Background and Mission

The Optoelectronics and Measurements Group (OPME) comprises an intensive collaboration network of researchers at the Optoelectronics and Measurement Techniques Laboratory at the University of Oulu, the Measurement and Sensor Laboratory (MILA) in Kajaani and VTT Electronics. OPME employs 37 post graduate students and 47 other persons in the research work. In accordance with the principles of Infotech Oulu, the group engages in basic research, drawing on the resources of the three organizations, as well as their extensive industrial connections and wide experience in technology transfer. The work includes cooperation projects related to long term research, but generally product development projects are omitted.

As a participant in the Infotech Oulu graduate school, the group also focuses its efforts to arrange lecture series and graduate school courses for graduate students. During 2004 the group organized the traditional 4th Infotech Oulu Workshop on Optoelectronic Devices and Instrumentation, concentrating this time on ‘Epitaxial growth and fabrication technology of semiconductor based optical devices’. In addition, the 4th topical meeting on the Optoelectronic Distance/Displacement Measurement and Applications was arranged by the group in Oulu. The ODIMAP IV conference gathered over 80 scientists all over the world to Oulu.

The OPME group performs basic research in optoelectronic measuring, and electronics testing techniques and communication systems with particular emphasis on the practical applications of these techniques. In this undertaking, the group focuses on measuring and modeling the propagation of light in turbulent and scattering media such as the atmosphere, human tissues, pulp and paper. Interesting basic properties of light are, for example, scattering, absorption, reflection and polarization plane changes when light propagates through non-homogenous media. These properties can be measured in several different ways. Interesting measurement techniques are photon time-of-flight and photoacoustic techniques, and high and low coherence interferometry. New materials, manufacturing technologies and integration of the systems are developed by combining customized micro-optical devices, optoelectronic devices and novel packaging technologies. The findings are used in applications in medicine, the paper, pulp and mechanical wood industry, as well as wireless communication and instrumentation.

In future, optical and electrical components will be based more and more on organic materials like polymers. This so called ‘polytronics’ enables roll-to-roll and printable manufacturing techniques to be used and this reduces manufacturing costs remarkably. Integration of traditional optoelectronic measurement techniques to polymer platforms is a great challenge, but it opens a lot of new solutions in different biomedical and industrial measurement applications. One example of this may be different biosensor applications where a biomolecular recognition process could be performed using polymer waveguides.

Scientific Progress

The following research examples illustrate the scientific progress of the OPME group. These research projects have been carried out in active collaboration between both domestic and international research institutions and industrial partners.

Numerical Modeling of the Readout Signal of the Super Resolution Disk

In the readout process of the AgOx super resolution disk, the signal-to-noise (SNR) ratio is nonlinearly related to the readout power. The mechanism responsible for this behavior has not been known so far. In our model, we assume that the Ag aggregates formed inside the bubble marks drift away from the center of the readout beam when the readout power is high enough, and therefore a donut shaped aperture is formed at a mark on the optical axis of the readout beam. The simulated modulation of the detected opti-
cal power for three different mark sizes is shown as the function of the aperture radius (readout power) in the figure below. At the threshold, the random Ag aggregates at the on-mark bubble pit are organized and the donut shaped structure is formed inside the bubble pit. The improved modulation arises from the reduced reflected optical power impinged on the detector at the on-mark situation because of this aperture, while the reflected power at the off-mark situation is fairly constant.

![The simulated modulation of detected optical power for three different mark sizes as the function of the aperture radius.](image)

**Efficiency of Wireless Systems**

Our aim in the Telecommunication Systems research field is to understand the efficiency of both radio links and radio networks. Nowadays, there is much interest in the higher layers of the system, for example, applications and services. However, all layers must be developed and we concentrate on the physical, data link and network layers. Link and area spectral efficiencies are closely related to adaptive transmission.

We have made an extensive review of the literature in the area of spectral efficiency, which is measured in terms of bit/s/Hz/cell. Conventionally, link spectral efficiency is estimated in terms of bit/s/Hz. We have summarized the fundamental limits, channel models, measures of spectral efficiency, and methods of improving spectral efficiency in cellular systems. A semi-analytical MATLAB simulation environment was developed to estimate the link and area spectral efficiencies closely related to adaptive transmission.

Surface analysis, including roughness estimation, is particularly important in printing papers, graphical boards and packaging boards, because parameters like roughness affect such optical properties of paper as gloss and ink absorption. There are several approaches for non-contact surface analysis of paper, but the need to see through a paper sheet calls for more sophisticated methods. Current measurement methods for structural analysis of paper tend to be either slow, labor-intensive, expensive or invasive. However, to improve paper quality, it is important to know its three-dimensional porous structure. Hitherto, research on paper has suffered from an absence of non-destructive, fast and cost-effective measurement techniques for micro and macrostructure imaging.

We have proposed a new method for paper structure characterization: optical coherence tomography (OCT), which has been used mainly for non-invasive cross-sectional imaging in biological systems, but now offers us the capacity to reconstruct cross-sectional images of paper from its projections. Three images representing the capabilities of the OCT technique in the imaging of paper and pulp are presented in the figure below. This reveals that not only the surfaces of different paper grades can be studied, but also the 3 dimensional porous structure, which has a key role in determination of distribution of fibers, fillers and other additives in the papermaking process.

![Images measured using an OCT device. Topography of laboratory paper (left), 3D-structural image of paper simulation network (middle) and 3D-structural image of copy paper (right).](image)

**Paper Research Using Optical Coherence Tomography**

The growth of paper making industry has triggered a continuous search for improved methods for diagnosing and characterizing paper during recent decades. By and large, testing tends to be focused on the goal of ensuring that the paper produced meets end-user specifications at the lowest possible cost. On the macroscopic level, paper can be characterized by numerous parameters, including, for example, density, bulk, porosity, thickness and roughness. All these parameters have an effect on paper quality, and can be used to classify different types of paper as suitable for particular purposes.
groups has to be active. In addition to the imaging of paper, the technique has been applied to fluid mechanics evaluation by using the ability of the method to determine the velocity profiles of flowing suspensions like pulp and coating paste.

**Interferometric Biosensors**

Optical biosensors are a promising tool for sensing of biomolecules because they enable direct recognition without any label agents. One fascinating optical technique is interferometry based on polymer waveguides. In the interferometric biosensor, the sample path is covered by a thin antibody layer. This can be Y-shape immunoglobulins with specific binding sites. Antibodies trap antigens from the measured analyte and change the evanescent light field in the sample path of the interferometer. Thus, the biochemical process changes the phase of the sample arm and produces the interference pattern, interferogram, to the output of the interferometer.

The research has been focused on developing free space test setups for different interferometer configurations an example of which is shown in the figure below.

![A test setup of a free space Mach-Zehnder interferometer for biomolecular detection.](image)

Interferogram readout techniques based on linear sensor array and a CDD-camera are being developed. An example of detecting 0.7 mg/ml concentration difference in a glucose water solution using a CCD camera is shown in the following figure. Using the linear sensor array, the smallest detectable concentration difference is approximately 6 µg/ml. However, due to thermal effects in the surrounding measurement environment the smallest measured concentration difference was 58 µg/ml.

**Electronics Testing Techniques**

Research has been done to utilize the IEEE 1149.4 Mixed-Signal Test Bus Standard in measurements. The suitability of the test bus has been extended to radio frequencies (up to GHz-range) by building a special radio frequency analogue boundary module (RF-ABM), which can be used for basic RF power and frequency measurements. The RF-ABM uses a combination of mixing and sub-sampling as the method to down-convert the RF signal into a low frequency suitable for the 1149.4 standard. In the low frequencies, calculation methods have been developed to get the values of the components forming impedances between the 1149.4 compatible IC’s pins. The values are calculated from the measured voltages achieved through the test bus, taking the loading effect of the measuring equipment into account, and thus enabling the use of low cost instruments. In addition, the use of a Wheatstone bridge for small resistance measurements for characterizing the ball grid wear-out has been studied in the 1149.4 environment.

**Peeking Inside the Wood**

Applying microwaves and ultrasound in research on mechanical wood started in MILA in the year 1999 with the PUUMI project. Because both microwave and ultrasound can penetrate wood, these techniques may be utilized when one needs information on the inner structure of wood material. Such a study may be regarded as another mainstream in our wood research - our goal is to locate branches, decayed parts and other essential structural factors in order to optimize the sawing and cutting processes.

![Detected interferograms of glucose concentrations 1,4 mg/ml (left) ja 2,1 mg/ml (right). In the image on the left, the maximum intensity of the interferogram is located at vertical pixel number 300. On the right, the minimum intensity of the interferogram is located at vertical pixel number 300. This optical path difference corresponds to 0.7 mg/ml concentration difference.](image)
etration of microwaves into wood is restricted. In the study of wood logs, the suitable frequency may be found at range of 1-3 GHz. Then the wavelength in wood is about 2-5 cm and diameter of the log under investigation can be even 6 m. It should be noticed that the resolution (i.e. wavelength in wood) changes also according to the electrical characteristics of the wood material.

In order to improve the resolution of the measurement, the difference between signals of two waves possessing orthogonal plane polarizations is detected. The tests, which were carried out in the MOKSA project, showed that the size of knots down to 10 mm in sawn timber may be observed. Similar tests with wood logs have been done and promising results were obtained.

In the SYDÄNPUU project we explore the possibilities of using non-contact ultrasound technique to detect the valuable heartwood portion of green sawn pine. The method was first tested in laboratory conditions, and later on tests were continued in a special testing environment that simulates real sawmill circumstances. In the figure below, an example of board measured under laboratory conditions is shown.

The main outcome of the study was that the non-contact ultrasound measurement can distinguish the heartwood from the rest of the wood material, not only with green boards but also with frozen ones. It was also possible to roughly determine the heartwood profile. In addition, we came to the conclusion that our ultrasound device operates well in high speeds, even when using speed of 5 m/s.

**Exploitation of the results**

Active interaction with industry ensures the rapid application of research results. The work of the group paves the way for the introduction of a new generation of optoelectronic sensors and instruments based on micro-optics, micromechanics and microelectronics, especially polymer based optical sensors.

The research results of the group have been presented at scientific conferences and published in professional journals. In projects funded by TEKES, the acquired knowledge has been directly transferred to the participating enterprises. Also commissioned research has been directly reported to the enterprises concerned, and several senior and junior researchers have taken up employment with them.

**Future Goals**

Attaining an acknowledged position as a top European research unit in its own field forms a key objective for the group. Another important goal involves becoming a central cooperation partner for Finnish industry in the development and application of measuring techniques and instrument technology. In addition, the group advances the scientific understanding of optoelectronics and measurement applications, and produces high-quality dissertations and publications. Finally, the highly applicable, in-depth, information produced by the group also makes a contribution to product development and the creation of new business opportunities.

The key elements in the development of smart sensor network are the field of measurement physics and modeling. The group will continue modeling of the propagation of light in turbulent and scattering media. Also new measurement techniques in combination with traditional ones will be developed forward to new applications.

The aim is to combine customized photonic devices and advanced materials and packaging technologies for their implementation in novel systems for optical communications, wireless instrumentation and machine automation. The new packaging and manufacturing techniques will be developed. Module integration is an important step when sensor networks are developed. In this step, new measurement techniques, communication methods and sensor materials are integrated into a suitable module that is competitive and reliable in the measurement environment. One aim is also the harnessing paper production technology for cost effective optoelectronics.
As a participant of Infotech Oulu graduate school, the group will continue effective education of graduate students. The aim is to continue the traditional workshop series on Optoelectronics Devices and Instrumentation. In addition, internationally well known scientists will be invited to give lectures to the students.

**Personnel**

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>professors &amp; doctors</td>
<td>14</td>
</tr>
<tr>
<td>graduate students</td>
<td>37</td>
</tr>
<tr>
<td>others</td>
<td>33</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>84</strong></td>
</tr>
<tr>
<td>person years (univ. 80%, VTT 20%)</td>
<td>60</td>
</tr>
</tbody>
</table>

**External Funding**

<table>
<thead>
<tr>
<th>Source</th>
<th>EUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academy of Finland</td>
<td>104 000</td>
</tr>
<tr>
<td>Ministry of Education</td>
<td>140 000</td>
</tr>
<tr>
<td>Tekes</td>
<td>1 287 800</td>
</tr>
<tr>
<td>other domestic public</td>
<td>1 195 900</td>
</tr>
<tr>
<td>domestic private</td>
<td>260 200</td>
</tr>
<tr>
<td>EU + other international</td>
<td>691 200</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>3 679 100</strong></td>
</tr>
</tbody>
</table>

**Doctoral theses**


Sorjonen M (2004) Optical characterization of paper with DOE sensor. University of Joensuu, Department of Physics, Väisälä Laboratory, Dissertations 44.

**Selected Publications**


