales, on the statistics of clocks and oscillators, and on the definition, realization, and distribution of UTC and UTC (NIST) since that time. He has also worked on instruments and methods for detecting gravitational waves, for studying the dynamics of seismic zones, and for measuring long baselines to very high accuracy. Dr. Levine is a member of the IEEE and a Fellow of the American Physical Society.

AN INTRODUCTION TO ATOMIC AND QUARTZ CLOCK HARDWARE FOR SPACE APPLICATIONS

Leo A. Mallette
The Boeing Company

Accurate and stable frequency reference sources are critical for commercial, navigation, military, and scientific space applications. Each piece of flight hardware has requirement-types that are generic such as size, weight, power, and reliability, and requirement-types that are specific to the hardware function. The key requirement-types for frequency reference sources are phase noise and stability. Both are important for satellites, but stability is especially important for navigation satellites. Several levels of frequency references are suitable for space applications. This tutorial discusses similarities and differences among single distributed oscillators for communications satellites, master oscillator groups for communications systems, and atomic clocks for military and navigation systems. Photographs from several manufacturers are presented.

Dr. Leo Mallette is a technical project manager and has worked in the aerospace industry since 1974. His strengths are building relationships with suppliers, implementing contractual direction, and gathering the best resources to apply to technical problems. He is nationally known for his expertise in quartz and atomic clocks. He received the BS and MS degrees in electrical engineering from the University of Central Florida and the MBA and Ed.D. degrees from Pepperdine University and is an adjunct instructor for the University of Phoenix-Online. Dr. Mallette has published over 50 conference and journal articles on atomic frequency standards, satellite systems, ground stations, optical detectors, circuits, genealogy, and organizational leadership. He is the co-editor of The SPELIT Power Matrix (2007) and is working on the book Writing for Conferences. Leo is a senior member of the IEEE, a member of the advisory board for the PTTI

Conference and the Technical Program Chairman for the 2009 PTTI conference. He and his wife Kathy live in Irvine and Rancho Mirage, California. He enjoys playing with his granddaughters, gardening projects, traveling, and writing.

PIEZOELECTRIC BIOSENSORS: RECENT ADVANCES AND APPLICATIONS

Ryszard M. Lec
Drexel University

Modern biosensors developed with advanced microfabrication and signal processing techniques are becoming inexpensive, accurate, and reliable. Increasing miniaturization of biosensors leads to realization of complex analytical systems such as BioChemLab-on-a-Chip. This rapid progress in miniature devices and instrumentation development will significantly impact the practice of medical care as well as future advances in the chemical, pharmaceutical and environmental industries. In this tutorial piezoelectric biosensors as well other important biosensor technologies and applications are presented and the challenges facing biosensor developers in the coming decade are discussed.

Ryszard M. Lec is a Professor at the School of Biomedical Engineering, Science and Health Systems, Drexel University. Dr. Lec has been active in the areas of material science and instrumentation for more than 20 years. Specifically, his research efforts have been devoted to the study of viscoelastic, acousto-optic (AO) and ultrasonic properties liquid and solid media with the focus on biomedical applications. In addition, he has developed several associated electronic instrumentation including ultrasonic spectrometers, acousto-optic Q-switches and filters, and acoustic resonant systems. Since the middle of the eighties his interest has been directed on the application of acoustic, piezoelectric, ultrasonic and optical technologies for the development of sensors. In particular, he has designed and fabricated a variety of sensors for the medical, biochemical, chemical, automotive and environmental industries. These included immunosensors, micro-viscometers, engine oil quality sensors, gas sensors and sensors for monitoring the kinetics of interfacial biochemical processes involving cells, viruses, bacteria, etc. Recently, his research interests were extended to include the utilization of artificial intelligence for the development of smart sensors. He has authored and co-authored over 60 publications and one book, and is co-inventor of 4 issued US patents.