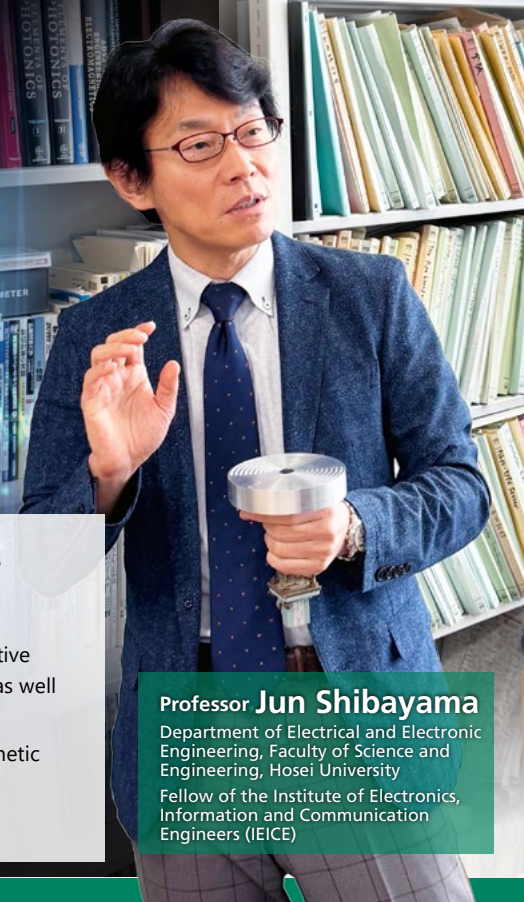


Synergy between Nanophotonics and Terahertz with Advanced Electromagnetic Field Analysis:

Interview Professor Jun Shibayama, Hosei University

Cutting-edge fields such as nanophotonics and terahertz technology are seeing rapid and innovative development. Techniques for manipulating light at the nanoscale and high-sensitivity sensing in the terahertz range are expected to lead to significant advances in communications and biosensing applications. Opening the door to this new era hinges on developing functional devices from innovative perspectives. Achieving these advances requires a precise analysis of complex physical phenomena, as well as electromagnetic field analysis methods that ensure stability and computational efficiency.

Anritsu interviewed Professor Jun Shibayama of Hosei University, a leading researcher in electromagnetic field analysis within the fields of nanophotonics and terahertz. The interview covered his research achievements and the pivotal role of electromagnetic analysis.



Professor Jun Shibayama
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1. Physical Properties and Their Application to Nanophotonics

— Could you tell us about nanophotonics and, in particular, “plasmonics,” which is one of your research themes?

Shibayama: Nanophotonics is the control of light and electromagnetic waves at the nanometer scale (10^{-9} meters), i.e., at dimensions smaller than the wavelength of light. There is a subfield of nanophotonics known as “plasmonics,” which exploits Surface Plasmon Polaritons (SPPs). These are surface electromagnetic waves that propagate along the interface between a metal and a dielectric, such as glass or silicon. SPPs arise from the interaction between incident light and the collective oscillations of free electrons in the metal.

Conventional far-field optics are limited by the diffraction limit, which makes it challenging to confine light to regions smaller than approximately the wavelength. By harnessing SPPs, however, we can concentrate and guide electromagnetic energy in subwavelength volumes near the surface, effectively circumventing the far-field diffraction limit in the near field. These unique properties suggest promising applications, including optoelectronic devices for next-generation high-speed optical communications, photonic nanocircuits, and biosensors.

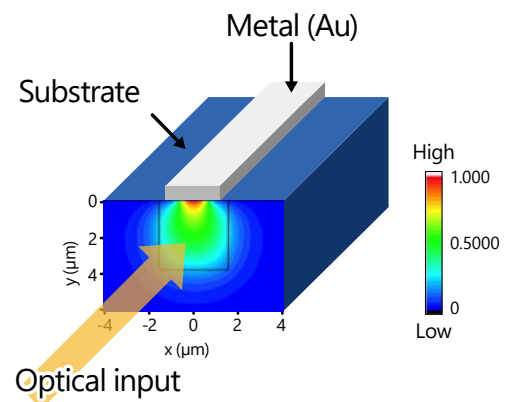


Figure 1 Example of a plasmonic waveguide and the corresponding electromagnetic field distribution

Figure 1 shows a plasmonic waveguide consisting of a thin gold (Au) film formed on a dielectric substrate, along with a front-view simulation of the electromagnetic field distribution of the SPP propagating through this structure. The wavelength of the incident light is $1.55 \mu\text{m}$. As shown in Figure 1, the field is strongly confined to a region smaller than the light wavelength, with localization occurring at the submicron scale ($<1 \mu\text{m}$).

2. Research Focus in Nanophotonics and Terahertz

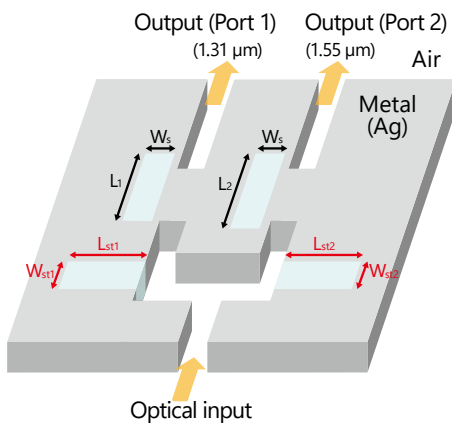
— Could you describe the nanophotonics research topics that you are currently focusing on?

Shibayama: In nanophotonics, the goal is to miniaturize photonic circuits even further. To that end, we are designing plasmonic waveguides based on a Metal–Insulator–Metal (MIM) structure. By sandwiching a central dielectric layer between metallic claddings, this structure confines and guides SPPs within regions that are far smaller than the free-space wavelength. Consequently, it enables a substantial reduction in footprint relative to conventional optical waveguides.

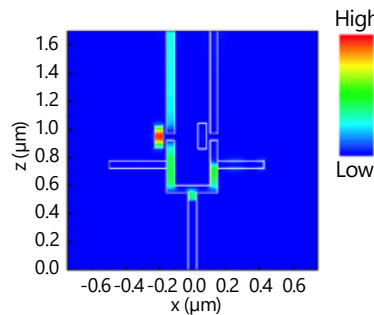
We are also conducting research into functional devices based on plasmonic waveguides. For example, we have proposed an ultra-compact wavelength splitter utilizing a plasmonic waveguide (Figure 2). Its operating principle is as follows:

- (1) Light incident on the lower gap region in Figure 2(a) is converted into an SPP at the metal surface. The SPP then propagates along the gap.
- (2) The dimensions of the dielectric region (shown in light blue) influence the wavelength-selective characteristics of the SPP. When the structure is designed to separate wavelengths of $1.31\ \mu\text{m}$ and $1.55\ \mu\text{m}$, the $1.31\text{-}\mu\text{m}$ component exits through Port 1, while the $1.55\text{-}\mu\text{m}$ component exits through Port 2.

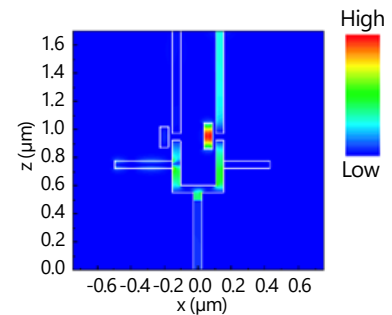
This structure enables wavelength separation at different output ports through the precise engineering of parameters such as the gap width, dielectric dimensions, and branching angle. Furthermore, because it exploits the strong field confinement of SPPs in the nanoscale regions, it provides optical control at dimensions smaller than the wavelength. This enables an ultra-compact wavelength splitter that would be difficult to configure using conventional optical components. However, challenges remain, such as improving the SPP coupling efficiency at the input interface and reducing losses caused by metal absorption.



(a) Proposed structure



(b) $1.31\ \mu\text{m}$

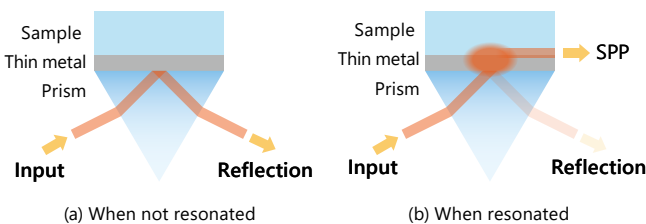


(c) $1.55\ \mu\text{m}$

Figure 2 Ultra-compact wavelength splitter based on a plasmonic waveguide

— Could you tell us about your research themes and activities in the terahertz field?

Shibayama: We are also exploring the application of photonic technologies to the terahertz field. In the optical regime, sensors that exploit SPPs for material characterization have already been commercialized. These sensors are known as Surface Plasmon Resonance (SPR) sensors.



(a) When not resonated

(b) When resonated

Figure 3 Fundamental configuration of an SPR sensor

In an SPR sensor, a sample — such as biomolecules or DNA — is placed on the surface of a thin metal film. By measuring the optical absorption spectrum of the sample, we can detect its properties, such as its refractive index and concentration. Our goal is to realize a similar sensing mechanism in the terahertz frequency range.

In order to do so, SPPs and SPRs must be generated in the terahertz band. These phenomena occur naturally in the optical region but not on metal surfaces at terahertz frequencies. However, the situation changes when semiconductors are used. For SPP or SPR to occur, the real part of the permittivity must be negative. Certain materials can exhibit this property in the THz range. Indium antimonide (InSb) is one promising candidate.

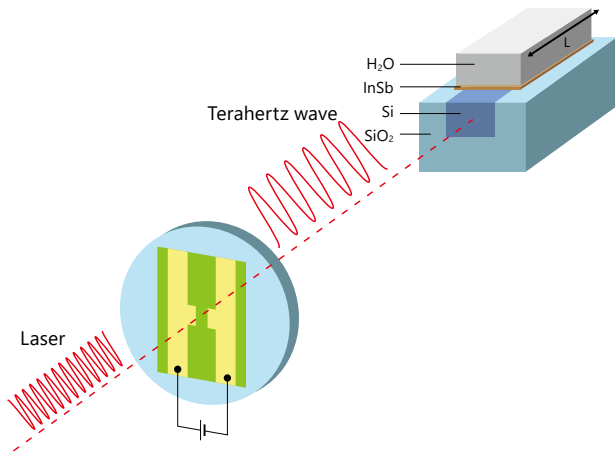


Figure 4 Photoconductive antenna and terahertz SPR sensor

Figure 4, top right, illustrates our proposed terahertz SPR sensor. The device consists of a multilayer thin-film stack of $\text{SiO}_2/\text{Si}/\text{InSb}$, where the InSb layer functions as the negative-permittivity material. A water layer (H_2O) placed on top of the InSb serves as the sensing target. When a terahertz wave is incident on this structure, SPR occurs, and the attenuation of the THz wave varies according to the refractive index of the sample.

An additional component is required to generate the terahertz wave for the SPR sensor. An example is shown at bottom-left in Figure 4: a photoconductive antenna that converts optical pulses into terahertz radiation. This antenna is fabricated on a semiconductor substrate with H-shaped metal electrodes. When femtosecond laser pulses illuminate the gap between the electrodes, carriers (electrons and holes) are generated in the semiconductor. These carriers are accelerated by a bias voltage applied across the electrodes, resulting in the emission of terahertz waves from the antenna.

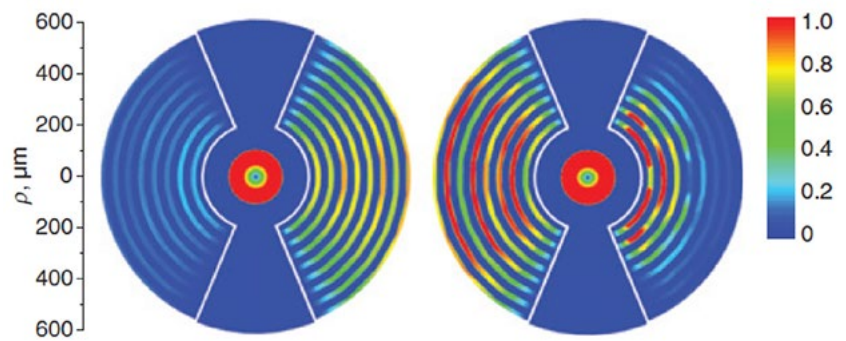
A terahertz-band SPR sensor based on InSb is expected to be able to enable a wide range of applications, including the detection of temperature variations and solution concentrations, as well as diverse biosensing and non-destructive testing. This is made possible by leveraging the high material penetration capability of terahertz waves and their ability to probe molecular vibrational modes. Additionally, terahertz radiation enables direct observation of molecular vibrational bands that are challenging to monitor using conventional SPR sensing in the visible and near-infrared regions. This capability opens the door to broader applications, such as characterizing new materials and analyzing pharmacokinetics in the medical and chemical fields.

Shibayama: In the terahertz domain, we have also proposed a novel functional device: a terahertz surface-wave splitter that controls the output direction according to the frequency of the incident wave. Figure 5 (a) shows the structure of the splitter (scaled up to microwave dimensions for illustrative purposes), consisting of concentric grooves (a grating) etched into a metallic substrate. Although SPPs do not naturally propagate on a flat metal surface at terahertz frequencies, introducing subwavelength grooves enables the propagation of spoof SPPs. Figures 5 (b) and 5 (c) present the simulated electromagnetic field distributions for frequencies at 1 THz and 1.5 THz, respectively.

The operating principle is as follows: when a terahertz wave is incident at the center of the disk-shaped meta surface, spoof SPPs are excited along the grating on the metal substrate. At 1 THz, the spoof SPP primarily propagates to the right, whereas at 1.5 THz, it propagates to the left. This splitter can direct terahertz waves to different paths depending on the frequency, making it a promising candidate for components in terahertz communication systems. However, the current design has insufficient energy confinement at the surface and requires further optimization.



(a)



(b) 1 THz

(c) 1.5 THz

Figure 5 Terahertz surface-wave splitter

- (a) External view of a terahertz surface-wave splitter (scaled up to microwave dimensions)
- (b) (c) Simulated electromagnetic field distributions for frequencies of 1 THz and 1.5 THz

3. The Expected Role of Electromagnetic Field Analysis and Emerging Technical Challenges

— What is driving the demand for electromagnetic field analysis, and what role is it expected to play?

Shibayama: In these lines of research, electromagnetic field analysis, or computational electromagnetics, plays a pivotal role. In the R&D of electromagnetic-based functional devices, high-fidelity and computationally efficient electromagnetic simulations at the design stage are indispensable for reducing prototyping costs and shortening development time. This need is particularly acute in fine-scale regimes, such as nanophotonics and the terahertz band, where increasingly sophisticated modeling and numerical methods are required. These heightened requirements, in turn, bring the resulting technical challenges into sharper focus.

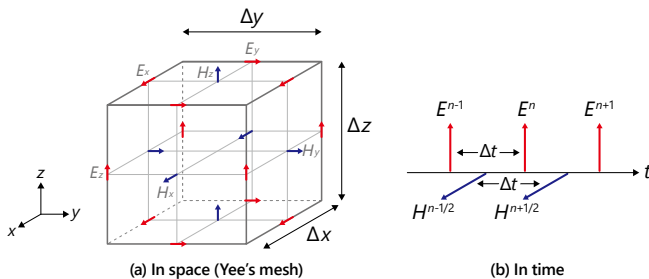


Figure 6 Electromagnetic field arrangement in the FDTD method

(a) Spatial Arrangement (Yee Mesh):

In a Cartesian coordinate system, the electric field E (red arrows) is positioned along the edges of a cubic cell, while the magnetic field H (blue arrows) is placed at the centers of the faces, staggered alternately.

(b) Temporal Arrangement:

The electric and magnetic fields are staggered in time by half-time steps ($\Delta t/2$).

The Yee mesh is well-suited for discretizing Maxwell's equations and is widely respected for its numerical stability.

— What technical challenges are currently coming to the fore in electromagnetic field analysis?

Shibayama: The principal challenge facing electromagnetic analysis is managing the growth of computational cost and memory consumption. In particular, when dealing with SPPs, the electromagnetic fields vary sharply at metal-dielectric interfaces. To capture this behavior with high fidelity, the spatial discretization (grid resolution) must be very fine.

Representative methods for computing SPPs include the Finite-Difference Time-Domain (FDTD) approach, which directly solves Maxwell's equations in the time domain. Explicit FDTD (see glossary note*) is commonly used, but it must satisfy the Courant stability condition.

Because SPP simulations require very small spatial steps, the Courant condition forces the time step to become correspondingly small, which results in prohibitively long runtimes. Furthermore, faithfully reproducing SPP physics necessitates the proper dispersion modeling of metals and semiconductors (i.e., frequency-dependent permittivity). If dispersion is not modeled appropriately, the simulation results can deviate from the underlying physics. In real materials, additional factors — such as nonlinearity, temperature effects, and variations in carrier density — also influence SPP behavior.

Incorporating these effects into the analysis substantially increases the model complexity. Additionally, when analyzing complex geometries or nanometer-scale features, both advanced meshing strategies and careful specification of the boundary conditions across the simulation domain become critical.

Addressing these challenges — so that analyses are both more realistic and more computationally efficient — will require continued advances in numerical methods as well as progress in parallel computing.

— Professor Shibayama pioneered the introduction of implicit computational techniques into the FDTD method, achieving a simplified yet highly efficient approach to electromagnetic field analysis. In recognition of these contributions, the Professor received the Electronics Society Award, the highest honor of the IEICE Electronics Society, in 2018, and was named an IEICE Fellow in 2023. Could you summarize the key aspects of this achievement?

Shibayama: The FDTD method is widely used because of its relatively simple computational procedure. However, it suffers from a major drawback: to maintain numerical stability under the Courant condition, the time steps must be reduced in proportion to the spatial discretization. When analyzing fine-scale structures such as those in nanophotonics and plasmonics, the spatial grid must be extremely fine. This makes the time step very small and results in prohibitively long computation times.

To overcome this limitation, we were the first to incorporate an implicit scheme — the Locally One-Dimensional (LOD) method — into FDTD, thereby completely removing the time-step restriction imposed by the Courant condition. The LOD approach performs implicit updates sequentially along each spatial direction, allowing the time step to be chosen independently of the spatial resolution. This dramatically improves the computational efficiency. In practice, the LOD-FDTD method has been shown to reduce the computation time by between one-half and one-tenth compared to the conventional explicit FDTD. While the implicit nature of LOD-FDTD introduces additional complexity — since linear equation solving systems are required rather than simple algebraic updates, the ability to use much larger time steps provides a significant overall advantage.

The simplicity and efficiency of the LOD-FDTD have gained worldwide recognition: as of 2025, the original paper describing this method had been cited over 400 times. Today, researchers around the globe continue to refine and extend upon the method, which is now featured in textbooks both in Japan and abroad. LOD-FDTD also plays a critical role in the research of the nanophotonic and terahertz functional devices discussed in this article.

— What should young engineers keep in mind when working in electromagnetic field analysis?

Shibayama: Electromagnetic field analysis is an extremely powerful tool, but it is essential to recognize that blindly trusting simulation results can lead to incorrect conclusions. This is particularly critical when analyzing structures with frequency-dependent material properties (dispersion), such as metals in plasmonics. We need to keep the following points in mind:

- Understand the applicability and limitations of each numerical method:
Different computational techniques, such as the FDTD method and the finite element method (FEM), have distinct strengths and constraints. For example, a thorough analysis of SPR typically necessitates high-resolution meshing, meticulous boundary condition design, and careful consideration of numerical stability and accuracy.
- Verify that the chosen method is capable of attaining the required level of accuracy:
Before proceeding, confirm that the selected EM analysis method can achieve the necessary level of precision. Start by comparing your results against published benchmark models or reference simulations for comparable structures. In photonics and terahertz research, there are widely shared benchmark cases available to validate your approach. If the required accuracy is not achieved, reconsider the method or adjust the simulation parameters accordingly.
- Accurately define material properties:
Correctly specifying material parameters, such as their permittivity, conductivity, and frequency dependence are essential. For dispersive materials, using a single permittivity value at a single wavelength is insufficient. Rather, adopt physical dispersion models, such as the Drude or Lorentz models, to better capture frequency-dependent behavior.
- Validate the plausibility of the results:
Ensure that the computed field distributions and interface behaviors align with theoretical expectations and physical principles. For instance, in SPP or SPR simulations, check for strong electric field confinement at the metal-dielectric interface, and verify compliance with the energy conservation and loss characteristics.

4. Future Research Directions of Professor Shibayama

— Could you tell us about the directions in which you aim to direct your research in the future?

Shibayama: To date, our laboratory has primarily focused on theoretical electromagnetic field analysis, particularly on developing efficient computational methods such as the LOD-FDTD method, and leveraging these techniques to propose novel device concepts. Going forward, we plan to build on this theoretical foundation and place greater emphasis on collaborative research involving experimental validation in order to develop practical devices.

One example of this initiative is our joint research project with Tokyo Metropolitan University and the National Institute of Information and Communications Technology (NICT), where we are conducting a 3D electromagnetic field analysis of terahertz-band SPR sensors. Once the simulation results are finalized, we intend to fabricate prototype devices and experimentally verify their performance and operating characteristics. A primary goal of this research is to implement terahertz SPR sensors in practice. Although theoretical analysis has confirmed their feasibility, there are significant challenges that remain in the fabrication process. These include achieving high-quality InSb layers on silicon substrates and ensuring structural compatibility for device integration. To address these issues, we will continue to collaborate closely with our partners at Tokyo Metropolitan University and NICT, making progress through iterative prototyping and performance evaluation.

In addition, Hosei University strengthened its photonics research capabilities in 2024 by welcoming Professor Takeshi Fujisawa from Hokkaido University. Professor Fujisawa actively promotes experimental research alongside theoretical studies using electromagnetic field analysis. We are currently exploring new collaborative research opportunities with his group.

In this way, research that initially took place primarily within our laboratory has evolved into multi-institutional collaborations. This collaborative approach establishes a seamless workflow — from device design using electromagnetic analysis, through fabrication and performance validation, to real-world implementation — thereby accelerating the transition from theoretical advances to practical technologies.

— Thank you very much for your time today.

*1: Explicit and implicit methods

Explicit and implicit methods are widely used for time integration in numerical analyses involving temporal evolution.

The explicit method calculates the value at the next time step sequentially and directly, using only the known values from the current time. Because of their relatively simple computational requirements, explicit schemes are often regarded as being well-suited to beginners in the area of electromagnetic field analysis. However, explicit methods are constrained by a stability requirement known as the Courant condition, which mandates that the time step be sufficiently small. This restriction can lead to longer overall computation times. If the time step exceeds the Courant limit, the numerical solution becomes unstable.

The implicit method formulates equations that incorporate unknown values at the next time step and then solves these simultaneous equations to obtain a solution. This approach provides numerical stability even with relatively large time steps, which can significantly reduce the total simulation time.

For more detailed information on the research discussed in this article, please refer to the following publication authored by Professor Shibayama.



Jun Shibayama, “FDTD Analysis of Plasmonic Devices,” Springer Series in Optical Sciences, volume 78, Sep. 2025.

<https://link.springer.com/book/9789819681297>