Proceedings of the Joint Workshop on

Frontier Photonics and Electronics

4 - 5 March, 2010
Sydney, Australia

at
School of Electrical Engineering and Telecommunications
Faculty of Engineering
University of New South Wales

Sponsored by:
Photonics and Optical Communications
University of New South Wales

Global COE in secure-Life Electronics
University of Tokyo

iPL, University of Sydney
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## Contents

<table>
<thead>
<tr>
<th>Session 1: Fibre Sensors and Applications</th>
</tr>
</thead>
</table>
| [1-1] Recent Progress in Fiber Optic Nerve Systems for Security Life and Society | 2  
| Kazuo Hotate and Zuyuan He, The University of Tokyo, Japan |
| Takashi Kubota and Tatsuaki Hashimoto, The University of Tokyo, Japan |
| [1-3] Progress of Fiber Optic Hydrophone | 10  
| Zhou Meng, Yongming Hu, Zhengliang Hu, National University of Defense Technology, China |
| [1-4] Advances in Distributed and Multiplexed Fiber Optic Sensors | 13  
| Zuyuan He and Kazuo Hotate, The University of Tokyo, Japan |

<table>
<thead>
<tr>
<th>Session 2: Nano Photonic Materials and Applications</th>
</tr>
</thead>
</table>
| [2-1] Porphyrins for ‘Molecular Electronics’ and Photonic Applications: An Overview | 20  
| Maxwell J. Crossley, The University of Sydney, Australia |
| [2-2] Progress in developing nano-scale photonic devices driven by an optical near-field using ZnO quantum dots | 23  
| Takashi Yatsui and Motoichi Ohtsu, The University of Tokyo, Japan |
| [2-3] Nonlinear optical imaging of nanoparticle penetration in human skin | 27  
| A. V. Zvyagin*, X. Zhao*, Z. Song*, T. Kelf*, W. Sanchez*, M. S. Roberts*  
| * Macquarie University, Australia; † The University of Queensland, Australia |

<table>
<thead>
<tr>
<th>Session 3: Structured and Special Fibre Sensors</th>
</tr>
</thead>
</table>
| [3-1] An Overview of Structured Optical Fibres and Gratings for Sensing | 37  
| J. Canning, The University of Sydney, Australia |
| [3-2] Microstructured waveguide couplers for optical sensing | 40  
| Graham Town and Ravi McCosker, Macquarie University, Australia |
| [3-3] Side Polished Fiber and its Application | 42  
| Zhe Chen, Jun Zhang, Jieyuan Tang and Jianhui Yu, Jinan University, China |
| [3-4] Bragg grating writing in photonic crystal fibres: Progress and applications | 44  
| Kevin Cook*, John Canning*, Alexandre A. P. Pohl*, John Holdsworth* and Michael Stevenson*  
| * The University of Sydney, Australia; † Federal University of Technology, Brazil;  
| ‡ University of Newcastle, Australia |
| [3-5] Regenerated Gratings | 47  
| John Canning*, Somnath Bandyopadhyay†, Michael Stevenson*, Palas Biswas‡, Jacob Fenton*, Matthias Aslund‡,  
| * The University of Sydney, Australia; † Central Glass and Ceramic Research Institute (CGCRI), India |
### Session 4  Nonlinear Photonic Effects & Properties

| [4-1] | Rogue waves, super-continuum generation and Akhmediev breathers | Nail Ahkmediev, Australian National University, Australia |
| [4-2] | Solid state Raman lasers | Xingyu Zhang, Qingpu Wang, Zhenhua Cong, Xiaohan Chen, Zhaojun Liu, Shuzhen Fan, Xiaolei Zhang, Shuta Li, Fufang Su, Shuanghong Ding, Shandong University, China |
| [4-3] | Rogue waves in optical Fibres | Adrian Ankiewicz and Nail Ahkmediev, Australian National University, Australia |
| [4-4] | Spinmotive force in magnetic tunnel junction | Pham Nam Hai and Masaaki Tanaka, The University of Tokyo, Japan |
| [4-5] | Second Harmonic Generation in Periodically Poled Silica Fibres | Albert Canagasabey a,b, Costantino Corbari *, Morten Ibsen * and Peter G Kazansky *, a University of Southampton, United Kingdom; b The University of New South Wales, Australia |

### Session 5:  Fibre Sensors and Applications 2

| [5-1] | Optical Feedback Self-mixing Interferometric Sensing | Jiangtao Xi and Yanguang Yu, University of Wollongong, Australia |
| [5-2] | 447nm Laser of Diode-side-pumped Nd:YAP crystal | Chen Zhenqiang, Li Jingzhao, Li Anming and Li Zhen, Jinan University, China |
| [5-3] | Measurement and Analysis of Mode hopping in the ultra-narrow line-width fiber ring laser | Zhengliang Hu, Pan Xu, Mingxiang Ma, Zhou Meng, Yongming Hu, National University of Defense Technology, China |
| [5-4] | Fiber Vibration Sensor and its Application | Jun Chang a,b, Qingpu Wang *, Xingyu Zhang *, Haifeng Qi b, Chang Wang b, Liangzhu Ma b, a Shandong University, China; b Shandong Academy of Science, China |
| [5-5] | Optical fibre sensors and the constructed common mode | Andrew Michie *, Ian Bassett *, John Haywood * and Mamdouh Matar a, a The University of Sydney, Australia; b Smart Digital Optics Pty Limited, Australia |

### Session 6:  Photonic and Optoelectronic Effects and Devices

| [6-1] | Control of TM modes in the terahertz range using a simple waveguide structure with a photonic crystal electrode | Yohei Sakasegawa, Toshiyuki Ihara, and Kaz Hirakawa, The University of Tokyo, Japan |
| [6-2] | Low Impedance Bulk LTSA for Real-Time Millimeter Wave Imaging Front-End | Damri Radenamad, Takashi Aoyagi, Akira Hirose, The University of Tokyo, Japan |
| [6-3] | A Real-Time Large-Scale Multiple-Chip K-means Learning Processor System for Visual Sensors | Yitao Ma and Tadashi Shibata, The University of Tokyo, Japan |
| [6-4] | Electromigration at quantum point contacts of ferromagnetic metals under intense electrical stresses | Kenji Yoshida, Akinori Umeno, Shuichi Sakata, and Kazuhiko Hirakawa, The University of Tokyo, Japan |
| [6-5] | Fabrication of Multi-Stacked InAs/GaNAs Quantum Dots for Application to Semiconductor Optical Amplifier | Ayami Takata, Ryuji Oshima and Yoshitaka Okada, The University of Tokyo, Japan |
| [6-6] | Acousto-Optic Effect in Fiber Bragg Gratings | Roberson Assis de Oliveira a*, John Canning *, Alexandre Almeida Prado Pohl a, a Federal University of Technology, Brazil; b The University of Sydney, Australia |
[6-7] A new method to fabricate sea-island bicomponent microstructured polymer optical fibre
Yuqing Liu a, Chuanxiong Zhang a, Colin Brackley a, Shouren Yang a, Fan Yang a and Gang-Ding Peng b
a CSIRO Materials Science and Engineering, Australia; b The University of New South Wales, Australia

[6-8] Chirped Fiber Grating with Nonlinear Effective Index Modulation
Binbin Yan a,b, Chongxiu Yu a, Mo Li a, Jinjin Guo b and Gang-Ding Peng b
a University of Posts and Telecommunications, China; b The University of New South Wales, Australia

[6-9] Development on the Bismuth-doped Silica-based Optical Fibers
Jian-Xiang WEN a,b and Gang-Ding PENG a
a The University of New South Wales, Australia; a Shanghai University, China

Session 7: Photonic and Fibre Sensors

[7-1] Synthesis of Optical Coherence Function for Distributed Long-length FBG Sensor
Koji Kajiwara, Zuyuan He and Kazuo Hotate, The University of Tokyo, Japan

[7-2] Noise Reduction in Digitalized Resonator Fiber Optic Gyro by a Resonator with Twin 90° Polarization-axis Rotated Splices
Xijing Wang, Zuyuan He, and Kazuo Hotate, The University of Tokyo, Japan

[7-3] Ultra-high strain-resolution FBG sensor for static strain measurement using cross-correlation processing
Qingwen LIU, Zuyuan HE, Tomochika TOKUNAGA and Kazuo HOTATE, The University of Tokyo, Japan

[7-4] Fibre Ring Laser Intra-Cavity Absorption Spectroscopy For Gas Sensing
Mo Li a,b, Kun Liu a,c and Gang-Ding Peng a,b
a The University of New South Wales, Australia; b Harbin Institute of Technology, China; c Tianjin University, Tianjin, China

[7-5] Failure Analysis of Laminated Composites with embedded Fibre Bragg Gratings (FBG)
Raju a, Prusty B.G a, Kelly D.W. a, Peng G.D. a, Lyons D. a
a The University of New South Wales, Australia; b EMP Composites, Australia

[7-6] A smart seismic geophone based on distributed-feedback fiber lasers
Shaohua Chen a,b Gang-Ding Peng a,b
a The University of New South Wales, Australia; b China University of Petroleum, China

[7-7] Porphyrin-based optical fibre acid sensor
George Huyang, John Canning, Mattias Aslund, Danial Stocks, Tony Khoury and Maxwell J. Crossley,
The University of Sydney, Australia

[7-8] Point measurement of magnetic field strength using compound phase-shifted FBGs
Philip Orr and Pawel Niewczas, University of Strathclyde, UK

[7-9] Sensitivity Enhancement in Composite Cavity Fiber Laser Hydrophone
Asrul Izam Azmi, Deep Sen and Gang-Ding Peng, The University of New South Wales, Australia

[7-10] Porphyrin assisted self-assembly of mesostructured silica spheres
Masood Naqshbandi, John Canning, Danijel Boskovic, Hank de Bruyn and Maxwell J. Crossley,
The University of Sydney, Australia

Workshop Photo

Author Index
Joint Workshop on
Frontier Photonics and Electronics

Organization by

Venue: University of New South Wales
Time: Thursday and Friday, 4 and 5 March 2010

This workshop brings together Japanese and Australian researchers who are working in photonics and electronics. We will have about 50 researchers from University of Tokyo, University of NSW and University of Sydney. In addition, we will also invite several colleagues from Chinese universities and other Australian universities to give presentations.

This workshop will serve as a platform for enhancing the interaction and understanding and for strengthening academic links and research collaboration among the staff and research students of the participating universities. It will be an exciting opportunity that brings together academics and research students into a close, interactive environment and form future international partnerships of excellence.

The workshop will have presentations reporting on the latest progress in related research fields. Each presenter is invited to submit a paper 2 or more pages to be included in paper collection of the workshop. It is intended to be a stimulating forum and enjoyable gathering enabling exchange of ideas and opening up international collaboration opportunities among the universities.

The participating universities, including The University of Tokyo, UNSW, Sydney University, are all leading research universities in our respective countries. It is important to establish new partnerships among the universities, strengthen collaboration through sharing the universities’ resources and expertise.

We look forward to seeing you at the workshop in UNSW and take the opportunity to further enhance and extend successful collaborations.

Organizers:

Prof Kazuo Hotate
School of Engineering / Graduate School of Engineering, The University of Tokyo

Prof Gang-Ding Peng
Photonics and Optical Communications, School of Electrical Engineering & Telecommunications
University of New South Wales

Prof John Canning
Interdisciplinary Photonics Laboratories (iPL), School of Chemistry, The University of Sydney

A/Prof Zuyuan He
School of Engineering / Graduate School of Engineering, The University of Tokyo
# Joint Workshop on Frontier Photonics and Electronics

**Venue:** Room G3, Electrical Engineering Building  
University of New South Wales

**Time:** Thursday and Friday, 4 and 5 March 2010

## Day 1: Thursday, 4 March, 2010

**Tea Time:** 9:10-9:40 am  
**Room G3, Electrical Engineering Building, UNSW**

**Welcome & Opening:** 9:40-10:00 am  
Prof Graham Davies, Prof Eliathamby Ambikairajah  
Chair: Prof John Canning

### Session 1: Fibre Sensors and Applications  
Chair: Prof Gang-Ding Peng  
10:00-12:00 pm

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00-10:30</td>
<td>Prof Kazuo Hotate, University Of Tokyo, Japan</td>
<td>Recent progress in fiber optic nerve systems for security life and society</td>
</tr>
<tr>
<td>10:30-11:00</td>
<td>Prof Takashi Kubota, University Of Tokyo, Japan</td>
<td>Optical sensors for spacecraft navigation in deep space exploration</td>
</tr>
<tr>
<td>11:00-11:30</td>
<td>Prof Zhou Meng, National University Of Defense Technology, China</td>
<td>Development of fiber optic hydrophone</td>
</tr>
<tr>
<td>11:30-12:00</td>
<td>Prof Zuyuan He, University Of Tokyo, Japan</td>
<td>Advances in distributed and multiplexed fiber optic sensors</td>
</tr>
</tbody>
</table>

**Lunch:** 12:00 noon – 13:00 pm  
**Room G3, Electrical Engineering Building, UNSW**

### Session 2: Nano Photonic Materials and Applications  
Chair: Prof Yong-Ming Hu  
13:00-15:00 pm

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:00-13:30</td>
<td>Prof Maxwell Crossley, University of Sydney, Australia</td>
<td>Porphyrins for Photonic Applications</td>
</tr>
<tr>
<td>13:30-13:55</td>
<td>Prof Takashi Yatsui, University of Tokyo, Japan</td>
<td>Progress in developing nano-scale photonic devices driven by an optical near-field</td>
</tr>
<tr>
<td>13:55-14:20</td>
<td>Prof Andrei V. Zvyagin, Macquarie University, Australia</td>
<td>Nonlinear optical imaging of nanoparticle penetration in human skin</td>
</tr>
<tr>
<td>14:20-14:40</td>
<td>Prof Chee Yee Kwok, University of NSW, Australia</td>
<td>Issues in IC 3D integration: Electrical, Optical, Fluidic Connectivity</td>
</tr>
<tr>
<td>14:40-15:00</td>
<td>Prof Gang-Ding Peng, University of NSW, Australia</td>
<td>Photosensitive Polymer Optical Materials, Fibres and Polymer Optical Fibre Gratings</td>
</tr>
<tr>
<td>Session 3: Structured and Special Fibre Sensors</td>
<td>15:30-17:30 pm</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>Chair: Dr Adrian Ankiewicz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:30</td>
<td>Prof John Canning, University of Sydney, Australia</td>
<td>Overview of Structured fibre Sensors</td>
</tr>
<tr>
<td>16:00</td>
<td>Prof Graham Town, Macquarie University, Australia</td>
<td>Novel approaches to optical sensing with microstructured waveguides</td>
</tr>
<tr>
<td>16:30</td>
<td>Prof Zhe Chen, Jinan University, China</td>
<td>Side polished fiber and its application</td>
</tr>
<tr>
<td>16:50</td>
<td>Dr Kevin Cook, University of Sydney, Australia</td>
<td>Bragg gratings in photonic crystal fibres: Progress and applications</td>
</tr>
<tr>
<td>17:10</td>
<td>Dr Michael Stevenson, University of Sydney, Australia</td>
<td>Regenerated gratings</td>
</tr>
</tbody>
</table>

**Tea time:** 17:30 – 18:00 pm
Room G3, Electrical Engineering Building, UNSW

**Dinner:** 18:45 – 21:30 pm

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**Day 2: Friday 5 March, 2010**

<table>
<thead>
<tr>
<th>Session 4: Nonlinear Photonic Effects &amp; Properties</th>
<th>10:00-12:00 noon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chair: Dr Kevin Cook</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>Prof Nail Ahkmediev, Australian National University, Australia</td>
<td>Rogue waves, supercontinuum generation and Ahkmediev breathers</td>
</tr>
<tr>
<td>10:30</td>
<td>Prof Xing-Yu Zhang, Shandong University, China</td>
<td>Solid state Raman lasers</td>
</tr>
<tr>
<td>11:00</td>
<td>Dr Adrian Ankiewicz, Australian National University, Australia</td>
<td>Rogue waves in optical fibres</td>
</tr>
<tr>
<td>11:20</td>
<td>Dr Nam Hai Pham, University of Tokyo, Japan</td>
<td>Spin motiveforce in magnetic tunnel junction</td>
</tr>
<tr>
<td>11:40</td>
<td>Dr Albert Canagasabey, University of NSW, Australia</td>
<td>SHG in periodically poled silica fibres</td>
</tr>
<tr>
<td>Session 5:</td>
<td><em>Fibre Sensors and Applications 2</em></td>
<td>13:00-14:50 pm</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td></td>
<td>Chair: Dr Albert Canagasabey</td>
<td></td>
</tr>
<tr>
<td>13:00-13:20</td>
<td>Prof Jiangtao Xi, University of Wollongong, Australia</td>
<td>Optical feedback self-mixing interferometric sensing</td>
</tr>
<tr>
<td>13:20-13:40</td>
<td>Prof Zhenqiang Chen, Jinan University, China</td>
<td>447nm blue laser of Diode-side-pumped Nd:YAP crystal</td>
</tr>
<tr>
<td>13:40-14:00</td>
<td>Dr Zheng-Liang Hu, National University of Defense Technology, China</td>
<td>Mode hopping mechanism and measurement in ultranarrow line-width ring fiber laser</td>
</tr>
<tr>
<td>14:00-14:20</td>
<td>Prof Jun Chang, Shandong University, China</td>
<td>Fiber vibration, acoustic sensor and its application</td>
</tr>
<tr>
<td>14:20-14:40</td>
<td>Dr Andrew Michie, University of Sydney, Australia</td>
<td>Optical fibre sensing and constructed common mode</td>
</tr>
</tbody>
</table>

**Tea Time:** 14:40 – 15:00 pm  
Room G3, Electrical Engineering Building, UNSW

<table>
<thead>
<tr>
<th>Session 6:</th>
<th><em>Short Presentation &amp; Poster Session</em></th>
<th>15:00-15:45 pm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chair: Dr Michael Stevenson</td>
<td></td>
</tr>
<tr>
<td><strong>Photonic and Optoelectronic Effects and Devices</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[6-1]</td>
<td>Mr Yohei Sakasegawa, University of Tokyo, Japan</td>
<td>Control of the TM Mode in the Terahertz Range Using a Simple Waveguide Structure with a Photonic Crystal Electrode, Yohei Sakasegawa, Toshiyuki Ihara, and Kazuhiko Hirakawa</td>
</tr>
<tr>
<td>[6-2]</td>
<td>Mr Damri Radenamad, University of Tokyo, Japan</td>
<td>Low Impedance Bulk LTSA for Real-Time Millimeter-Wave Imaging Front-End Damri Radenamad, Takashi Aoyagi, and Akira Hirose</td>
</tr>
<tr>
<td>[6-3]</td>
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<td>A Real-Time Large-Scale K-means Learning Processor System for Visual Sensors Yitao Ma and Tadashi Shibata</td>
</tr>
<tr>
<td>[6-4]</td>
<td>Mr Kenji Yoshida, University of Tokyo, Japan</td>
<td>Electromigration at Quantum Point Contacts of Ferromagnetic Metals under Intense Electrical Stresses Kenji Yoshida, Akinori Umeno, Shuichi Sakata, and Kazuhiko Hirakawa</td>
</tr>
<tr>
<td>[6-5]</td>
<td>Ms Ayami Takata, University of Tokyo, Japan</td>
<td>Fabrication of Multi-stacked InAs/GaNAs Quantum Dots for Application to Semiconductor Optical Amplifiers Ayami Takata, Ryuji Oshima, and Yoshitaka Okada</td>
</tr>
<tr>
<td>[6-6]</td>
<td>Mr Roberson Assis de Oliveira, University of Sydney, Australia</td>
<td>Acousto-Optic Effects in Fiber Bragg Gratings</td>
</tr>
<tr>
<td>[6-7]</td>
<td>Mr Fan Yang, University of NSW, Australia</td>
<td>Extrusion fabrication of sea-island bicomponent microstructured polymer optical fibre Yuqing Liu, Chuanxiong Zhang, Colin Brackley, Shouren Yang, Fan Yang and Gang-Ding Peng</td>
</tr>
<tr>
<td>[6-8]</td>
<td>Ms Jinjin Guo, University of NSW, Australia</td>
<td>Chirped fibre grating with nonlinear effective index modulation Binbin Yan, Chongxiu Yu, Mo Li, Jinjin Guo and Gang-Ding Peng</td>
</tr>
</tbody>
</table>
### Session 7: Short Presentation & Poster Session 15:45-16:30 pm

**Chair:** Prof Jun Chang

**Photonic and Fibre Sensors**

<table>
<thead>
<tr>
<th>Session 7-1</th>
<th>Mr Koji Kajiwara, University of Tokyo, Japan</th>
<th>Synthesis of Optical Coherence Function for Distributed Long-length FBG Sensor Koji Kajiwara, Zuyuan He, and Kazuo Hotate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Session 7-2</td>
<td>Ms Xijing Wang, University of Tokyo, Japan</td>
<td>Noise Reduction in Digitalized Resonator Fiber Optic Gyro by a Resonator with Twin 90° polarization-axis Rotated Splices Xijing Wang, Zuyuan He, and Kazuo Hotate</td>
</tr>
<tr>
<td>Session 7-3</td>
<td>Mr Qingwen Liu, University of Tokyo, Japan</td>
<td>Ultra-high Strain-resolution FBG Sensor for Static Strain Measurement using Cross-correlation Processing Qingwen Liu, Zuyuan He, Tomochika Tokunaga, and Kazuo Hotate</td>
</tr>
<tr>
<td>Session 7-4</td>
<td>Ms Mo Li, University of NSW, Australia</td>
<td>Fibre ring fibre intercavity gas sensor Mo Li, Jingmin Dai and Gang-Ding Peng</td>
</tr>
<tr>
<td>Session 7-5</td>
<td>Mr Raju, University of NSW, Australia</td>
<td>Delamination characterisation of curved composites using acoustic emission and fibre Bragg gratings Raju, B. G. Prusty, D. W. Kelly, D. Lyons and G. D. Peng</td>
</tr>
<tr>
<td>Session 7-6</td>
<td>Ms Shaohua Chen, University of NSW, Australia</td>
<td>A smart seismic geophone based on distributed-feedback fiber lasers Shaohua Chen and G. D. Peng</td>
</tr>
<tr>
<td>Session 7-7</td>
<td>Mr George Huyang, University of Sydney, Australia</td>
<td>An acid sensor</td>
</tr>
<tr>
<td>Session 7-8</td>
<td>Mr Philip Orr, University of Sydney, Australia</td>
<td>Point measurement of magnetic field strength using compound phase-shifted FBGs Philip Orr and Pawel Niewczas</td>
</tr>
<tr>
<td>Session 7-9</td>
<td>Mr Asrul Izam Azmi, University of NSW, Australia</td>
<td>Sensitivity Enhancement in Composite Cavity Fiber Laser Hydrophone Asrul Izam Azmi, Deep Sen and G. D. Peng</td>
</tr>
<tr>
<td>Session 7-10</td>
<td>Mr Masood Naqshbandi, University of Sydney, Australia</td>
<td>Porphyrin assisted self-assembly of mesostructured silica spheres</td>
</tr>
</tbody>
</table>

### Session 8: 16:30-18:00 pm

**Poster Presentation and Discussion**

**Chair:** Prof John Canning

**Thank you for your attendance!**
Session 1: Fibre Sensors and Applications
Recent Progress in Fiber Optic Nerve Systems for Security Life and Society

Kazuo Hotate and Zuyuan He

Dept. of Electrical Engineering and Information Systems, Graduate School of Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
hotate@sagnac.t.u-tokyo.ac.jp

Abstract — “Fiber optic nerve systems” have been studied to make structures and materials that can feel pain. We have developed the nerve systems with mm-order spatial resolution and kHz-order measurement speed, using optical correlation domain techniques.

Keywords — Optical fiber sensors, Distributed sensing, Brillouin scattering, FBG sensors, Smart materials and structures.

I. INTRODUCTION

Optical fibers can act as a sensor for strain or temperature through the properties, such as Brillouin scattering. By applying ways to analyze distribution of the property along the fiber, “fiber optic nerve systems” are realized to sense damages induced in materials and structures, in which the fiber is embedded.

Time domain techniques with pulsed lightwave have been studied for distribution sensing, and much improved recently. However, these have difficulties in realizing ultimate performances. We have proposed an “optical correlation domain technique” with continuous lightwaves [1]. By applying the technique to fiber Brillouin distributed strain sensing, we have realized 1.6mm spatial resolution, that is the highest resolution ever reported. Recently simultaneous measurement of strain and temperature distribution has also been demonstrated by using only one fiber. Systems for multiplexed fiber Bragg grating sensors have also been developed using the correlation domain technique.

II. BRILLOUIN OPTICAL CORRELATION DOMAIN ANALYSIS SYSTEM

Brillouin scattering has a frequency of about 11GHz down-shifted from the input lightwave. The frequency shift is changed by longitudinal strain applied to the fiber [2]. As a way to have the distributed information, we have proposed and developed a technique named “Brillouin Optical Correlation Domain Analysis; BOCDA” [3]. It is based on control of the correlation between the pump and probe continuous lightwaves, which excite the Stimulated Brillouin Scattering (SBS).

It is the point in our system that the pump and the probe are identically frequency-modulated at the laser source. As a result, SBS occurs exclusively at the correlation peak position, where the two lightwaves are highly correlated. The correlation peak width determines the spatial resolution. We can shift the correlation peak position along the fiber by simply changing the FM frequency. Then, the distributed measurement can be achieved.

Measurement range of 1,020 m with spatial resolution of 7 cm has been demonstrated [4]. The resolution of 1.6 mm has also been achieved, that is the highest resolution ever reported [5]. Sampling rate for one position has been much improved to be 1 kHz [6]. Recently, a new system, in which distribution of spontaneous Brillouin scattering can be measured, has also been proposed and demonstrated [7].

We have recently achieved discriminative sensing of strain and temperature only using a single optical fiber. We proposed to use a Panda-type polarization-maintaining fiber (PMF) for complete discrimination of strain and temperature [8, 9]. The experimental setup is shown in Fig. 1.

![Fig. 1. System for simultaneous measurement of strain and temperature distribution along a Birefringent optical fiber with correlation-based continuous-wave technique [9].](image)

In this system, Brillouin frequency shift is measured at first to obtain one relation between strain and temperature. Then, the birefringence is measured by observing the birefringence-determined frequency deviation of the dynamic acoustic grating generated with SBS process.
[10] to obtain the other relation between these. The strain and temperature can be figured out from the two relations.

Based on our theoretical and experimental findings that birefringence has opposite dependence on temperature compared to Brillouin frequency shift [8], the strain and the temperature can be detected discriminatively with a high accuracy. We succeeded experimentally in discriminating the strain and the temperature with an accuracy of 3~4 με and 0.07~0.08ºC [8]. Fully-distributed measurement for the two parameters, strain and temperature, has also been achieved with 12-cm spatial resolution as shown in Fig. 2 [9]

III. MULTIPLEXED FIBER BRAGG GRATING SENSORS WITH SAME BRAGG WAVELENGTH

Fiber Bragg grating multiplexed strain sensing has been widely studied [2]. We have proposed a scheme, in which the FBGs with the same Bragg wavelength can be multiplexed by using the correlation domain technique [11]. By newly introduced scheme to enhance the measurement speed, dynamic strain measurement has been demonstrated with 10kHz sampling rate.

Recently, we have also developed a system, in which the Bragg wavelength distribution inside a long-length FBG can be measured by the correlation domain technique [12]. Figure 3 shows a spectrum and Bragg wavelength distribution along a 100mm length FBG [12].

IV. CONCLUSION

By the correlation domain technique with continuous lightwaves, the BOCDA system has been developed as a fiber optic nerve system having a mm-order spatial resolution. Simultaneous measurement of strain and temperature distribution has also been realized. We have also developed the multiplexing scheme for the Bragg grating sensors with the same Bragg wavelength and the scheme for distributed Bragg wavelength sensing along a long-length FBG.

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Abstract — Intelligent instruments are required for navigation and guidance of spacecraft in deep space exploration. Advanced technology such as electronics, photonics, optics can make it possible to develop intelligent navigation sensors. Advanced technology has been developed in the Asteroid Sample Return mission, Hayabusa. Hayabusa spacecraft could rendezvous the target asteroid Itokawa and perform touchdown to collect samples from the asteroid surface by using advanced sensors. This paper introduces the outline of Hayabusa mission. This paper also presents the developed optical navigation sensors and flight results.

Keywords — Deep space exploration, Optical navigation sensors, Descent and touchdown, Hayabusa mission.

I. INTRODUCTION

In-situ observations of small bodies like asteroids or comets are scientifically very important because their sizes are too small to have high internal pressures and temperatures, which means they should hold the early chemistry of the solar system. In recent years, some rendezvous or sample-return missions to small body have received a lot of attention in the world. NEAR spacecraft[1] was successfully put into the orbit of the asteroid 433 Eros in February 2000. The Institute of Space and Astronautical Science (ISAS) of Japan launched the MUSES-C[2] spacecraft toward Asteroid 1998SF36 Itokawa in May 2003. After the launch, the spacecraft was renamed "Hayabusa". Rosetta[3] spacecraft was successfully launched to explore the comet in 2004.

In deep space missions, ground based operation is very limited due to the communication delay and low bit-rate communication. Therefore, autonomy is required for deep space exploration. On the other hand, because little information on the target asteroid is known in advance, robotics technology is used for the spacecraft to approach, rendezvous with, and land on the asteroid safely. In MUSES-C mission, Hayabusa spacecraft introduced a dynamic touch down the surface of the target asteroid and then a method to collect samples automatically by using the novel sampler system. Hayabusa spacecraft arrived at the target asteroid on 12th September in 2005 and observed the asteroid for about two months. And then two touchdowns were performed in November 2005. This paper introduces the outline of Hayabusa mission. Then this paper presents the autonomous guidance and navigation scheme used in MUSES-C sample return mission. This paper also describes the novel navigation sensors based on advanced technology such as electronics, photonics, and optics. Finally the flight results on touchdown dynamics are shown and discussed.

II. DESCENT AND TOUCHDOWN

The GNC scenario of Hayabusa mission is shown in Fig.1. The sampling scheme of HAYABUSA is so-called touch and go way, that is, the spacecraft shoots a small bullet to the surface just after touch-down has detected, collects ejected fragments with sampler horn, and lifts off before one of solar cell panels might hit the surface. Therefore, the control of the descending velocity and cancellation of the horizontal speed is essential for both the successful sampling and the spacecraft safety. The required conditions from the spacecraft system are that the relative velocity is within +/- 8cm/s in horizontal and 10 cm/s +0/-5 cm/s in vertical. To cancel the horizontal velocity, some kinds of strategies are prepared. The primary method is the usage of an artificial landmark, namely Target Marker (TM), which is released from the spacecraft at the altitude of about 30 m. By tracking TM on the surface, the spacecraft can cancel the horizontal relative speed Another method is natural terrain tracking which is the backup method of TM tracking (TMT) and also for the engineering experiment. Even though AWT(Auto Window Tracking) mode described above can also be used for this purpose, only the correlation of designated areas on the image (FWT: Fixed Window Tracking) is enough to detect horizontal displacement, namely horizontal speed. After TM is successfully captured, the relative navigation logic is initiated to obtain the position with respect to TM. The spacecraft moves to the position right above the TM, and then the attitude of the spacecraft is aligned to the local surface determined from four beams of Laser Range Finder (LRF-S1) measurements. The spacecraft is guided to the touchdown point and stays there until the relative velocity and attitude is stabilized within required value.
After the alignment, the spacecraft starts descending again and touches down the asteroid surface to collect samples. During the touchdown descent, some potential obstacles are checked with Fan Beam Sensors (FBS). If any obstacle is detected, the sequence is terminated and emergency ascent is initiated. When the touchdown is detected, the spacecraft collects the sample as soon as possible and then lifts off.

![Image of spacecraft descending and touching down on asteroid]

**Fig. 1. GNC Scenario for Final Descent and Touchdown**

### III. GNC SYSTEM

When the spacecraft was designed, the exact size, the shape, and the surface condition of the target asteroid were unknown. The GNC system was designed so that it could cope with various situations within the severe weight and power restrictions for the spacecraft.

Figure 2 shows the GNC system of Hayabusa. TSAS (Two axis Sun Aspect Sensor), STT (Star Tracker) and IRU (Inertial Reference Unit) are combined to determine the spacecraft attitude. ACM (ACceleroMeter) is used to accurately measure the velocity increment gained by RCS (Reaction Control System) firings. RW (Reaction Wheel) and RCS thrusters are used for attitude and position control. Twelve thrusters were installed on the spacecraft and this arrangement allows the control of translational and rotational motion independently.

The spacecraft has two kinds of optical navigation cameras. The narrow angle camera (ONC-T) is used for mapping and multiple scientific observations. The wide angle camera (ONC-W) is used for mapping and regional safety monitoring of surface obstacles. ONC-E (Electronics) works as image processor for the navigation purpose. Measurement of the altitude is performed by LIDAR (Light radio Detecting And Ranging). LIDAR covers the measurement range from 50[m] to 50[km]. Laser Range Finder (LRF) is used at a lower altitude. LRF has four beams that can measure the range from 7[m] to 100[m]. The four beams provide the height information as well as the attitude information with respect to the surface. In the final descent phase to the asteroid, the spacecraft orbit motion is synchronized with respect to the surface using image data. To cancel the relative horizontal speed, the spacecraft drops a Target Marker that can act as a navigation target.

The GNC logic is implemented in AOCU (Attitude and Orbit Control Unit), where a high performance microprocessor is equipped. Figure 3 shows the block diagram of GNC functions[5]. The core of onboard navigation system is an extended Kalman filter. The filter outputs the estimated position and velocity relative to ITOKAWA. The state dynamics for the Kalman filter[6] employs orbit dynamics model around ITOKAWA. Simple gravity field model is included in the dynamics. The observations for spacecraft position come from ONC, LIDAR and LRF.

![Diagram of GNC system and components]

**Fig. 2. AOCS and GNC Components**

![Diagram of AOCU and GNC functions]

**Fig. 3. AOCS and GNC Components**
IV. NAVIGATION SENSORS

A. ONC-W

Hayabusa spacecraft[4] has one telescopic camera ONC-T and two wide FOV cameras: ONC-W1 and W2. ONC-W1 whose FOV aligned to -Z axis of the spacecraft is used for on-board navigation. ONC-W2 has the FOV of -Y direction, which is used for terminator observation phase. The FOV of ONC-W1 is 60deg x 60deg and the resolution is 1000(H) x 1024(V). The overview of ONC-W1 is shown in Fig.4.

B. LIDAR

LIDAR(LIght Detection And Ranging sensor) is a pulse laser radar which measures the travelling time of the pulse between the spacecraft and the asteroid surface. A Photo of the prototype model is shown in Fig.5. Since the magnitude of received signal will change about 10 to the power of six order between 50km and 50m, LIDAR has automatic gain control function of APD. Transmitting pulse can be synchronized with external signal such as AOCS timing. This function is not only for precise range measurement but also synchronization with the exposure of ONC-T, which helps the alignment measurement of both sensors. To minimize the weigh of optics, the reflecting mirror is made of SiC.

C. LRF

LRF(Laser Range Finder)[7] consists of four beams sensors for navigation(LRF-S1), one beam sensor for touchdown detection(LRF-S2), and an electronics circuit. Photos of LRF-S1 and LRF-S2 are shown in Fig.6. LRF detects the range to the surface with the phase deference between AM-modulated transmitting and receiving laser light. LRF-S1 has four beams canted 30deg from vertical direction and AOCU can calculate relative attitude and position to the surface using four beam range information. The target of LRF-S2 is the side surface of the sampler horn and it detects the change of the length of the horn which means that the horn has collided with the surface. LRF has single electronics and S1 and S2 are switched by commands when used.

D. FBS

BS(Fan Beam Sensors) are sensors for detecting obstacles bigger than 10cm. A pair of a transmitter (FBS-T) and a receiver (FBS-R), shown in Fig.7, forms a three-dimensional detection area. Four pairs of FBS cover almost half of the area beneath the spacecraft's solar cell panels.

V. FINAL DESCENT AND TOUCHDOWN

The sampling method of HAYABUSA is so-called touch and go way, that is, the spacecraft shoots a small bullet to the surface just after touch-down has detected, collects ejected fragments with sampler horn, and lifts off before one of solar cell panels might hit the surface. Therefore, the control of the descending velocity and cancellation of the horizontal speed is essential for both
the successful sampling and the spacecraft safety. The required conditions from the spacecraft system are that the relative velocity is within +/- 8 cm/s in horizontal and 10 cm/s +0/-5 cm/s in vertical.

A. Final Descent

Figure 8 shows the final descent and touchdown sequence. To cancel the horizontal velocity, the novel scheme is prepared. The new method is the usage of an artificial landmark, namely Target Marker (TM), which is released from the spacecraft at the altitude of about 30 m. By tracking TM on the surface, the spacecraft can cancel the horizontal relative speed (TMT mode). After TM is successfully captured, the relative navigation logic is initiated to obtain the position with respect to TM. The spacecraft moves to the position right above the TM, and then the attitude of the spacecraft is aligned to the local horizon determined from four beams of Laser Range Finder (LRF-S1) measurements. The spacecraft is guided to the touchdown point and stays there until the relative velocity and attitude is stabilized within required value. The Six DOF controller[6] is activated after the navigation filter solution converges.

Fig. 8. Final Descent and Touchdown Sequence

B. Touchdown

After the alignment, the spacecraft starts descending again and touches down the asteroid surface to collect samples. During the touchdown descent, some potential obstacles are checked with Fan Beam Sensors (FBS). If any obstacle is detected, the touchdown and sampling sequence is terminated and emergency ascent is initiated. When the touchdown is detected, the spacecraft collects the sample as soon as possible and then lifts off. Figure 9 shows the sensors used for touchdown detection. Before the touchdown descent, AOCU changes the sensor from LRF-S1 to LRF-S2, which can sense the distance between LRF and the target on the horn and also sense the brightness of the target on the horn. LRF-S2, ACM and IRU are used for touchdown detection.

Fig. 9. Touchdown Detection

C. Sample Collection

A sample collection technique is what the Hayabusa spacecraft demonstrates first in the world. Different from the large planets, the asteroid is a very small object whose gravity field is too little for any sampler to dig and drill the surface. Nevertheless, the spacecraft has to cope even with the hard surface such as rocks, while it is requested to function for soft surface like sands as well. Therefore, Hayabusa spacecraft has a novel sample collection system as shown in Fig.10. The proposed method is the combination of the shooting projectile and the fragment catcher. The basic idea is retrieving fragments from the surface ejected by the projectile shot. And a key in the mechanism is the use of the catcher whose inlet surface covers the shot area that is concealed from the main body of the spacecraft, so that the fragments and dusts cannot hit the spacecraft at all. The spacecraft extends a mast whose tip end is equipped with a gun shooting a projectile of 10[g] at the speed of 300[m/sec]. A tiny hole that opens above a flange relieves the high-pressured gas after the shot. It has deceleration device inside that absorbs the fragments/projectile kinetic energy.

Fig. 10. Sampling System
VI. FLIGHT RESULTS

A. Touchdown #1

The first landing for sampling was tried on November 20th in 2005. The guidance and the navigation were all performed in order as planned. Figure 11 shows the flight profile in the final descent phase taken from TD#1 event. The topmost graph plots the data from ONC operated in TMT mode. The image of the target marker was successfully acquired with ONC-W1 and the processor in ONC output the direction of the marker in its field of view. During this operation, until the target marker left the field of view of ONC-W1, the marker was kept tracked. Also plotted in this graph are the navigation residuals (black dotted line) of ONC observations. The residual indicates the difference of estimated marker direction and actual direction. The residuals were kept around zero, indicating that onboard navigation filter worked as designed. The four lines in the second graph show the data from each channel of LRF. Data from LRF-C was initially different from the data of other channels. The data later became almost the same with other channels. This means the spacecraft attitude and position is properly guided so that the attitude align the local surface. The attitude profile, expressed by Z-Y-X euler angles, also indicates that attitude maneuver was properly executed to align the spacecraft to local surface.

The guidance accuracy was within 30 meters in terms of the hovering point. TM with 880,000 names was released at about 40m altitude, and ONC-W1 could track TM properly. Figure 12 shows the low-altitude image, in which the shadow of Hayabusa spacecraft on the surface and the shinning released TM could be seen. The first touching-down was unfortunately terminated by the obstacle detection of FBS, which has fan-shaped detection area beneath the solar cell panels.

After the obstacle had detected, the spacecraft continued descending because the attitude error was so large enough to prevent ascending thruster firing. As a result, the spacecraft did unexpected touchdown without sampling sequence, and stayed on the surface for about 34 minutes until the forced ascent was commanded.

B. Analysis on Touchdown Dynamics

Figure 13 shows the altitude measured by LRF. Based on the altitude data, dynamics motion on sample horn and the spacecraft is analyzed in mainly the direction of z-axis. The disturbances such as thruster projection, asteroid gravity, solar pressure are taken into consideration. It is estimated that the solar pressure is -1.261*10^-7 [m/s^2], thruster input is 2.899*10^-7 [m/s^2]. As a result, the surface gravity in the direction of x-axis is 7.4*10^-5 [m/s^2]. Figure 14 shows the estimated horn behavior. It is estimated that the period during touchdown is 2.35 [s].
V. CONCLUSION

This paper has presented the AOCS and GNC schemes in the final descent and touchdown phase for Hayabusa spacecraft. Touchdown sequence and sampler horn system have been presented. This paper also has presented novel navigation sensors and the flight results in Hayabusa mission.

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Progress of Fiber Optic Hydrophone

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Abstract — Fiber optic hydrophone has been developed over the past three decades for military and civil applications. This paper introduces the principles and structures of fiber optic hydrophones based on interferometric fiber sensors. The characteristics of the FOH system are given, and the multiplexing methods are analyzed. A long transmission system noise of FOH is discussed.

Keywords — fiber optic hydrophone, sensitivity, noise, multiplexing, long transmission

I. INTRODUCTION

Fiber optic hydrophone (FOH) is a kind of underwater acoustic sensor based on fiber optic and optoelectronic detector technologies. High-performance FOH converts acoustic signal into optical one using interferometric techniques, which is quite different from the traditional piezoelectricity hydrophone. FOH, therefore, enjoys advantages such as high sensitivity, immunity to electromagnetic interference, electrically passive sensor, multiplexability, and high reliability.

The origins of FOH are traceable to the mid-1970s. Researchers in Naval Research Laboratory reported the first paper on FOH in 1977 [1] and an acoustic sensing system was demonstrated. From then on, more and more country invested money and effort in it. A 96-element all-fibre optic hydrophone system was developed in 2000 by Litton and Defense Evaluation and Research Agency (DERA) [2], which was used to detect underground petroleum and earth gas. Recently, a remotely pumped and interrogated 96-channel FOH array was deployed offshore on the seabed for defense and security by UK [3]. We also carried out sea trials of a 32-element FOH system in 2002 [4], and a 128-element FOH system in 2009 in which a 64-element FOH module was explored to meet a large-scale array requirement. This paper discusses the principle, structure, multiplexing methods, and long transmission system noise of fiber optic hydrophones.

II. PRINCIPLE AND STRUCTURE OF FOH

In principle, every kind of FOH detects the deformation of acoustic material or structure to obtain the acoustic signal in sound field, which is based on fiber techniques. The structure of high-performance FOH is a fiber interferometer. Fig.1 shows an all polarization-maintaining fiber (PMF) Michelson interferometer. The output of the laser is passed through a polarizer. The linearly polarized light is then coupled into the interferometer, consisting of a PMF coupler, PMF sensing and reference arms. The ends of both arms are coated with reflecting films.

![Fig.1: All polarization-maintaining fiber Michelson interferometer](image)

A typical mandrel type fiber hydrophone, consisting of an inner metal rigid support tube and an outer compliant cylinder, is shown in Fig 2. The inner and outer tubes are wrapped with reference and sensing fibers with high numerical aperture, respectively. The hydrophone sensitivity is affected by lots of factors. Theoretical calculations and experimental results show that the Young’s modulus of elasticity, Poisson ratio of the compliant layer, and the length of sensing fiber are the mainly factors once the size of the hydrophone is given [5]. The material of outer tube and the length of sensing fiber, consequently, are important for hydrophone sensitivity. Normally, sensitivity achieves -120dB ~ -160dB (dB rel rad/μPa) with a length of several to tens meters of the sensing fiber.

![Fig.2: Structure of mandrel type fiber hydrophone](image)
III. CHARACTERISTICS OF FOH

We have developed several kinds of fiber optic hydrophone shown in Fig. 3 to meet different application requirements. These hydrophone systems have the same optical structures and signal processing systems to demodulate acoustic signal.

The pressure and acceleration sensitivities are measured and the typical results are shown in Fig. 4. The acoustic pressure sensitivity achieves -143dB. Both pressure and acceleration sensitivities are very important in the towed hydrophone array. When the acceleration sensitivity is less than -30dB, the difference between pressure and acceleration sensitivities reaches -110dB.

The source noise, including phase and intensity noise is the main noise of the FOH system. We have developed an all polarization-maintaining fiber ring laser [6] using unpumped EDF as a saturable-absorber as Fig. 5. Fast tuning frequency achieves ~96kHz with PZT modulator in the ring cavity. The relative intensity noise of the laser is less than -110dB with relaxation oscillation suppression. The linewidth is not larger than 1kHz, and the phase noise is about -110dB (@1kHz) when measured with optical phase difference of unbalanced interferometer in 20 meters.

With this laser, the noise-equivalent phase of hydrophone system has been measured to be $4.5 \times 10^{-6} \text{ rad} / \sqrt{\text{Hz}}$ (1kHz). With the acoustic pressure sensitivity of -143dB, we can deduce that the noise-equivalent sound pressure achieves 36dB, which is lower than the Deep Sea State Zero (DSS0).

The ability to multiplex fiber optic hydrophones is a key in applications. The choice of multiplexing approach is strongly dependent on the application. Different multiplexing schemes affect the performance in a variety of ways. The key to selecting the best multiplexing scheme is to find the best balance between performance and cost.

When the number of multiplexing elements is not very large, a space division multiplexing (SDM) technique is preferred for the array [4]. This multiplexing method, compared with mostly commonly used multiplexing techniques, namely time division multiplexing (TDM) and wavelength division multiplexing (WDM), is easy to operate and the crosstalk of the system is the least. Of course, with the multiplexing elements increasing, TDM and WDM can be combined to multiplex a large number of elements on a pair of fibers. We have developed a 64-element multiplexing system onto two fibers with TDM and WDM techniques. Regarding this 64-element system as an optical module, we can use SDM approach to combine several optical modules to interrogate a very large-scale hydrophone array. At the same time, we have also developed a real-time digital signal processing system to demodulate the acoustic signal from interferometer. A modular circuit in our system can
process 64 elements signals parallel. The signal processing capability of the system can be expanded by assembling modules together.

IV. LONG TRANSMISSION SYSTEM NOISE

Many hydrophone applications, in particular seismic exploration for undersea oil deposits, require a long transmission system (50–500km). The remotely interrogated hydrophone system employs EDFAs which will induce the relative intensity noise (RIN) (shot noise and beat noise) and the phase noise (G-M effect). There are also less well known optical nonlinear contributors to the system noise, including the intensity noise from SBS, SRS, FWM and MI, terms related to the producing of one wavelength and the depletion of another existed wavelength, and phase noise from the Gordon-Mollenauer effect, XPM, SPM and MI effects, terms related to the Kerr effect in nonlinear mediums. According to experiments with long transmission distance and different injecting optical power levels, however, we believe that these nonlinear effects not be significant contributors to the overall noise when the transmission power and multiplexing method are set to be optimal.

V. CONCLUSION

The principle and structure of fiber optic hydrophone based on interferometric fiber optical sensors are given. The acoustic pressure sensitivity achieves -143dB. While the acceleration sensitivity is less than –30dB, the difference between pressure and acceleration sensitivities reaches –110dB. With narrow-linewidth fiber laser, the noise-equivalent sound pressure achieves 36dB. A 64-element optical and circuit modules of FOH are developed with TDM and WDM techniques. The long transmission noise in FOH system is discussed.

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Advances in Distributed and Multiplexed Fiber Optic Sensors

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Abstract — Recent progresses in fiber optic sensors for security life and society are reviewed. In last year, the research on the distributed fiber optic sensing systems based on Brillouin scattering advanced. We have succeeded in applying the Brillouin optical correlation domain analysis system in the structure health monitoring for airplanes in flight. We newly proposed a Brillouin optical correlation-domain reflectometry; especially, succeeded in discriminative sensing of strain and temperature by using both the stimulated Brillouin scattering and the birefringence in a polarization maintaining fiber. We have also demonstrated a distributed strain sensing system using a long fiber Bragg grating. For diagnoses of fiber to the home subscriber access networks, a novel high-speed high-accuracy optical reflectometry is proposed by synthesis of optical coherence function. These progresses contribute to the development of sensing technologies that is essential to realize security life in 21st century.

Keywords — Distributed fiber optic sensors, Brillouin scattering, strain sensing, fiber Bragg grating, smart materials and structures, reflectometry, fiber optic gyroscope

I. INTRODUCTION

In last year, the major recent research activities on fiber optic sensors have continuously been concentrated on distributed and multiplexed fiber optic sensors, which provide us “fiber optic nerve systems” to make materials and structures perceptive to “pain” [15,25,28,30,31].

Fiber Bragg gratings act as strain/temperature sensors, with wavelength division multiplexing (WDM) techniques as sensor multiplexing schemes. Brillouin and Raman scattering in the fiber provide us with strain and temperature sensing mechanisms, respectively. By combining fiber sensors with optical time domain reflectometry (OTDR), distributed strain and temperature sensing systems have been developed. However, they have shown difficulties in realizing satisfactory performances, such as achieving a high spatial resolution and a high sampling rate.

In our group, we have proposed and developed a scheme for distributed sensing, which is not based on OTDR, but on the synthesis of the interference characteristics of continuous lightwaves [13]. A spatial resolution of 1.6 mm and sampling speed of 1,000 Hz have already been realized, which are 500 times finer and 100,000 times faster than those of the OTDR schemes, respectively [8,12]. These fiber optic nerve systems will be able to create novel health monitoring functions for materials and structures. Aircraft wings, spacecraft fuel tanks, bridges and multi-story buildings will become perceptive to damage with these schemes and thereby prevent disasters, as schematically illustrated in Fig. 1.

In last year, we have succeeded in applying the Brillouin optical correlation domain analysis (BOCDA) system in the structure health monitoring for airplanes in flight. We also newly proposed a Brillouin optical correlation-domain reflectometry (BOCDR). Especially, we succeeded in discriminative sensing of strain and temperature by using both the Brillouin scattering and the birefringence in a polarization maintaining fiber. We have also demonstrated a distributed strain sensing system using a long fiber Bragg grating (FBG).

On the other hand, for diagnoses of fiber to the home (FTTH) subscriber access networks, a novel high-speed high-accuracy optical reflectometry is proposed by synthesis of optical coherence function (SOCF). In addition, studies on resonator fiber-optic gyro (R-FOG) by use of photonic band-gap fiber (PBF) have been performed.

In this report, we present a concise summary on these research activities with a detailed list of major relevant publications.

Fig. 1. Fiber optic nerve systems contribute to realize security life in the 21st century society.
by sweeping the frequency amplifier. We obtain the Brillouin gain spectrum (BGS) power due to the Brillouin gain is detected by a lock-in optical correlation domain analysis (BOCDA) has been fiber-optic distributed sensing system based on Brillouin modulated by a single side band modulator (SSBM) with radio frequency, and launched into the fiber under test chopped by an electro-optic modulator (EOM1) with a One output of the coupler, serving as the pump, is advanced. Figure 1 shows the latest BOCDA system [10]. changing the FM frequency $f_m$. The increase in the probe stimulation. The selective excitation of the stimulated Brillouin spectrum is broadened to suppress the correlated. At positions other than the coherence peak, $\nu$, so that a sideband at $\nu_0 - \nu$ is generated, serving as the probe. The probe propagates against the pump in the fiber and reached the photodetector (PD), where the optical signal is converted into electrical signal, and then detected synchronously at the beat frequency between EOM1 and EOM2 [10].

It is the point in our system that the pump and the probe are identically frequency-modulated (FM) at the LD. As a result, SBS occurs exclusively at the correlation peak position, where the two lightwaves are highly correlated. At positions other than the coherence peak, Brillouin spectrum is broadened to suppress the stimulation. The selective excitation of the stimulated scattering is schematically shown in Fig. 2 [13]. We can sweep the correlation peak along the fiber by simply changing the FM frequency $f_{\nu_0}$. The increase in the probe power due to the Brillouin gain is detected by a lock-in amplifier. We obtain the Brillouin gain spectrum (BGS) by sweeping the frequency $\nu$. Then, the BGS distribution along FUT is obtained.

**II. DISTRIBUTED FIBER OPTIC SENSING SYSTEMS BASED ON BRILLOUIN SCATTERING**

The research on the improvement and application of fiber-optic distributed sensing system based on Brillouin optical correlation domain analysis (BOCDA) has been advanced. Figure 1 shows the latest BOCDA system [10]. One output of the coupler, serving as the pump, is chopped by an electro-optic modulator (EOM1) with a radio frequency, and launched into the fiber under test (FUT). The other output is chopped by EOM2 and modulated by a single side band modulator (SSBM) with a microwave frequency $\nu$, so that a sideband at $\nu_0 - \nu$ is generated, serving as the probe. The probe propagates against the pump in the fiber and reached the photodetector (PD), where the optical signal is converted into electrical signal, and then detected synchronously at the beat frequency between EOM1 and EOM2 [10].

A spatial resolution of 1.6 mm and sampling speed of 1,000 Hz have already been realized, which are 500 times finer and 100,000 times faster than those of the OTDR schemes, respectively [8,12]. The BOCDA system has also been applied to concrete crack detection, featuring the high spatial resolution [13].

In this year, we have succeeded in applying the BOCDA system in the structure health monitoring for airplanes in flight [18,26] as shown in Fig. 4, which shows the feasibility of BOCDA as an advanced technique of fiber optic nerve system for aircrafts and other mechanical structures. Its application in temperature distribution measurement is also under investigation.

Aiming at cost-reduction of BOCDA system, a simplified Brillouin optical correlation domain analysis (S-BOCDA) with time-division pump-probe generation scheme has been developed [2]. In the S-BOCDA system, the pump and probe waves are generated through direct current modulation of the laser source. Analyses on the optimization of the modulation parameters and evaluation
reflectometry (BOCDR) has been newly proposed to improve the SN ratio. Distributed measurement with 7.4-mm configuration has been improved. We proposed a new BOCDA system to achieve 0.5% of the pump-probe frequency difference of 11 GHz. The effect of this optimization was carried out. For the flatness, we have achieved 0.3% strain and flatness, which have opposite dependence on temperature compared to Brillouin frequency shift as shown in Fig. 6(b) [24], the temperature dependence of Brillouin frequency shift is measured by observing the birefringence-determined frequency deviation of the dynamic acoustic grating generated with SBS process to obtain the other equation of strain and temperature. Then, the strain and temperature can be detected in Fig. 6(a). In this system, Brillouin frequency shift is observed in a single optical fiber. We propose to use a Panda-type polarization-maintaining fiber (PMF) for complete discrimination of strain and temperature by use of a single optical fiber. We proposed a new configuration to improve the SN ratio, which is based on simultaneous modulation with a sinusoidal and a noise waveform. Distributed measurement with 7.4-mm theoretical resolution was demonstrated with improved SN ratio.

In this year, a Brillouin optical correlation-domain reflectometry (BOCDR) has been newly proposed [3,16,19], which is capable of measuring the strain distribution along the fiber from a single end (see Fig. 5(a)). Spatial resolution of 13-mm as shown in Fig. 5(b), the best result ever reported in Brillouin-based reflectometers, and 50-Hz sampling rate were experimentally demonstrated. In addition, a temporal gating scheme was introduced to enlarge the measurement range while maintaining the spatial resolution; 66-cm resolution and 1-km measurement range were simultaneously achieved as shown in Fig. 5(c).

III. DISCRIMINATIVE SENSING OF STRAIN AND TEMPERATURE IN BRILLOUIN SCATTERING BASED FIBER OPTIC SENSORS

On the other hand, we achieved great progresses this year in the research on discriminative sensing of strain and temperature by use of a single optical fiber. We proposed a new configuration to improve the SN ratio, which is based on simultaneous modulation with a sinusoidal and a noise waveform. Distributed measurement with 7.4-mm theoretical resolution was demonstrated with improved SN ratio.
discriminatively with a high accuracy. We succeeded experimentally in discriminating the strain and the temperature with an accuracy of 3–4 με and 0.07–0.08 °C [24]. Fully-distributed discriminative sensing has been also achieved by use of correlation-based continuous wave technique with 12-cm spatial resolution together with an accuracy of 12 με and 0.3 °C as shown in Fig. 7 [17].

IV. DISTRIBUTED/MULTIPLEXED FIBER BRAGG GRATING SENSORS BY SYNTHESIS OF OPTICAL COHERENCE FUNCTION

Research on distributed/multiplexed fiber Bragg grating (FBG) sensors by synthesis of optical coherence function (SOCF) progressed. A distributed strain sensing system using a long FBG has been proposed and demonstrated [6,23]. The experimental setup is shown in Fig. 8(a). Based on SOCF, the Bragg wavelength of local section in a long FBG around the measuring position can be measured. In the process of synthesizing coherence function, an apodization is introduced to obtain the proper reflection spectrum. Experiment and simulation have been carried out, and 9.8-mm spatial resolution was realized as shown in Fig. 7(b). The performance of the sensing system is also evaluated by simulation.

On the other hand, multiplexed FBG sensors by SOCF has studied, which can solve the problems (cost-inefficiency and limitation of multiplexable FBG numbers) in conventional wavelength division multiplexed FBG sensors requiring FBGs of different Bragg wavelength. In this year, new schemes have been proposed to expand the measurement range, which was limited to 10 m at 10 kHz sampling rate. The measurement range is affected by the beat frequency shift effect due to optical path length difference between the reference light and the reflected light. For longer measurement range, approaches which relieve the frequency shift with new sampling method have been proposed, and their effectiveness is being investigated.

V. HIGH PERFORMANCE OPTICAL REFLECTOMETRY FOR DIAGNOSES OF OPTICAL FIBER ACCESS NETWORKS

For diagnoses of fiber optic subscriber access networks (FTTH), a novel high-speed high-accuracy optical reflectometry is reported by synthesis of optical coherence function (SOCF) [21]. In this new scheme, the optical frequency of a laser light source is linearly swept, which realizes the wavelength domain averaging optically for enhancing the accuracy without time-consuming numerical processing, in addition to a sinusoidal modulation to synthesize a coherence peak for distance-resolved measurement. In this year, a new scheme of continuous chirping on the modulation frequency has been introduced to sweep the sensing position along the fiber continuously at a high speed. In experiments, a
measurement for a reflection distribution profile, which used to take more than 300 seconds previously, is obtained within 3-5 seconds. The experimental setup and result are shown in Fig. 9. Polarization diversity measures have also been implemented and the effect from polarization state variation has been suppressed, so that the Rayleigh scattering distribution in optical fiber has been observed. With this scheme, a distributed pressure sensor was also proposed and demonstrated.

Studies on the improvement of frequency-modulated continuous wave (FM CW) optical reflectometry have also been carried out. To enhance the reflectivity accuracy, a new wavelength domain averaging method is proposed, in which interference signals acquired during a full-range light frequency sweeping are divided into multiple sessions; reflection distributions deduced from each sessions respectively are averaged to get a high-accuracy profile. By the new scheme, the limitation on the measurement speed or the limitation from the sweeping speed of available laser source in conventional schemes can be relieved. The effectiveness of the new proposal has been confirmed experimentally, and the measurement for reflectivity distribution of improved accuracy was obtained.

VI. CONCLUSION

The latest developments and applications of fiber optic sensors for reliability and security are reviewed, including the application of BOCDA system in the structure health monitoring for airplanes in flight; the demonstration of one-end access distributed sensing system BOC DR; especially, the success in discriminative sensing of strain and temperature by using both the stimulated Brillouin scattering and the birefringence in a polarization maintaining fiber. The distributed strain sensing system using a long fiber Bragg grating and a novel high-speed high-accuracy optical reflectometry by SOCF are also introduced. Fiber optic sensors and fiber nerve systems are expected to be a core technology to realize materials and structures perceptible to damage. Such technologies will enhance the safety and security of the society in the 21st century.

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