"Precise analysis of material components with a single shot" GIST develops an ultra-small AI spectroscopy sensor capable of real-time precise component analysis

- Professor Heung-No Lee's team from the Department of Electrical Engineering and Computer Science achieves high precision, low power and miniaturization by combining AI restoration algorithms with ultra-small thin film filter sensors... A new concept computational spectrometer that restores wavelength information without mechanical scanning

- Precise restoration of 500~850nm spectrum with just a single shot, expected to be used in real-time blood sugar measurement, food safety inspection, and detection of counterfeit documents... Published in the international academic journal 《Scientific Reports》

▲ (From left) Department of Electrical Engineering and Computer Science student Youngin Choi, Professor Heung-no Lee, and researcher David S. Bhatti

The Gwangju Institute of Science and Technology (GIST, President Lim Ki-chul) announced that Professor Heung-No Lee's research team in the Department of Electrical Engineering and Computer Science has developed a new concept computational spectrometer* technology that can reconstruct precise spectral information with just one image capture by combining an artificial intelligence (AI) restoration algorithm with a multilayer thin film filter* ultra-small sensor announced in 2022.

In a previous study (Scientific Reports, March 2022), the research team successfully demonstrated the hardware feasibility of a 'single-shot spectrometer' that can precisely restore the 500-850 nm spectrum with just a single image capture by combining a multilayer thin film filter structure manufactured with an ultra-precision process at the semiconductor process level with a CMOS sensor*.

* multilayer thin-film filter (MTF): An optical filter made by stacking multiple layers of thin films (tens to thousands of nanometers thick) with different refractive indices, which can selectively transmit only light of a specific wavelength band. When these filters are arranged in a grid shape, various wavelength information can be collected simultaneously, and are used to efficiently extract spectral information in a spectrometer.

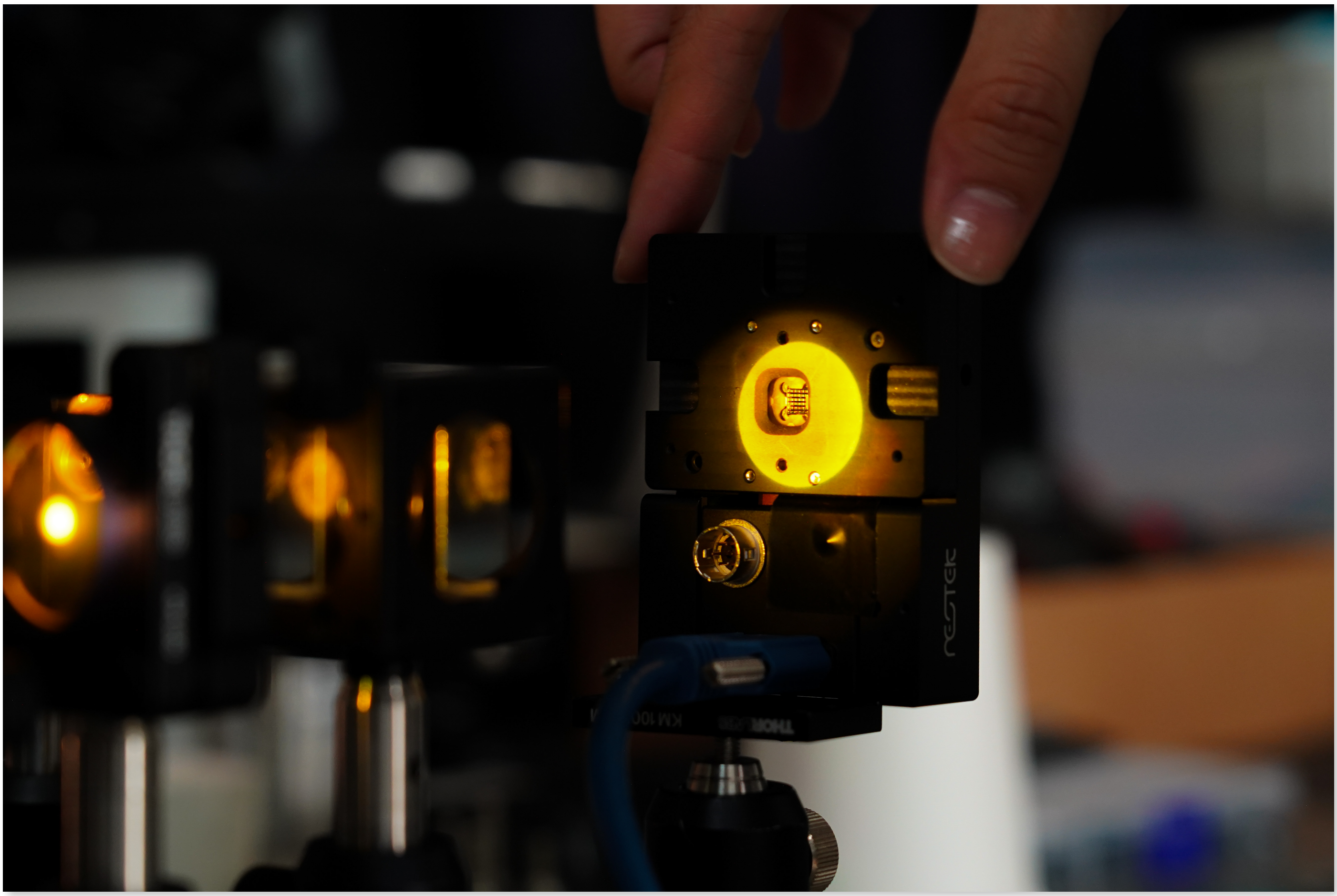
* computational spectrometer: A digital spectrometer that does not mechanically separate wavelengths like conventional spectrometers, but instead restores the entire spectrum through computational algorithms such as AI by compressing and measuring data using filters.

* CMOS (complementary metal-oxide semiconductor) sensor: A semiconductor-based sensor that converts light into electrical signals and is used in most imaging devices such as smartphone cameras. It has excellent low-power and high-speed characteristics and is suitable for combination with small optical measurement systems.

In this study, this was advanced one step further, and the measurement accuracy and processing speed were significantly improved by precisely designing the AI restoration algorithm and optimizing the entire system.

In particular, by actually implementing a hardware-software fusion structure that compresses and measures optical signals into filter units and then restores the entire spectrum using AI, the hyperspectral fusion technology that enables high-precision wavelength analysis without mechanical scanning was completed.

This has simultaneously achieved high precision, low power, and miniaturization that overcome the limitations of existing spectrometers, and has also specifically suggested the possibility of its use as a next-generation optical sensor platform for mobile devices and field diagnostic sensors.



▲ Proposed computational spectrometer experimental setup and sensor prototype. The experimental system collects light passing through a CMOS sensor with a multilayer thin film filter as a single image, and restores it in real time using an AI-based algorithm. The photo shows the light incident on the filter during the experiment.

A spectrometer is a core analytical device that can non-invasively identify components, structures, and conditions by analyzing the unique wavelength characteristics that appear when a substance interacts with light. It is used as an essential tool for accurate and rapid analysis in various fields such as medical diagnosis, food quality inspection, environmental pollution monitoring, and art appraisal.

However, existing high-resolution spectrometers require large and heavy mechanical devices for precise wavelength analysis, and have many limitations in real-time field applications due to their complex structure and long measurement time.

In particular, in order to be suitable for portable or mobile sensors, they must satisfy 'miniaturization, real-time, and low-cost' at the same time, but computational spectrometers developed to date have had difficulty in commercialization due to limitations in restoration accuracy or filter resolution.

In response, the research team proposed a new computational spectrometer structure that combines an ultra-small filter sensor based on a multilayer thin film filter and a U-Net*-based AI restoration algorithm, and demonstrated its performance through experiments.

▲ Shows a measurement environment where the light source, filter array, and detector array are precisely aligned.

The research team designed 36 different filters by combining titanium dioxide (TiO_2)* and silicon dioxide (SiO_2)* thin films with different refractive indices, and mounted them in a 6×6 array on a commercial CMOS image sensor.

The sensor manufactured in this way can measure wavelength information ranging from 500 to 850 nm in a distributed manner by filter unit with just a single image capture.

* U-Net: An artificial intelligence deep learning model structure specialized in image segmentation, which restores the input image to a high-resolution output through a U-shaped encoder-decoder structure. It is widely used in medical image analysis and optical signal restoration.

* TiO_2 (titanium dioxide): An inorganic oxide composed of titanium and oxygen, it is mainly used in white pigments, UV blockers, and photocatalysts. Due to its high refractive index and stable chemical properties, it is also used in optical coatings and electronic devices, and is particularly noteworthy in the field of environmental purification due to its excellent UV absorption and decomposition capabilities.

* SiO_2 (silicon dioxide): An inorganic compound composed of silicon and oxygen, it is the main component of sand and glass. It has high insulation and transparency, and is widely used as an insulating film or protective film in semiconductor manufacturing processes. It is also important as an optical material, and has excellent thermal and chemical stability.

The measured image signal is restored to the full spectrum through a deep learning model that applies residual connection* to the U-Net structure.

This model, which learned a total of 3,223 actual spectrum data, enables faster and more precise restoration than the existing optimization-based method, and achieved high accuracy of root mean square error (RMSE)* 0.0288 in the wavelength range of 500 to 850 nm.

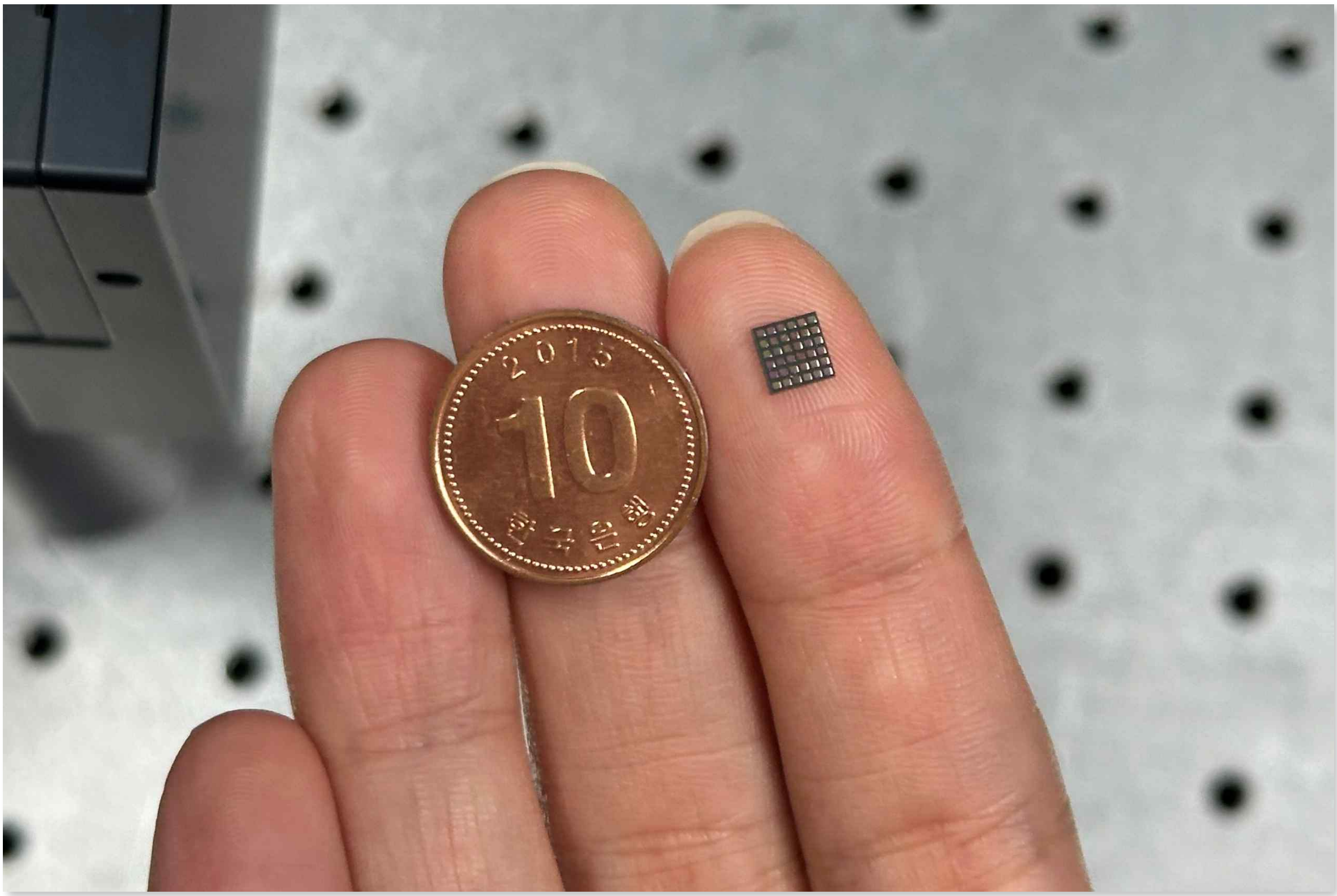
In addition, the measurement speed was increased by implementing a non-scanning* structure that measures the full spectrum with just a single shot, and the possibility of commercialization such as miniaturization, mass production, and low-power operation was secured based on high compatibility with CMOS sensors*.

* residual connection: A connection method that directly adds input signals to outputs to increase learning stability and accuracy in deep learning models. It can transmit information without signal loss, enabling effective learning even in deep neural network structures.

* root mean square error (RMSE): An indicator that represents the average error between predicted values and actual values. A smaller value indicates a higher prediction accuracy of the model. It is used as a quantitative indicator in evaluating spectral restoration performance.

* non-scanning (computational spectrometer): A structure that can simultaneously measure the entire spectrum information with a single shot, rather than scanning each wavelength line like a conventional spectrometer. It is advantageous for miniaturization because the measurement speed is fast and there are no mechanical parts.

The research team also confirmed the structural uniformity and high manufacturing yield of the multilayer thin film filter using a scanning electron microscope (SEM)*. By reducing the overall size of the sensor to 4.5×4.5mm2, we have achieved ultra-miniaturization that allows it to be directly installed in various application environments such as mobile devices, wearable devices, and field diagnostic platforms.



▲ A sensor prototype compared to the size of a coin, confirming that it is an ultra-small structure smaller than a fingernail.

This technology is attracting attention as a next-generation precision optical sensor platform that can be used in various fields such as mobile medical diagnosis, food safety inspection, detection of counterfeit documents, and real-time environmental monitoring, and it is expected to become a key source technology leading to a paradigm shift in the optical industry as an AI-based optical technology.

* scanning electron microscope (SEM): This is a device that obtains high-resolution images by scanning an electron beam on the surface of a sample and using the signal generated, and can observe microstructures down to tens of nanometers. It is widely used for structural analysis of nanomaterials and checking the uniformity of thin film manufacturing.

Professor Heung-No Lee said, “This study is a case of integrating ultra-small hardware and AI algorithms to simultaneously increase the precision and efficiency of computational spectrometers,” and added, “If combined with the large language model (LLM) in the future, it will be possible to have a user experience where users can scan their health status or food quality with a hyperspectral camera installed inside their smartphones and receive real-time guidance on the results in natural language.”

This study was supervised by Professor Lee Heung-no of the Department of Electrical Engineering and Computer Science at GIST, and jointly participated by Postdoctoral Researcher David S. Bhatti, PhD candidate Youngin Choi, and Professor Hoon Hahn Yoon of the Department of Semiconductor Engineering, and was supported by the Ministry of Science and ICT and the Institute of Information and Communications Technology Planning and Evaluation (IITP). The results of the study were published online in the international academic journal 《Scientific Reports》 on July 1, 2025.