

ISSN 1726-5749

SENSORS & TRANSDUCERS

vol. 90
Special
4/08



Modern Sensing Technologies

International Frequency Sensor Association Publishing





Sensors & Transducers

Special Issue
April 2008

www.sensorsportal.com

ISSN 1726-5479

Editor-in-Chief: Sergey Y. Yurish

Guest Editors: Subhas Chandra Mukhopadhyay and Gourab Sen Gupta

Editors for Western Europe

Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vittorio, Università di Brescia, Italy

Editors for North America

Datskos, Panos G., Oak Ridge National Laboratory, USA
Fabien, J. Josse, Marquette University, USA
Katz, Evgeny, Clarkson University, USA

Editor South America

Costa-Felix, Rodrigo, Inmetro, Brazil

Editor for Eastern Europe

Sachenko, Anatoly, Ternopil State Economic University, Ukraine

Editor for Asia

Ohyama, Shinji, Tokyo Institute of Technology, Japan

Editorial Advisory Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Northern University of Engineering, Malaysia
Annamalai, Karthikeyan, National Institute of Advanced Industrial Science and Technology, Japan
Arcega, Francisco, University of Zaragoza, Spain
Arguel, Philippe, CNRS, France
Ahn, Jae-Pyoung, Korea Institute of Science and Technology, Korea
Arndt, Michael, Robert Bosch GmbH, Germany
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygtantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
Bahreyni, Behraad, University of Manitoba, Canada
Baoxian, Ye, Zhengzhou University, China
Barford, Lee, Agilent Laboratories, USA
Barlingay, Ravindra, RF Arrays Systems, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Binnie, T. David, Napier University, UK
Bischoff, Gerlinde, Inst. Analytical Chemistry, Germany
Bodas, Dhananjay, IMTEK, Germany
Borges Carval, Nuno, Universidade de Aveiro, Portugal
Bousbia-Salah, Mounir, University of Annaba, Algeria
Bouvet, Marcel, CNRS – UPMC, France
Brudzewski, Kazimierz, Warsaw University of Technology, Poland
Cai, Chenxin, Nanjing Normal University, China
Cai, Qingyun, Hunan University, China
Campanella, Luigi, University La Sapienza, Italy
Carvalho, Vitor, Minho University, Portugal
Cecelja, Franjo, Brunel University, London, UK
Cerde Belmonte, Judith, Imperial College London, UK
Chakrabarty, Chandan Kumar, Universiti Tenaga Nasional, Malaysia
Chakravorty, Dipankar, Association for the Cultivation of Science, India
Changhai, Ru, Harbin Engineering University, China
Chaudhari, Gajanan, Shri Shivaji Science College, India
Chen, Jiming, Zhejiang University, China
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiriac, Horia, National Institute of Research and Development, Romania
Chowdhuri, Arijit, University of Delhi, India
Chung, Wen-Yaw, Chung Yuan Christian University, Taiwan
Corres, Jesus, Universidad Publica de Navarra, Spain
Cortes, Camilo A., Universidad Nacional de Colombia, Colombia
Courtois, Christian, Université de Valenciennes, France
Cusano, Andrea, University of Sannio, Italy
D'Amico, Arnaldo, Università di Tor Vergata, Italy
De Stefano, Luca, Institute for Microelectronics and Microsystem, Italy
Deshmukh, Kiran, Shri Shivaji Mahavidyalaya, Barshi, India
Kang, Moonho, Sunmoon University, Korea South
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA
Kausel, Wilfried, University of Music, Vienna, Austria

Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding Jian, Ning, Jiangsu University, China
Djordjević, Alexandar, City University of Hong Kong, Hong Kong
Donato, Nicola, University of Messina, Italy
Donato, Patricio, Universidad de Mar del Plata, Argentina
Dong, Feng, Tianjin University, China
Drljaca, Predrag, Instersema Sensoric SA, Switzerland
Dubey, Venketesh, Bournemouth University, UK
Enderle, Stefan, University of Ulm and KTB Mechatronics GmbH, Germany
Erdem, Gursan K. Arzum, Ege University, Turkey
Erkmen, Aydan M., Middle East Technical University, Turkey
Estelle, Patrice, Insa Rennes, France
Estrada, Horacio, University of North Carolina, USA
Faiz, Adil, INSA Lyon, France
Fericean, Sorin, Balluff GmbH, Germany
Fernandes, Joana M., University of Porto, Portugal
Francioso, Luca, CNR-IMM Institute for Microelectronics and Microsystems, Italy
Francis, Laurent, University Catholique de Louvain, Belgium
Fu, Weiling, South-Western Hospital, Chongqing, China
Gaura, Elena, Coventry University, UK
Geng, Yanfeng, China University of Petroleum, China
Gole, James, Georgia Institute of Technology, USA
Gong, Hao, National University of Singapore, Singapore
Gonzalez de la Rosa, Juan Jose, University of Cadiz, Spain
Granel, Annette, Goteborg University, Sweden
Graff, Mason, The University of Texas at Arlington, USA
Guan, Shan, Eastman Kodak, USA
Guillet, Bruno, University of Caen, France
Guo, Zhen, New Jersey Institute of Technology, USA
Gupta, Narendra Kumar, Napier University, UK
Hadjiloucas, Sillas, The University of Reading, UK
Hashsham, Syed, Michigan State University, USA
Hernandez, Alvaro, University of Alcalá, Spain
Hernandez, Wilmar, Universidad Politecnica de Madrid, Spain
Homentcovschi, Dorel, SUNY Binghamton, USA
Horstman, Tom, U.S. Automation Group, LLC, USA
Hsiai, Tzung (John), University of Southern California, USA
Huang, Jeng-Sheng, Chung Yuan Christian University, Taiwan
Huang, Star, National Tsing Hua University, Taiwan
Huang, Wei, PSG Design Center, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Ecole Centrale de Lyon, France
Jaime Calvo-Galleg, Jaime, Universidad de Salamanca, Spain
James, Daniel, Griffith University, Australia
Janting, Jakob, DELTA Danish Electronics, Denmark
Jiang, Liudi, University of Southampton, UK
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia
Rodriguez, Angel, Universidad Politecnica de Catalunya, Spain
Rothberg, Steve, Loughborough University, UK
Sadana, Ajit, University of Mississippi, USA

Kavasoglu, Nese, Mugla University, Turkey
Ke, Cathy, Tyndall National Institute, Ireland
Khan, Asif, Aligarh Muslim University, Aligarh, India
Kim, Min Young, Koh Young Technology, Inc., Korea South
Ko, Sang Choon, Electronics and Telecommunications Research Institute, Korea South
Kockar, Hakan, Balikesir University, Turkey
Kotulska, Malgorzata, Wroclaw University of Technology, Poland
Kratz, Henrik, Uppsala University, Sweden
Kumar, Arun, University of South Florida, USA
Kumar, Subodh, National Physical Laboratory, India
Kung, Chih-Hsien, Chang-Jung Christian University, Taiwan
Lacnjevac, Caslav, University of Belgrade, Serbia
Lay-Ekuakille, Aime, University of Lecce, Italy
Lee, Jang Myung, Pusan National University, Korea South
Lee, Jun Su, Amkor Technology, Inc. South Korea
Lei, Hua, National Starch and Chemical Company, USA
Li, Genxi, Nanjing University, China
Li, Hui, Shanghai Jiaotong University, China
Li, Xian-Fang, Central South University, China
Liang, Yuanchang, University of Washington, USA
Liawruangrath, Saisunee, Chiang Mai University, Thailand
Liew, Kim Meow, City University of Hong Kong, Hong Kong
Lin, Hermann, National Kaohsiung University, Taiwan
Lin, Paul, Cleveland State University, USA
Linderholm, Pontus, EPFL - Microsystems Laboratory, Switzerland
Liu, Aihua, University of Oklahoma, USA
Liu Changgeng, Louisiana State University, USA
Liu, Cheng-Hsien, National Tsing Hua University, Taiwan
Liu, Songqin, Southeast University, China
Lodeiro, Carlos, Universidade NOVA de Lisboa, Portugal
Lorenzo, Maria Encarnacio, Universidad Autonoma de Madrid, Spain
Lukaszewicz, Jerzy Pawel, Nicholas Copernicus University, Poland
Ma, Zhanfang, Northeast Normal University, China
Majstorovic, Vidosav, University of Belgrade, Serbia
Marquez, Alfredo, Centro de Investigacion en Materiales Avanzados, Mexico
Matay, Ladislav, Slovak Academy of Sciences, Slovakia
Mathur, Prafull, National Physical Laboratory, India
Maurya, D.K., Institute of Materials Research and Engineering, Singapore
Mekid, Samir, University of Manchester, UK
Melnyk, Ivan, Photon Control Inc., Canada
Mendes, Paulo, University of Minho, Portugal
Mennell, Julie, Northumbria University, UK
Mi, Bin, Boston Scientific Corporation, USA
Minas, Graca, University of Minho, Portugal
Moghavvemi, Mahmoud, University of Malaya, Malaysia
Mohammadi, Mohammad-Reza, University of Cambridge, UK
Molina Flores, Esteban, Benemérita Universidad Autónoma de Puebla, Mexico
Moradi, Majid, University of Kerman, Iran
Morello, Rosario, DIMET, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mukhopadhyay, Subhas, Massey University, New Zealand
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucin, University of Guelma, Algeria
Pamidighanta, Sayanu, Bharat Electronics Limited (BEL), India
Pan, Jisheng, Institute of Materials Research & Engineering, Singapore
Park, Joon-Shik, Korea Electronics Technology Institute, Korea South
Penza, Michele, ENEA C.R., Italy
Pereira, Jose Miguel, Instituto Politecnico de Seteal, Portugal
Petsev, Dimiter, University of New Mexico, USA
Pogacnik, Lea, University of Ljubljana, Slovenia
Post, Michael, National Research Council, Canada
Prance, Robert, University of Sussex, UK
Prasad, Ambika, Gulbarga University, India
Prateepasen, Asa, Kingmoungut's University of Technology, Thailand
Pullini, Daniele, Centro Ricerche FIAT, Italy
Pumera, Martin, National Institute for Materials Science, Japan
Radhakrishnan, S., National Chemical Laboratory, Pune, India
Rajanna, K., Indian Institute of Science, India
Ramadan, Qasem, Institute of Microelectronics, Singapore
Rao, Basuthkar, Tata Inst. of Fundamental Research, India
Raouf, Kosai, Joseph Fourier University of Grenoble, France
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Robert, Michel, University Henri Poincare, France
Rezazadeh, Ghader, Urmia University, Iran
Royo, Santiago, Universitat Politècnica de Catalunya, Spain
Sadeghian Marnani, Hamed, TU Delft, The Netherlands
Sandacci, Serghei, Sensor Technology Ltd., UK
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Saxena, Vibha, Bhabha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Shearwood, Christopher, Nanyang Technological University, Singapore
Shin, Kyuho, Samsung Advanced Institute of Technology, Korea
Shmali, Yuriy, Kharkiv National University of Radio Electronics, Ukraine
Silva Grao, Pedro, Technical University of Lisbon, Portugal
Singh, V. R., National Physical Laboratory, India
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technol., India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., Northwestern University, USA
Stefan-van Staden, Raluca-Ioana, University of Pretoria, South Africa
Sumriddetchka, Sarun, National Electronics and Computer Technology Center, Thailand
Sun, Chengliang, Polytechnic University, Hong-Kong
Sun, Dongming, Jilin University, China
Sun, Junhua, Beijing University of Aeronautics and Astronautics, China
Sun, Zhiqiang, Central South University, China
Suri, C. Raman, Institute of Microbial Technology, India
Sysoev, Victor, Saratov State Technical University, Russia
Szewczyk, Roman, Industrial Research Institute for Automation and Measurement, Poland
Tan, Ooi Kiang, Nanyang Technological University, Singapore
Tang, Dianping, Southwest University, China
Tang, Jaw-Luen, National Chung Cheng University, Taiwan
Teker, Kasif, Frostburg State University, USA
Thumbavanam Pad, Kartik, Carnegie Mellon University, USA
Tian, Gui Yun, University of Newcastle, UK
Tsiantos, Vassilios, Technological Educational Institute of Kaval, Greece
Tsigara, Anna, National Hellenic Research Foundation, Greece
Twomey, Karen, University College Cork, Ireland
Valente, Antonio, Vila Real, - U.T.A.D., Portugal
Vaseashta, Ashok, Marshall University, USA
Vazques, Carmen, Carlos III University in Madrid, Spain
Vieira, Manuela, Instituto Superior de Engenharia de Lisboa, Portugal
Vigna, Benedetto, STMicroelectronics, Italy
Vrba, Radimir, Brno University of Technology, Czech Republic
Wandelt, Barbara, Technical University of Lodz, Poland
Wang, Jiangping, Xi'an Shiyou University, China
Wang, Kedong, Beihang University, China
Wang, Liang, Advanced Micro Devices, USA
Wang, Mi, University of Leeds, UK
Wang, Shinn-Fwu, Ching Yun University, Taiwan
Wang, Wei-Chih, University of Washington, USA
Wang, Wensheng, University of Pennsylvania, USA
Watson, Steven, Center for NanoSpace Technologies Inc., USA
Weiping, Yan, Dalian University of Technology, China
Wells, Stephen, Southern Company Services, USA
Wolkenberg, Andrzej, Institute of Electron Technology, Poland
Woods, R. Clive, Louisiana State University, USA
Wu, DerHo, National Pingtung University of Science and Technology, Taiwan
Wu, Zhaoyang, Hunan University, China
Xiu Tao, Ge, Chuzhou University, China
Xu, Lisheng, The Chinese University of Hong Kong, Hong Kong
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Wuqiang, The University of Manchester, UK
Ymeti, Aurel, University of Twente, Netherland
Yu, Haihu, Wuhan University of Technology, China
Yufera Garcia, Alberto, Seville University, Spain
Zagnoni, Michele, University of Southampton, UK
Zeni, Luigi, Second University of Naples, Italy
Zhong, Haoxiang, Henan Normal University, China
Zhang, Minglong, Shanghai University, China
Zhang, Qintao, University of California at Berkeley, USA
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China
Zhou, Zhi-Gang, Tsinghua University, China
Zorzano, Luis, Universidad de La Rioja, Spain
Zourob, Mohammed, University of Cambridge, UK

Contents

Volume 90
Special Issue
April 2008

www.sensorsportal.com

ISSN 1726-5479

Special Issue on Modern Sensing Technologies

Editorial

Modern Sensing Technologies

Subhas Chandra Mukhopadhyay and Gourab Sen Gupta 1

Sensors for Medical/Biological Applications

Characteristics and Application of CMC Sensors in Robotic Medical and Autonomous Systems

X. Chen, S. Yang, H. Natuhara K. Kawabe, T. Takemitsu and S. Motojima 1

SGFET as Charge Sensor: Application to Chemical and Biological Species Detection

T. Mohammed-Brahim, A.-C. Salaün, F. Le Bihan 11

Estimation of Low Concentration Magnetic Fluid Weight Density and Detection inside an Artificial Medium Using a Novel GMR Sensor

Chinthaka Gooneratne, Agnieszka Łekawa, Masayoshi Iwahara, Makiko Kakikawa and Sotoshi Yamada 27

Design of an Enhanced Electric Field Sensor Circuit in 0.18 μm CMOS for a Lab-on-a-Chip Bio-cell Detection Micro-Array

S. M. Rezaul Hasan and Siti Noorjannah Ibrahim 39

Wireless Sensors

Coexistence of Wireless Sensor Networks in Factory Automation Scenarios

Paolo Ferrari, Alessandra Flammini, Daniele Marioli, Emiliano Sisinni, Andrea Taroni 48

Wireless Passive Strain Sensor Based on Surface Acoustic Wave Devices

T. Nomura, K. Kawasaki and A. Saitoh 61

Environmental Measurement OS for a Tiny CRF-STACK Used in Wireless Network

Vasanth Iyer, G. Rammurthy, M. B. Srinivas 72

Ubiquitous Healthcare Data Analysis And Monitoring Using Multiple Wireless Sensors for Elderly Person

Sachin Bhardwaj, Dae-Seok Lee, S.C. Mukhopadhyay and Wan-Young Chung 87

Capacitive Sensors

Resistive and Capacitive Based Sensing Technologies

Winncy Y. Du and Scott W. Yelich 100

A Versatile Prototyping System for Capacitive Sensing <i>Daniel Hrach, Hubert Zangl, Anton Fuchs and Thomas Bretterklieber</i>	117
The Physical Basis of Dielectric Moisture Sensing <i>J. H. Christie and I. M. Woodhead</i>	128
Sensors Signal Processing	
Kalman Filter for Indirect Measurement of Electrolytic Bath State Variables: Tuning Design and Practical Aspects <i>Carlos A. Braga, João V. da Fonseca Neto, Nilton F. Nagem, Jorge A. Farid and Fábio Nogueira da Silva</i>	139
Signal Processing for the Impedance Measurement on an Electrochemical Generator <i>El-Hassane Aglzim, Amar Rouane, Mustapha Nadi and Djilali Kourtiche</i>	150
Gas Sensors	
Gas Sensing Performance of Pure and Modified BST Thick Film Resistor <i>G. H. Jain, V. B. Gaikwad, D. D. Kajale, R. M. Chaudhari, R. L. Patil, N. K. Pawar, M. K. Deore, S. D. Shinde and L. A. Patil</i>	160
Zirconia Oxygen Sensor for the Process Application: State-of-the-Art <i>Pavel Shuk, Ed Bailey, Ulrich Guth</i>	174
Image Sensors	
Measurement of Digital Camera Image Noise for Imaging Applications <i>Kenji Irie, Alan E. McKinnon, Keith Unsworth, Ian M. Woodhead</i>	185
Calibration-free Image Sensor Modelling Using Mechanistic Deconvolution <i>Shen Hin Lim, Tomonari Furukawa</i>	195
Miscellaneous	
Functional Link Neural Network-based Intelligent Sensors for Harsh Environments <i>Jagdish C. Patra, Goutam Chakraborty and Subhas Mukhopadhyay</i>	209
MEMS Based Pressure Sensors – Linearity and Sensitivity Issues <i>Jaspreet Singh, K. Nagachenchaiah, M. M. Nayak</i>	221
Slip Validation and Prediction for Mars Exploration Rovers <i>Jeng Yen</i>	233
Actual Excitation-Based Rotor Position Sensing in Switched Reluctance Drives <i>Ibrahim Al-Bahadly</i>	243
A Portable Nuclear Magnetic Resonance Sensor System <i>R. Dykstra, M. Adams, P. T. Callaghan, A. Coy, C. D. Eccles, M. W. Hunter, T. Southern, R. L. Ward</i>	255
A Special Vibration Gyroscope <i>Wang Hong-wei, Chee Chen-jie, Teng Gong-qing, Jiang Shi-yu</i>	267
An Improved CMOS Sensor Circuit Using Parasitic Bipolar Junction Transistors for Monitoring the Freshness of Perishables <i>S. M. Rezaul Hasan and Siti Noorjannah Ibrahim</i>	276

Sensing Technique Using Laser-induced Breakdown Spectroscopy Integrated with Micro-droplet Ejection System <i>Satoshi Ikezawa, Muneaki Wakamatsu, Joanna Pawlat and Toshitsugu Ueda</i>	284
A Forward Solution for RF Impedance Tomography in Wood <i>Ian Woodhead, Nobuo Sobue, Ian Platt, John Christie.....</i>	294
A Micromachined Infrared Sensor for an Infrared Focal Plane Array <i>Seong M. Cho, Woo Seok Yang, Ho Jun Ryu, Sang Hoon Cheon, Byoung-Gon Yu, Chang Auck Choi.....</i>	302
Slip Prediction through Tactile Sensing <i>Somrak Petchartee and Gareth Monkman.....</i>	310
Broadband and Improved Radiation Characteristics of Aperture-Coupled Stacked Microstrip Antenna for Mobile Communications <i>Sajal Kumar Palit.....</i>	325
The Use of Bragg Gratings in the Core and Cladding of Optical Fibres for Accurate Strain Sensing <i>Ian G. Platt and Ian M. Woodhead.....</i>	333

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: <http://www.sensorsportal.com/HTML/DIGEST/Submission.htm>

Wireless Passive Strain Sensor Based on Surface Acoustic Wave Devices

T. Nomura, K. Kawasaki and A. Saitoh

Faculty of Engineering

Shibaura Institute of Technology, Tokyo, Japan

E-mail: nomurat@sic.shibaura-it.ac.jp

Received: 15 October 2007 / Accepted: 20 February 2008 / Published: 15 April 2008

Abstract: Surface acoustic wave (SAW) devices offer many attractive features for applications as chemical and physical sensors. In this paper, a novel SAW strain sensor that employs SAW delay lines has been designed. Two crossed delay lines were used to measure the two-dimensional strain. A wireless sensing system is also proposed for effective operation of the strain sensor. In addition, an electronic system for accurately measuring the phase characteristics of the signal wave from the passive strain sensor is proposed. *Copyright © 2008 IFSA.*

Keywords: Surface acoustic waves, SAW sensor, Strain sensor, Wireless sensing, SAW delay line

1. Introduction

Today, many different fields require measurement of strain and its distribution. Particularly notable today is the need for health and safety monitoring for the sake of safety and comfort, which requires constant monitoring of strains within complex structures and buildings as well as the strain distributions in mobile objects, typically the wings of an aircraft [1].

The traditional way to measure strain is using a resistance strain gauge, which is mainly structured to measure unidirectional strains. However, as is the case when measuring stress, rosette analysis is required when measuring strains on a plane. Rosette analysis requires multiple elements to be positioned together at a single location and used simultaneously. Consequently there a large number of elements and accordingly a large number of electrical supply lines, making the measurement process very complex.

A surface acoustic wave (SAW) can be easily excited on a piezoelectric substrate using an interdigital transducer (IDT). Most of such a wave's energy is concentrated within a depth of a single wavelength from the substrate's surface. Its propagation characteristics are easily affected by external physical and electrical changes. This is why applications of SAW's include sensors for measuring physical parameters. Recently, there have been many reports on SAW sensors that take advantage of SAW's propagation characteristics, which change easily in response to external factors [2], [3], [4], [5].

One advantage of using SAWs in sensors is that, since SAWs are slower than electromagnetic waves by approximately five orders of magnitude, these sensors can be made more compact. Furthermore, increasing the frequency of the sensors improve their precision and resolution.

In this paper, we clarify the relationship between changes in the propagation path length of a SAW and the phase of the wave. We then discuss a strain sensor that utilizes changes in the speed of a SAW caused by strain in the SAW device.

Although some reports on sensors using SAWs have been published, they mostly discussed one-dimensional strains [6], [7]. However in this study, we developed a SAW strain sensor that simultaneously measures strains in two directions using two SAW delay lines that intersect each other perpendicularly on a single substrate.

As demonstrated in the experiment reported below, we herein propose a two-dimensional strain sensor that simultaneously measures strains in two different directions using two delay lines that cross each other at right angles. These two delay lines exist on an anisotropic piezoelectric substrate (128° Y-cut, X-propagating LiNbO₃). As its working principle, this strain sensor monitors changes in the propagation path length caused by strains applied to the piezoelectric substrate. Furthermore, in this study we show that when this new SAW strain sensor is connected directly to an antenna it is capable of passive remote sensing.

2. Measurement of Strain Using SAW

In this section, the principle and the method of measurement of strain using SAW delay line is described.

2.1. Principle of Measurement

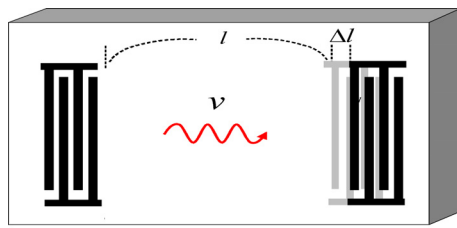
When a strain is applied to a substrate containing a SAW delay line, the propagation path length changes (see Figs. 1(a) and (b)). Let this change in propagation path length be denoted by Δl , and we then obtain the following expression for $\Delta\theta$, the phase difference between the input and output waves:

$$\begin{aligned}\theta + \Delta\theta &= \omega \frac{(l \pm \Delta l)}{v} \\ \Delta\theta &= \omega \frac{(l \pm \Delta l)}{v} - \omega \frac{l}{v} = \pm \omega \frac{\Delta l}{v}\end{aligned}\tag{1}$$

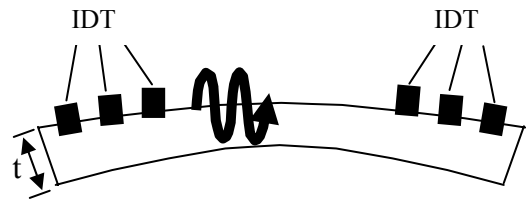
l : Propagation distance (m),
 v : Propagation velocity (m/s),
 θ : Phase difference (rad.),
 ω : frequency (rad. /s),

Therefore, by measuring the amount of phase change between the input and output of a delay line caused by a strain, we can determine the magnitude of the strain.

This magnitude of the strain can be calculated using Eqn. (1), using the amount of change caused by the strain, with reference to the phase difference when no strain is applied.



(a) Overview of SAW delay line and strain.



(b) Side view of an SAW delay line.

Fig. 1. Schematic diagram of strain sensor using SAW delay line.

2.2. Measurement System of Phase Change

For a SAW strain sensor to function correctly, changes in the phase of the SAW must be accurately measured. In the following, we briefly describe the circuit that was used to accurately measure the phase in our measurements.

Fig. 2 shows the measuring circuit that we used in the experiment to precisely measure phase changes produced by strain.

The standard signal generator (SSG) generates a continuous wave that is then divided into two by the power divider. One component is used as a reference wave and the other is used for measuring. This measurement component of the continuous wave is input into the mixer together with a rectangular wave from a pulse function generator (pulse FG). This produces a tone burst wave, which is used to excite the SAW device.

If the device is strained, the propagation length changes, and a phase difference that corresponds to the strain is produced. An automatic gain control amplifier (Amp.1 and Amp.2) is used to amplify the continuous wave divided for a reference and the tone burst wave in which a phase difference has been produced due to propagation through the SAW device, so that these two waves have equal amplitudes. If the continuous wave used as a reference and the tone burst wave with the phase difference are input into the mixer, the mixer outputs a signal that corresponds to the phase difference between the two waves. This phase difference signal from the mixer is used as the output signal.

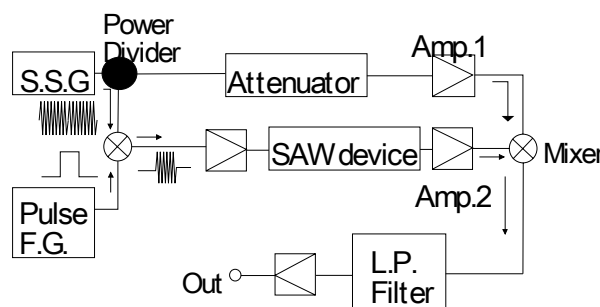


Fig. 2. Schematic diagram of strain sensor system.

3. Strain Sensor Using SAW Devices

We first clarify the characteristics of a one-dimensional strain sensor with a delay line, in order to understand the basic characteristics of a SAW strain sensor.

3.1. One-dimensional Strain Sensor

Fig. 3 shows a SAW sensor that measures unidirectional strains. This sensor has a pair of IDTs, one for receiving and the other for transmitting, fabricated on its piezoelectric substrate, as shown in Fig. 1(a). It measures strains in a single direction only, and is composed of a single-channel delay line. We constructed a strain sensor with a one-dimensional delay line on a 128° Y-cut, X-propagating LiNbO₃ substrate, and examined its characteristics. The sensor was composed of a delay line with a propagation path length of 100λ (λ : wavelength) and a frequency of 40 MHz.

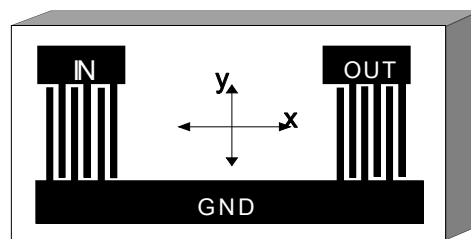


Fig. 3. One-dimensional strain sensor pattern.

3.2. Measurement Method

In the experiments, we attached the SAW strain sensor to a $10 \text{ cm} \times 10 \text{ cm}$ phosphor bronze plate, and fixed one side of the bronze plate as shown in Fig. 4. We then applied a load to the opposite side of the plate to produce a strain. A positive (+) strain indicated that the propagation path was stretched, while a negative (-) strain showed that the propagation path was reduced.

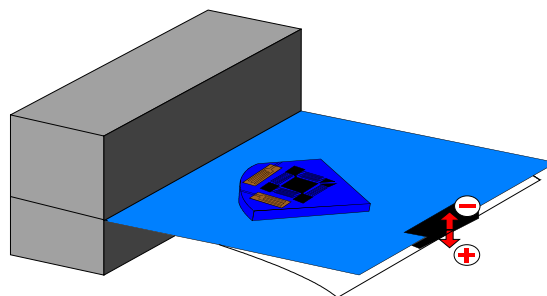


Fig. 4. Two-dimensional SAW strain sensor on a cantilever.

4. Characteristics of SAW Strain Sensor

In this section, we show the fundamental characteristics of SAW strain sensor obtained by using electric measurement system.

4.1. One-dimensional Strain Sensor

Fig. 5 shows, for the case when a strain in the x direction is applied to the delay line of Fig. 3, the strain in the substrate in the x direction as well as the phase difference caused by the change of the SAW propagating length in the x direction.

A positive (+) strain (strain is plotted on the horizontal axis) indicates that the propagation path is extended, while a negative (-) strain shows that the path is shortened. The strain in horizontal is measured by the strain gauge. We also measured the strain on the substrate using a resistance strain gauge attached close to the SAW propagation path. In these experiments, we varied the strain by 20 (μ strain) each time.

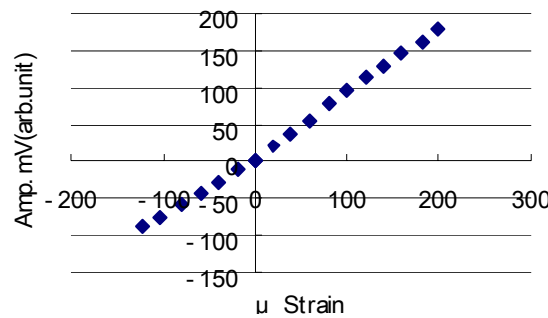


Fig. 5. Response of SAW sensor versus static strain.

From the figure, we can see that the strain and the phase difference are proportional, which implies that we can measure the strain using a SAW delay line.

Next, we investigated how the SAW phase difference is related to the strain direction. In our experiment, we used a cantilever to rotate the fixed bronze plate by 90°, setting the direction of the strain to the y direction shown in Fig. 4.

Fig. 6 shows the results of this particular experiment together with the results shown in Fig. 5 in the same plot. Thus, Fig. 6 shows the relationship between the strain in the x direction of the substrate and the phase difference caused by a change in the length of the SAW propagating in the x direction for the case when strains are applied in two directions (x and y). In other words, the horizontal axis in the figure denotes the strain in the x direction when strains are applied in both the x and y directions. In addition, the vertical axis shows the phase difference (in degrees), which we obtained by calculating the output of the measurement circuit and then converting it into a phase difference.

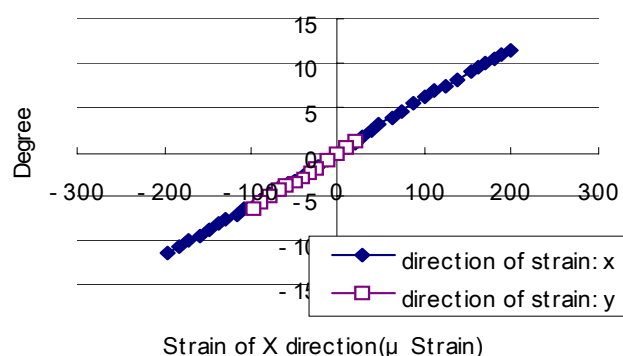


Fig. 6. Response of the SAW sensor versus static strain.

This plot shows that, regardless of whether the strain is in the x or y direction, the same relationship holds between the strain in the delay line and the phase difference of the propagating SAW. Thus, we can conclude that the phase difference of the SAW depends solely on the strain in the delay line, regardless of the direction of the strain.

4.2. Dependence on Surface Condition

Next we investigated the dependency to a surface condition of the SAW propagation path. Fig. 7 shows the results obtained from the electrical open and short condition on the propagation surface.

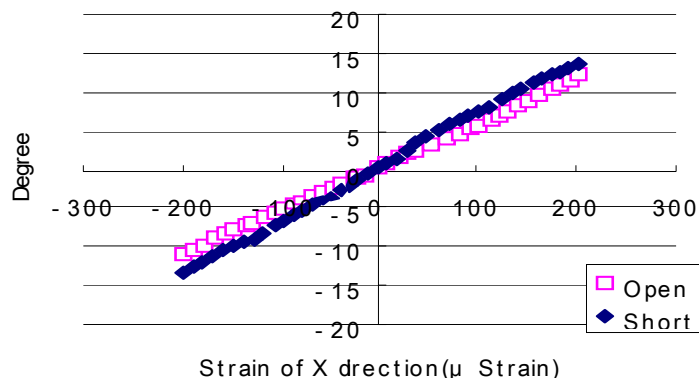


Fig. 7. Responses of the SAW sensor dependence on the surface condition. (1).

According to the Eqn.1, the phase change depends on the SAW velocity. On the electrical open surface, the velocity of SAW is 3880 m/s, and on the short surface 3990 m/s. The slight change of the phase was caused by this velocity difference as showed by the Eqn.1. This means the sensitivity of the strain sensor depend on the surface condition.

The response of the SAW sensor is also proportional to the length of the delay line. Fig. 8 shows dependence to path length. The results showed in Fig.8 are obtained from two delay lines arranged in parallel. The results show clearly that the sensitivity is proportional to the length of delay line. One delay line has 150λ , and the other $100, \lambda$ respectively.

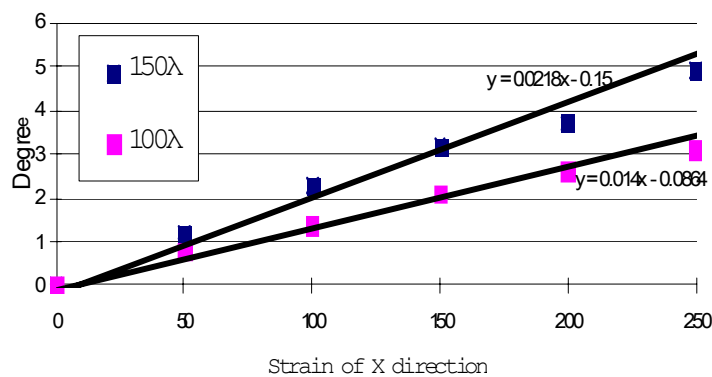


Fig. 8. Response of the SAW sensor dependence on the propagation length. (2).

4.3. Response to Dynamic Strain Sensor

Fig. 9 shows a response to a dynamic strain. The cantilever was vibrated by periodic force with 50 Hz. In the Fig. 9, the result obtained by the strain gauge is also shown. The response of the SAW sensor almost coincides with the results of conventional strain gauge.

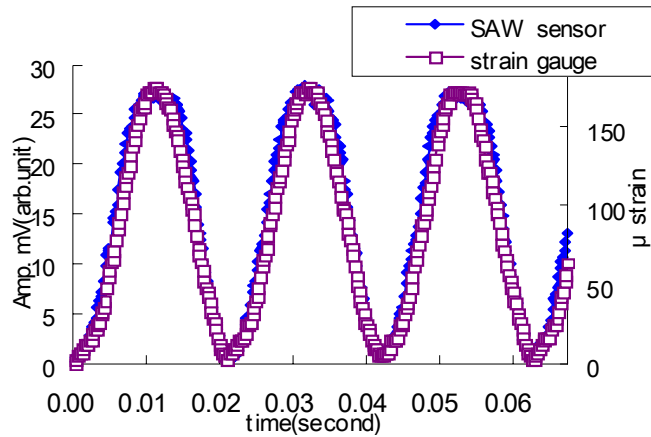


Fig. 9. Response of the SAW sensor to dynamic strain. (Frequency: 50 Hz)

Fig. 10 shows a response of the sensor when a dynamic strain was applied 0 μ strain to 140 μ strain. Fig. 11 also shows the change of response to the frequency of vibration on constant strain (30 μ strain). These results show the responses with a good linearity within the limits this measurement.

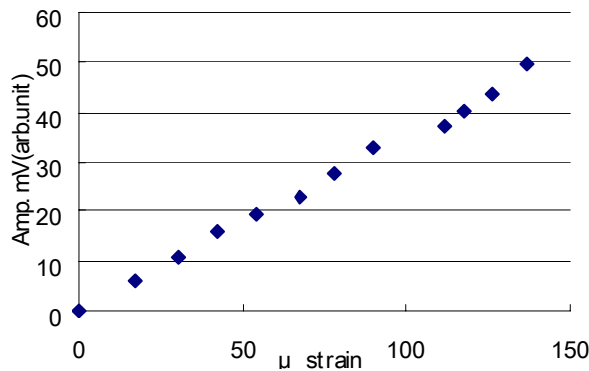


Fig. 10. Linearity of the SAW sensor to dynamic strain.

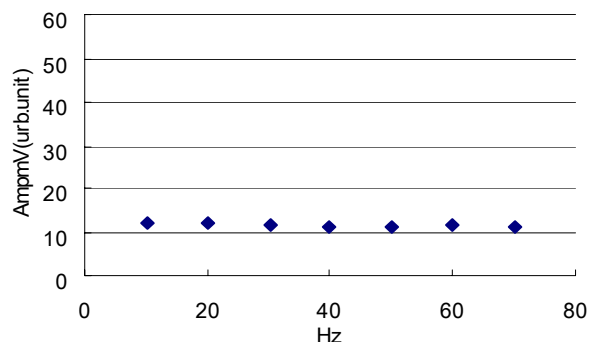


Fig. 11. Response of the SAW sensor as a function of vibration frequencies.

5. Two-dimensional SAW Strain Sensor

Fig. 12 shows the configuration of the SAW sensors designed to enable the simultaneous measurement of strains in two directions. In each of the two pairs of delay lines, the lines are orientated perpendicularly to each other to enable the simultaneous measurement of the strains in both the x and y directions.

We excited SAWs in two directions, x and y (see Fig. 12), and measured the phase changes in each of these two directions. In this way, we used a single SAW device to measure the strains in the two directions.

However, generally the excitation efficiency and velocity of SAWs in a piezoelectric substrate vary depending on their propagation direction as a result substrate's anisotropy. For this reason, there are cases when the output characteristics of the delay lines in the two directions cannot be made the same resulting in an error in the phase measurements.

To resolve this problem in two-dimensional strain measurement, it is desirable for the SAWs used to have the same excitation efficiency, velocity, and loss.

Since we used 128° Y-cut, X-propagating LiNbO_3 in our experiment, the propagation velocity and excitation efficiency differed considerably between the x direction and the perpendicular direction (90°) to x. In our substrate, however, the propagation characteristics were symmetric about the x-axis. We therefore installed the delay lines so that they were symmetric about the x-axis and made them intersect other at right angles ($X \pm 45^\circ$), when we created our two-dimensional strain sensor.

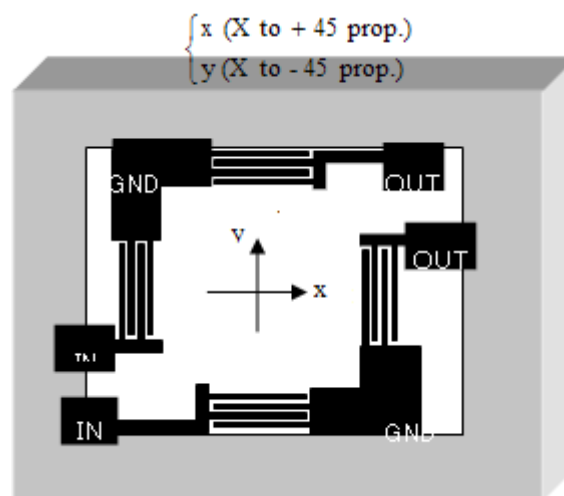


Fig. 12. Configuration of two-dimensional strain SAW sensor.

Fig. 13 shows the results of the experiments described above. The two lines in the plot indicate changes in the SAW phases produced by the strain in the delay lines in the two respective directions. The horizontal axis denotes the strain in each propagation path. At larger strains, the slopes of the lines differ significantly in the two directions. We conjecture that one cause for this was that the adhesion of the cantilever to the sensor was uneven (the piezoelectric substrate, part of the sensor, was rectangular and it was hard to apply the strains evenly over the substrate). However, in both of the two propagation directions, the phase difference of the SAW was proportional to the strain in the propagation path. This implies that it is possible to create a two-dimensional strain sensor device in which two sensors having the same characteristics intersect each other.

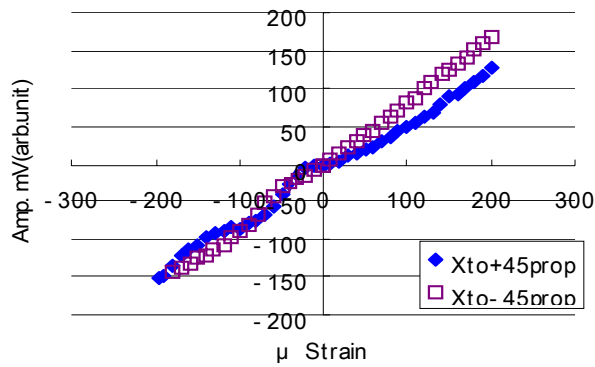


Fig. 13. Response of two-dimensional SAW sensor versus static strain.

6. Wireless SAW Strain Sensor

In this section, we tried remote passive sensing of strains, using a two-dimensional SAW strain sensor [5], [8].

Fig. 14 outlines the equipment we used for the remote sensing experiment. In this wireless strain measurement, we connected an antenna directly to the IDT of the delay-line SAW sensor shown in Fig. 7. A tone burst wave was used as the interrogation signal. The tone burst wave output from the interrogation unit is emitted from the sending antenna and received by the antenna attached to the SAW sensor. The IDT connected to the antenna directly excites a SAW and, after detecting strain, the signal is emitted from the same antenna.

Fig. 15 shows how the IDTs were connected to the antenna. These two IDTs were connected directly to each other and a signal from the antenna excited a SAW in both directions. Fig. 16 shows a typical waveform of the wireless SAW sensor.

In our experiment, we set the frequency to 50 MHz and the distance between the two antennas to 55 cm. Also, we used the same strain sensor in the $X \pm 45^\circ$ direction described in Section 4.

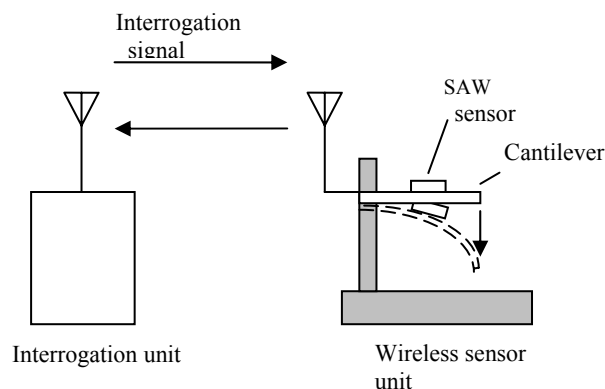


Fig. 14. Schematic diagram of the strain monitoring system.

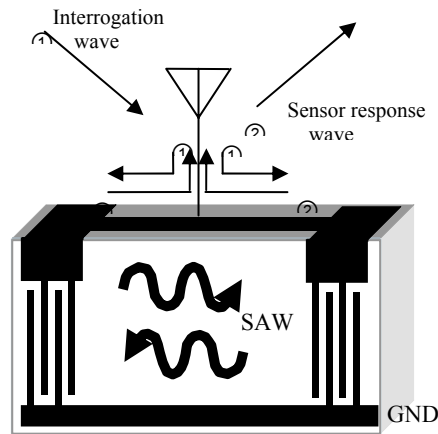


Fig. 15. Schematic diagram of the wireless SAW sensor.

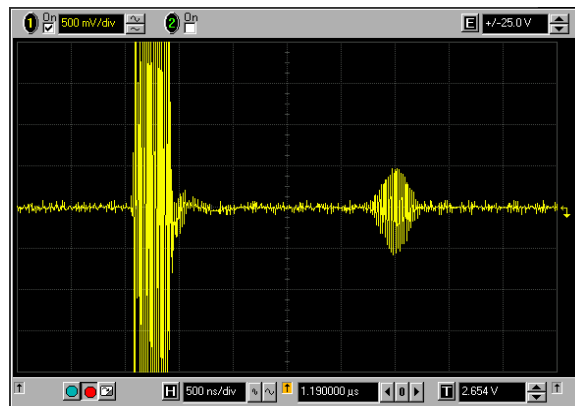


Fig. 16. Typical waveform of the wireless SAW sensor.

Fig. 17 shows the relationship between the strain and the output in each of the directions, in the wireless measurement. The response was proportional to the strain. The result is similar to the results of the wire measurements we conducted in Section 4. This implies that a SAW strain sensor is capable of measuring two-dimensional strains in a wireless system.

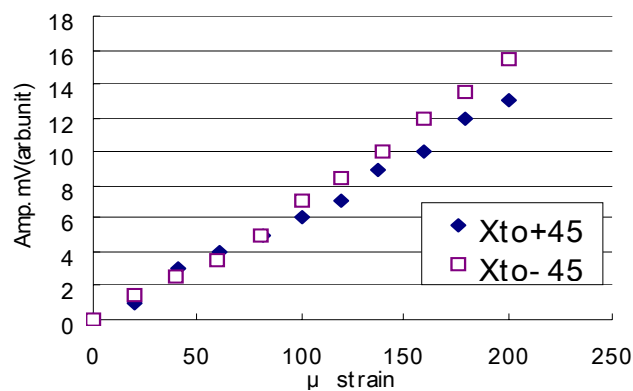


Fig. 17. Response of two-dimensional wireless SAW sensor versus applied strain.

7. Conclusion

This study proposed a strain sensor featuring a SAW device and investigated its characteristics. We obtained the following results:

Changes in the phase of a SAW delay line are proportional to the strain in the propagation path. This enables strains to be measured using SAWs.

We also demonstrated that, by placing two delay lines perpendicular to each other, we are able to measure strains in two different directions simultaneously. In such a case, by selecting the right propagation directions of the SAW, we can obtain similar characteristics in both directions.

Finally, we connected the sensor to an antenna and conducted an experiment that showed that wireless, passive measurement of strains is possible.

Acknowledgements

This research was supported in part by Research Fund C of the Ministry of Education, Culture, Sports, Science and Technology of Japan. The authors wish to express their gratitude for this assistance.

References

- [1]. V. K. Varadan, Microsensors, MEMS and NEMS for complex adaptive smart structures and systems, *Smart Materials and Structural Systems*, No. 1-1, 2001, pp. 135-148.
- [2]. H. Wohltjen and R. Dessy, Surface acoustic wave probe for chemical analysis 1, *Analytical Chem.*, Vol. 51, No. 9, 1979, pp. 1485-1475.
- [3]. H. Wohltjen, Surface acoustic wave micro-sensors, *Proc. of 4th International Conference on Solid-state sensors and actuators*, Tokyo, 1987, pp. 471-477.
- [4]. M. E. Motamedi and R. M. White, Special issue on acoustic sensors, *IEEE Trans. UFFC.*, Vol. UFFC-34, No. 2, 1987, pp. 122.
- [5]. A. Pohl, A review of wireless SAW sensors, *IEEE Trans. UFFC.*, Vol. 47, No. 2, March 2000, pp. 317-332.
- [6]. D. Hauden, F. Bindler, R. Coquerel, SAW cantilever beam accelerometer sensitivities, *Proceedings of IEEE 1985 Ultrasonics Symposium*, 1985, pp. 486-489.
- [7]. H. Scherr, G. Scholl, F. Seifert and R. Weigel, Quartz pressure sensor based on SAW reflective delay line, *Proc. of 1996 IEEE Ultrasonics Symposium*, 1996, pp. 347-350.
- [8]. J. Hayasaka, K. Tanaka, T. Miura, Y. Ikeda, and H. Kuwano, Wireless vibration sensor with a single-port surface acoustic wave sensor, *Proceedings of the 23rd Sensor Symposium*, 2006, pp. 455-458.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In addition, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 6-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: <http://www.sensorsportal.com/HTML/DIGEST/Submission.htm> Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2008.pdf



www.sensorsportal.com

**e-Impact Factor 2007:
156.504**



Subscription 2008

*Sensors & Transducers Journal (ISSN 1726-5479)
for scientists and engineers who need to be
at cutting-edge of sensor and measuring
technologies and their applications.*

*Keep up-to-date with the latest, most significant
advances in all areas of sensors and transducers.*

**Take an advantage of IFSA membership
and save **40 %** of subscription cost.**

Subscribe online:

http://www.sensorsportal.com/HTML/DIGEST/Journal_Subscription_2008.htm

www.sensorsportal.com