

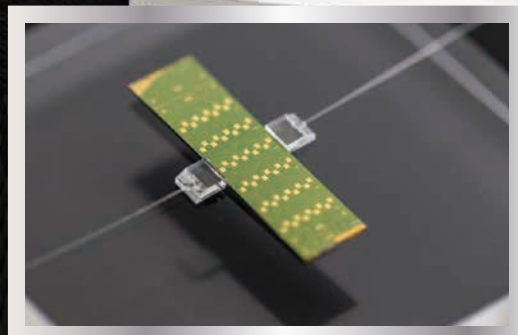
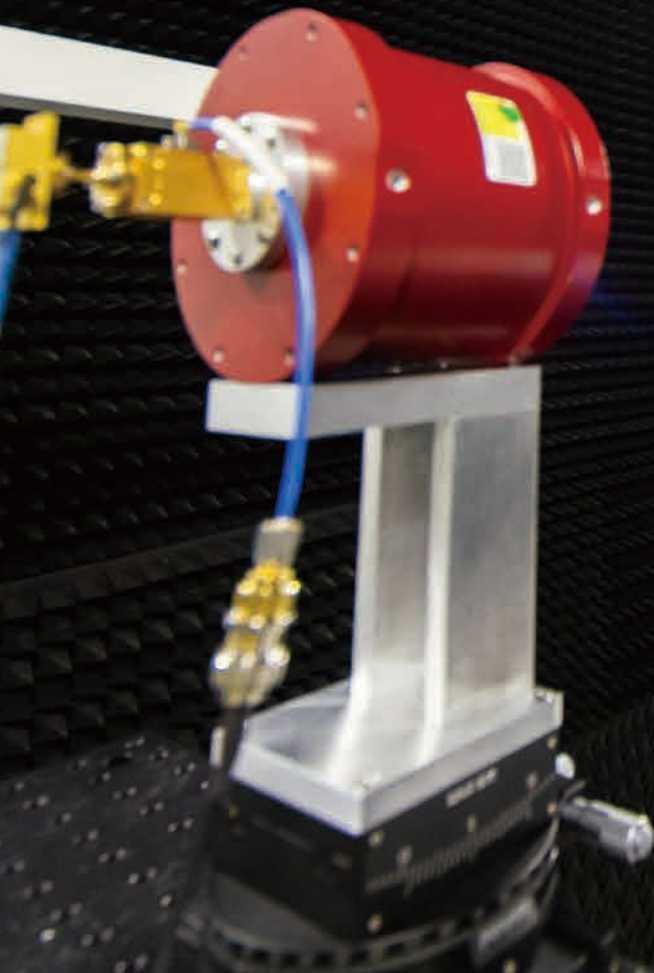
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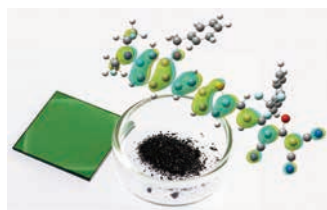
“EO Polymers Open the way to Ultrafast Optical Control” Feature on Nano-scale Functional Assembly ICT



DIALOG

The Art of Manipulating Light with Organic EO Polymers Infinite Potential for Applications from Communications to Three-Dimensional Displays





FEATURE

“EO Polymers Open the way to Ultrafast Optical Control” Feature on Nano-scale Functional Assembly ICT

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Terahertz wireless communication evaluation system using Radio over Fiber (RoF) technology. Terahertz waves emitted from a terahertz transmitter (foreground) are received by a terahertz receiver (background), composed of a parabolic mirror and an antenna coupled EO polymer optical modulator, enabling direct conversion from a radio signal to an optical signal.

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A 150 GHz band antenna coupled EO polymer optical modulator with optical fiber coupling

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Organic EO Polymer (Left) Thin Film, (Right Bottom) Powder, (Right Top) Molecular Structure



DIALOG

The Art of Manipulating Light with Organic EO Polymers Infinite Potential for Applications from Communications to Three-Dimensional Displays

Light is the star of ultra-high-speed communications. Essential to optical communications networks is the optical modulator, which converts electrical signals into optical signals. Its performance greatly influences communication speed. Currently, inorganic materials are used in optical modulators, which limits their speed and performance. The material expected to break through this limitation is the organic EO polymer. Its range of applications is also wide, from communications to display applications. However, because it can deliver remarkable performance, development is said to involve many challenges. This time, we present a roundtable discussion featuring researchers from the Nano-scale Functional Assembly ICT Laboratory at the Kobe Frontier Research Center, Advanced ICT Research Institute, who work day and night toward the implementation of organic EO polymers.

TANAKA Thank you all for joining us today. Since organic EO polymers may be difficult for the general public to picture, could you start with a brief explanation of what organic EO polymers are?

OTOMO Organic EO polymers are materials that exhibit the “electro-optic effect,” and we use the initials “EO” to call them EO polymers. They are materials in which the refractive index changes when a voltage is applied, and they are used in optical modulators for optical communications, which is an important device that determines the speed of optical communications. Currently, inorganic materials are used in optical modulators, but organic EO polymers are attracting attention because of the speed limitations of existing materials.

TANAKA Now, could everyone please introduce themselves, including an overview of your research?

OTOMO After graduating from university, I developed optical measurement devices for medical applications at a company, then studied in the United States and obtained my doctorate in research related to optical devices. That is where I encountered organic EO polymers and recognized the appeal of organic materials and the importance of materials development.

YAMADA I conducted research on the optical properties of organic materials during my graduate studies. At NICT, my research encompasses the development and evaluation of organic EO polymers, terahertz wave detection technologies, and optical phased array devices.

KAJI I conducted basic research on molecular measurements using lasers in graduate school. After joining NICT, I have been working on the development of devices that seamlessly convert terahertz wireless signals

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into optical signals, which is an essential technology for Beyond 5G wireless communications systems, using organic EO polymers.

■ Key Highlights of Research and Development

TANAKA Now, could you each share the “key point” from your own research that you most want to convey to our readers?

OTOMO Organic materials are often perceived as low cost and low performance, but I would like people to know that organic EO polymers offer high added value and high performance. When I mention that we are developing devices using organic materials, I am often told “that means it’ll be cheaper, doesn’t it?” However, lower cost alone does not lead to practical application. I strongly want to emphasize that organic EO polymers offer unique performance and functionalities that cannot be achieved with other materials.

YAMADA My key highlight is the tuning-ability to material properties through carefully designed organic EO polymer development. For example, if we can develop organic EO polymer materials that operate not only in the infrared region used for optical communications but also in the visible light range, new applications—such as 3D image displays using organic EO-polymer-optical phased arrays—become possible.

KAJI My key highlight is that we leverage a unique strength of organic EO polymers: the ability to operate at ultra-high frequencies, such as terahertz. By exploiting this capability, we can realize a device with previously unattainable functionality that directly converts terahertz wireless signals into optical signals.

■ Using Organic EO Polymers in Communications

TANAKA “Organic EO polymers in communications” might seem surprising to the general public. Could you tell us about the moment you first thought, “This is going to work!”?

OTOMO About 20 years ago, we experimentally confirmed a performance (efficiency) more than ten times higher than anything

achieved previously. We already knew that organic EO polymers were inherently capable of extremely high-speed operation, and we had been exploring new molecular designs ourselves, although without much success. Around that time, a research group in the United States reported an EO molecule with outstanding performance. The molecule was difficult to synthesize, making independent replication*¹ challenging. Fortunately, we had an expert in molecular synthesis in our laboratory, and we were soon able to synthesize the EO molecule ourselves. When we measured its properties, the results were astonishing. That experience marked the beginning of our full-scale research into organic EO polymers.

■ Where Do Organic Materials Excel?

TANAKA What are the points where organic materials excel compared to inorganic materials?

OTOMO Organic EO polymers are characterized by being high-speed and high-efficiency compared to existing materials. They also offer enormous flexibility in design. With inorganic materials, the structure and performance are determined by the combination of elements, but with organic materials, various functions can be created through combinations of common elements such as carbon, hydrogen, oxygen, and nitrogen.

YAMADA One of the key strengths of organic EO polymers is their superior responsiveness to high-frequency electric fields. As mentioned earlier, organic materials offer unlimited freedom in molecular design, which is a major advantage. At the same time, this freedom also makes them challenging, because the material with high-performance cannot be achieved without well-defined molecular design guidelines. Conversely, when molecular design is carried out properly, material properties can be finely tuned.

KAJI From a device development perspective, one of the major distinguishing features of organic materials compared with inorganic materials is their lower permittivity. This is

advantageous for ultra-high-speed operation and also allows the use of larger antennas when receiving terahertz waves. Furthermore, the closer match between the propagation speeds of high-frequency signals and optical waves in the material contributes to higher device efficiency.

■ The Ultimate Form of Materials Development: Molecular-Level Design

TANAKA You mentioned that organic materials are characterized by the ability to be designed at the molecular level. In your view, what specifically represents the ultimate aspect of organic materials development?

YAMADA I believe the ultimate strength lies in the ability to use molecular design to develop organic EO molecules operable across a wide range of optical wavelengths, and to engineer polymer backbones that yield materials combining properties that are otherwise difficult to achieve simultaneously, such as thermal stability, flexibility, and robustness.

■ NICT’s Strengths in Device Development

TANAKA One of our strengths is that we have an in-house environment capable of handling the entire workflow, from materials development to device processing and evaluation. Could you elaborate on this a bit more concretely?

YAMADA Because we can evaluate the performance of newly developed materials immediately, it becomes easier to plan device fabrication, which in turn accelerates the pace of research.

KAJI Our greatest strength lies in the ability to rapidly cycle through the entire process up to device evaluation. This allows us to develop devices using materials optimized for each device structure and fabrication process, even in the presence of various trade-offs in material performance. Moreover, by taking a comprehensive, bird’s-eye view of the en-

tire workflow, we can identify where the key challenges lie. I believe that the organic EO polymer transfer technology independently developed at NICT was conceived precisely because we operate in an environment where all stages of the process can be carried out in-house.

■ Challenges and Stories from the Lab

TANAKA I imagine there have been many instances of trial and error. Could you share some of the challenges and interesting episodes from your work?

OTOMO When you’re really struggling with an experiment and then happen to come across a single hint, there’s a moment when everything in your head suddenly comes together. In those moments, you can feel a rush of adrenaline. Once you experience that excitement even just once, research may be tough, but you simply can’t quit. (laughs)

KAJI We fabricate devices by hand through dozens of processing steps, which takes about a month. If a single mistake occurs near the end, however, everything has to be started over from scratch. It’s a continual series of challenges like that. On the other hand, what truly makes it rewarding is when a value calculated beforehand matches the experimental result perfectly.

■ Advantages of Collaborative Research with Industry and Universities

TANAKA You often conduct collaborative research with companies and universities. In what ways can NICT’s distinctive strengths be best leveraged in these collaborations?

OTOMO Because we conduct integrated research spanning materials, devices, and subsystems, companies from a wide range of fields can come to us and have their concepts developed into actual devices and evaluated. This end-to-end capability significantly accelerates development. Currently, we are engaged in collaborative research with 14 companies and 9 universities.

YAMADA In addition, because we hold numerous patents related to materials and device fabrication process technologies, which make it easier to collaborative research with companies and universities.

■ Economic Security

TANAKA The synthesis of organic EO polymers is highly complex and involves substantial accumulated know-how. Is there any concern that they could be replicated through reverse engineering*²?

OTOMO Organic EO polymers consist of organic molecules that exhibit the EO effect integrated with the polymer. As a result, even mass spectrometry cannot directly determine the molecular weight of the EO molecules themselves, making replication through reverse engineering extremely difficult.

YAMADA Organic EO polymer do not exhibit EO effects in their original form. Through a process called poling, EO molecules are aligned in a single direction. However, even with advances in elemental and structural analysis techniques, I believe that the actual alignment state of these molecules cannot be determined.

■ Overcoming the Weaknesses of Organic Materials through Hybridization

TANAKA Organic materials have both strengths and weaknesses. How have you worked to overcome those weaknesses?

OTOMO Organic materials have a relatively low refractive index, which tends to result in larger device sizes. In contrast, semiconductors have a high refractive index. By combining the two into hybrid structures, we are working toward the fabrication of compact, high-efficiency devices. Organic materials are often thought to degrade under intense light exposure; however, they remain stable in the absence of oxygen. We address this issue by encapsulating the materials with oxygen-impermeable films.

YAMADA Organic materials are often considered to have poor heat resistance, but our organic EO polymers exhibit sufficient thermal stability for specific applications.

■ Future Prospects

TANAKA Finally, could you briefly share your target or milestone for where you would like to be over the next three to five years?

OTOMO I aim to achieve the world’s fastest optical modulation and advance it to the point where it can be implemented in optical interconnects.

YAMADA Since the applications for organic EO polymers are expanding, I aim to develop high-performance materials that can operate across a wide range of wavelengths, including visible light, as well as general purpose technologies with broad applicability. On the device side, I would like to demonstrate the excellent light beam-steering capabilities of organic EO-polymer optical phased arrays towards realization of entirely new type of three-dimensional display.

KAJI Toward the realization of wireless communications using terahertz waves, we are pursuing device packaging for practical use. By integrating them into a variety of terahertz wireless communication systems, we aim to demonstrate system-level performance and ultimately lead to real-world deployment.

TANAKA Thank you very much for today.

*1 Replication study
A process in which another researcher verifies whether a research result is reproducible by testing it under various conditions.

*2 Reverse engineering
The process of analyzing a finished product to decipher its internal structure and operating principles.

Organic EO Polymers for Short Wavelengths Open a New Door of Light Control



OTOMO Akira

Director of Nano-scale Functional Assembly ICT Laboratory, Kobe Frontier Research Center, Advanced ICT Research Institute (Affiliations and titles are as of February 2026)

After graduating from university and studying in the United States, he joined Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT) in 1996. Since then, he has been engaged in research on the application of organic molecular photonics and nanophotonics to optical control technology. Ph.D. (Optical Science and Engineering)

Organic EO polymers have been developed with the aim of increasing the speed and reducing the power consumption of optical control devices, including optical modulators that are essential for optical communication systems using near infrared light. For this reason, it had long been assumed that they could not be used at shorter wavelengths such as visible light. We have broken this conventional wisdom and successfully developed organic EO polymers capable of highly efficient modulation even in the visible light range. Enabling high-speed, highly efficient modulation at shorter wavelengths opens up new possibilities, including three-dimensional image acquisition, display, and underwater optical wireless communications.

Background

As the transformation to a data-driven society advances and demand for data centers and AI servers surges rapidly, speeding up and reducing the power consumption of short-reach optical communication systems (optical interconnects)—the backbone of data communications—has become an urgent challenge. Organic EO polymers were originally developed to speed up long-distance optical communication systems, with the C-band (1,550 nm wavelength range) as the development target. However, optical interconnects operate in the O-band (1,310 nm wavelength range). We also focused on applying the beam steering function of optical phased arrays (OPAs), which consist of many optical modulators, to LiDAR*. This was because the realization of autonomous driving requires compact and high speed LiDAR. Long-range LiDAR, which irradiates space with high-power laser light of around 1 W, uses laser at a wavelength of 1,550 nm, which is safe for human eyes. However, short-range LiDAR operates with low-power laser light and therefore employs a wavelength of

905 nm, which enables the use of inexpensive Si detectors. Short-range LiDAR is not only needed for autonomous driving, autonomous drones and robots, but when combined with a camera, it can capture three-dimensional image information with added depth information. Furthermore, if this can be achieved with visible light, it also becomes applicable to display devices that render such three-dimensional image information. In this way, organic EO polymers that are more efficient than those in the C-band at shorter wavelengths are expected to expand the range of applications of optical control technology and become a source of new value.

Organic EO Polymers

Organic EO polymers exhibit the electro-optic effect (EO effect), in which the refractive index changes when a voltage is applied. This effect can be used to modulate light ON/OFF with electrical signals (Figure 1). This optical modulator is the device that determines the communication speed in optical communications. Organic molecules exhibit a large EO effect because π electrons confined within nanometer-scale molecules resonantly interact with the electric field of light, an electromagnetic wave, resulting in strong interactions. Furthermore, since electrons are extremely lightweight, this response is very fast. Therefore, EO polymers composed of organic molecules enable high-speed, low-power modulation. Although organic materials are often inferior in performance to inorganic materials, organic EO polymers are a rare type of material that exhibits superior performance.

Tuning of Molecular Structure

At the resonant wavelength, strong interaction with light leads to increased optical absorption. The EO effect also increases as the wavelength approaches the absorption wavelength. This is called the resonance effect. The resonant wavelength can be tuned

by freely designing the structure of organic molecules. The fundamental structure of organic EO molecules is the D- π -A structure, in which an electron-donor group (D), which has the property of pushing out electrons, and an electron-acceptor group (A), which has electron-withdrawing properties, are connected by a conjugated system in which π electrons are delocalized along the bonds (Figure 2a). The EO effect can be enhanced by combining substructures with strong electron-donating and electron-accepting properties.

Extending the conjugated system also increases the EO effect. Based on these guidelines, we have successfully designed and developed C-band organic EO molecules that exhibit an EO effect 53 times larger than at the initial stage of development (Figure 3a). However, lengthening the molecule shifts the resonant wavelength to longer wavelengths. In the absorption spectrum shown in Figure 3b, there appears to be no absorption at wavelengths above 1,000 nm. However, at the approximately 1 cm length used in modulators, the absorption loss is too large for use at short wavelengths below the O-band (Figure 3c). Therefore, to develop organic EO polymers usable at short wavelengths, tuning that balances the EO coefficient and absorption coefficient becomes critical.

Development of Short-Wavelength EO Polymers

To keep optical input/output loss in an optical modulator to around 50%, the permissible absorption loss is approximately 3 dB/cm. Since this is only a very slight absorption, the measurement was performed by fabricating thick films by etching grooves in glass and embedding the material within them. In developing C-band EO polymers, simply maximizing the EO coefficient was the criterion; however, since the EO coefficient and absorption coefficient are in a trade-off rela-

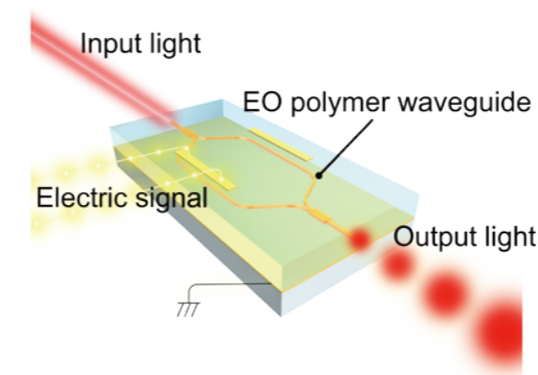


Figure 1 Organic EO polymer optical modulator

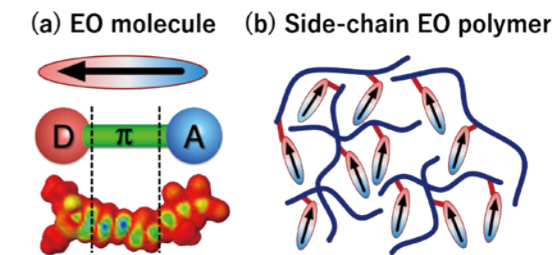


Figure 2 Basic structure of organic EO polymers

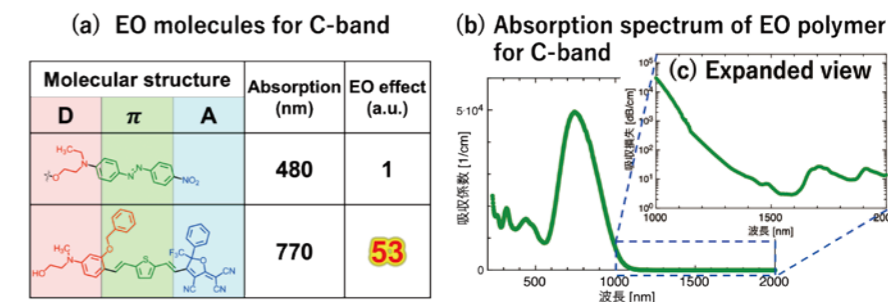


Figure 3 C-band EO polymer

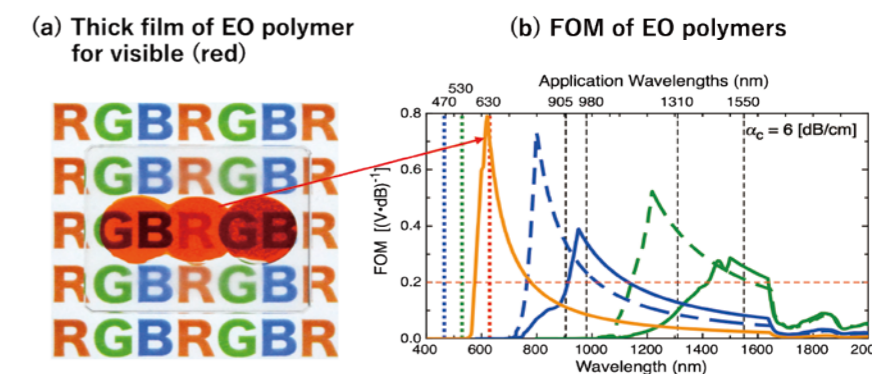


Figure 4 EO polymers for short wavelengths

tionship, focusing solely on individual values does not allow tuning for shorter wavelengths. Therefore, a new comparative metric is needed. One of the evaluation metrics for optical modulators is the loss-efficiency product (LEP), defined as the product of optical loss and efficiency. The LEP incorporates the EO figure of merit (n^2r), absorption coefficient (α), and wavelength (λ), making it an ideal metric for material tuning. By defining and comparing a figure of merit (FOM) for organic EO polymers based on the reciprocal of the LEP, we successfully developed organic EO polymers capable of high-efficiency modulation at various wavelengths up to and including visible light (Figure 4). The FOM of the developed visible-light (red) EO polymer is more than twice that of the C-band EO polymer, and an optical modulator fabricated with this polymer exhibited a modulation ef-

iciency more than three times higher.

Future Prospects

Organic EO polymers have been developed to achieve high performance at near-infrared wavelengths for accelerating optical communications. However, the realization of high-performance organic EO polymers at wavelengths below 1,000 nm, including in the visible light range, has opened up new possibilities for emerging functional devices such as three-dimensional cameras and 3D-AR smart glasses. We invite you to look forward to the future enabled by organic EO polymers.

* LiDAR
A sensing technology that irradiates laser light and precisely measures the distance and three-dimensional shape of a target based on the time required for the reflected light to return.

Ultra-high-speed Wireless-to-optical Signal Conversion using EO Polymers

Seamless conversion from terahertz wireless signals to optical signals



KAJI Takahiro

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(Affiliations and titles are as of February 2026)

After completing graduate school, Dr. KAJI served as a specially appointed assistant professor at the Global COE (Center of Excellence) Program before joining NICT in 2009. He is engaged in research on organic photonic devices and terahertz wave measurement. Ph.D.(Engineering).

Communications is heading toward an “ultra-high-speed era” in which videos and data arrive in an instant. The key to this lies in terahertz waves exceeding 100 GHz and a material called electro-optic (EO) polymer, which can directly convert those signals into optical signals. At NICT, we are developing devices that seamlessly bridge terahertz signals and optical signals using this technology, with the aim of realizing large-capacity communications of the future.

Background

In Beyond 5G, the frequency of radio waves used for wireless communications is expected to reach the terahertz band (100 GHz to 10 THz) in order to achieve ultra-high-speed, ultra-large-capacity wireless communications; however, such high-frequency wireless signals cannot be transmitted over long distances via electrical cables. Therefore, radio-over-fiber (RoF) technology, which converts wireless signals into optical signals and loads them onto optical fibers, becomes essential (Figure 1). Conventionally, two-stage signal conversion of wireless → electrical → optical was required, but this led to increased system complexity and high costs, including the need for electronic circuits operating at terahertz frequencies. By using EO polymers, direct signal conversion from high-frequency wireless signals in the terahertz band to optical signals can be achieved, greatly simplifying the configuration. Fur-

thermore, as an all-photonics technology, it can directly leverage the optical communications technologies accumulated to date, enabling ultra-high-speed, large-capacity wireless communications while also being easy to integrate into systems.

Development of Wireless-to-optical Signal Conversion Devices using EO Polymer Transfer Method

EO polymers, which have the property of changing their refractive index with an applied voltage, possess a large EO coefficient (r_{33}) and exhibit a large figure of merit for refractive index change. They also have a lower permittivity compared to inorganic materials, which is advantageous for high-frequency operation. In antenna devices, this allows for larger antenna sizes, and in traveling-wave optical modulators, the smaller velocity mismatch between high-frequency electromagnetic waves and light propagating through the material enables stronger interaction, thereby achieving highly efficient devices.

Regarding direct conversion from high-frequency wireless signals to optical signals, overseas research groups have proposed plasmonic waveguide-type devices (a waveguide that carries light by creating electron waves on the metal surface) in which EO polymers are embedded in microscopic metal gaps, and wireless transmission at frequencies close to 300 GHz has been reported. On the other hand, plasmonic waveguide-type devices have challenges such as large optical loss and

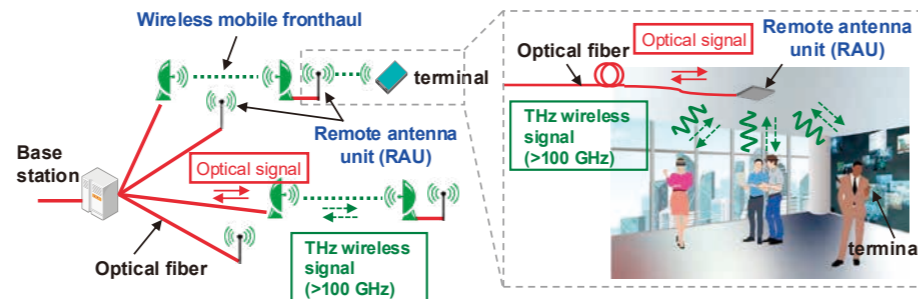


Figure 1 Schematic diagram of radio-over-fiber (RoF) using terahertz waves in Beyond 5G

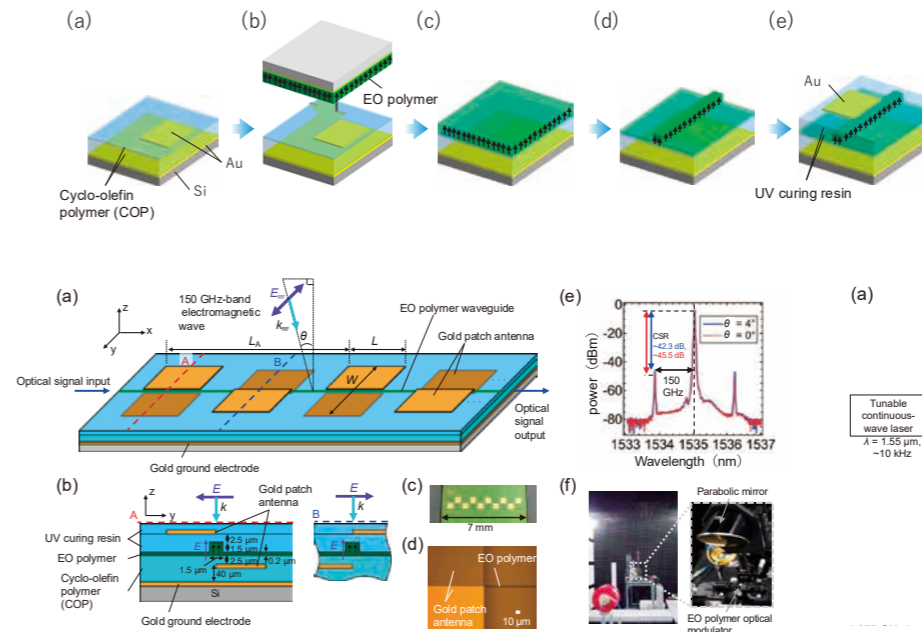


Figure 2 Device fabrication process using the transfer method (a) Preparation of a substrate with bottom antennas, (b)(c) Transfer of a poled EO polymer film, (d) Waveguide processing, (e) Formation of the upper cladding and top antennas

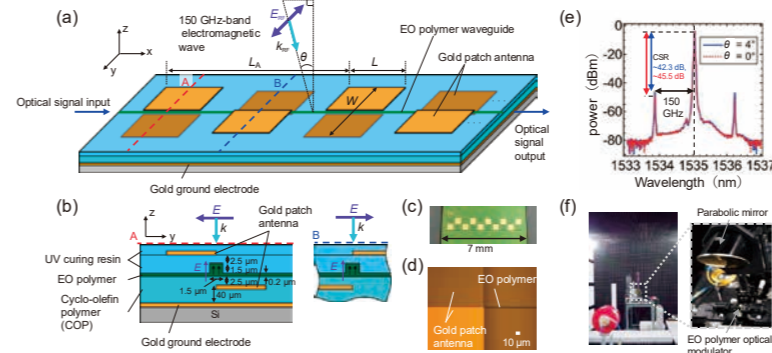


Figure 3 150 GHz-band antenna-coupled optical modulator: (a)(b) schematic diagrams, (c) appearance, (d) microscope image, (e) output spectrum under 150 GHz electromagnetic wave irradiation, (f) wireless transmission evaluation setup and wireless receiver unit

difficulty in mass production.

In device fabrication using EO polymers, a process called poling—which aligns the orientation of EO molecules within the EO polymer—is essential. NICT has succeeded in developing a unique process technology for transferring pre-poled EO polymer films onto various substrates (Figure 2). By using this proprietary EO polymer transfer method, it is possible to fabricate low-loss devices by combining EO polymers with cyclo-olefin polymers and other materials with low terahertz absorption loss, and mass production of devices also becomes feasible by performing transfers at the wafer (thin circular substrate) scale.

Development of Antenna-coupled Optical Modulator

Using the EO polymer transfer method, we fabricated a 150 GHz-band EO polymer optical modulator with an antenna array (Figure 3(a)–(d)). The EO polymer waveguide is arranged so that it is sandwiched between the edges of the upper and lower antennas. When terahertz waves are irradiated, voltage is efficiently applied to the waveguide, and light propagating through the waveguide is modulated by the refractive index change due to the EO effect (Pockels effect). Furthermore, by alternately arranging antenna pairs with inverted upper and lower antenna arrangements, not only the “peaks” but also the “troughs” of the terahertz wave can be utilized, resulting in a mechanism that efficiently modulates light.

Figure 3(e) shows the spectrum of the

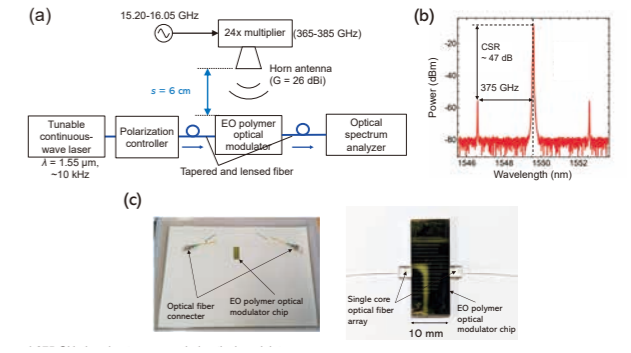


Figure 4 375 GHz-band antenna-coupled optical modulator: (a) evaluation setup, (b) output spectrum under 375 GHz electromagnetic wave irradiation, (c) modularization by optical fiber connection

output light when 150 GHz electromagnetic waves were irradiated onto such an EO polymer optical modulator. Clear optical modulation sidebands were observed at positions 150 GHz away from the frequency of the input light, demonstrating direct optical modulation by electromagnetic wave irradiation. Furthermore, we transmitted electromagnetic waves carrying modulated signals and conducted wireless transmission evaluation using RoF with the EO polymer optical modulator as a terahertz wave receiver (Figure 3(f)). We have successfully demonstrated wireless transmission at data rates (10 Gbps or higher) equivalent to or exceeding those required for uncompressed 4K video transmission in the 140 GHz band and the 150 GHz band.

Development of 375 GHz-band Optical Modulator

To achieve a significant increase in the data rate of wireless communications, it is essential to utilize higher frequency bands that can secure wider bandwidths. Therefore, we prototyped a 375 GHz-band optical modulator targeting operation at even higher frequency bands. Figure 4(a) and (b) show the evaluation setup for the device and the output spectrum when 375 GHz electromagnetic waves were irradiated, respectively. Optical modulation sidebands were observed, and it was demonstrated for the first time that direct optical modulation is possible even with the irradiation of high-frequency electromagnetic waves at 375 GHz.

We also prototyped a module in which

an optical fiber was connected to the 375 GHz-band optical modulator chip (Figure 4(c)). By modularizing the device, optical input/output to the device became more stable, system integration became easier, and system demonstrations combining various pieces of equipment became significantly easier to carry out.

Future Prospects

EO polymers have long attracted great attention for their high performance, but difficulties in device fabrication had been an obstacle to practical implementation. The EO polymer transfer technology independently developed by NICT can be considered one of the major breakthroughs toward the practical implementation of such devices. Going forward, we intend to advance improvements in materials, device fabrication processes, and device structures to pursue further enhancement of device performance, while also accelerating efforts toward social implementation, such as developing packaging technology and conducting system demonstrations.

Reference

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Fabrication of Electro-optic Polymer Free-standing and Laminated Films and its Applications to Ultra-high Frequency Electric Field Detection



YAMADA Toshiki

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After completing his doctoral course, he became a JST-CREST researcher in 1996. Dr. YAMADA joined Communications Research Laboratory (currently NICT) in 1999. Engaged in research on the development of electro-optic polymer materials and their evaluation techniques, optical modulation devices, and terahertz wave detection techniques. Ph.D. (Engineering).

EO polymers have large electro-optic coefficients which indicate how much the refractive index for an optical wave changes when an electric field is applied, and show excellent response to ultra-high-frequency electric fields (high-speed oscillations of the electric field). For this reason, EO polymers are highly advantageous for detecting ultra-high-frequency electric and/or terahertz electric fields. We developed new techniques to fabricate poled EO polymer free-standing films and laminated films with stacked free-standing films, for ultra-high-frequency electric field detection applications using EO polymers. Using the EO polymer laminated films, we successfully achieved ultra-broadband electric field detection.

In recent years, the range of applications of EO polymers has been expanding, and we have also developed technol-

ogies to make EO polymer free-standing and laminated films commonly used.

Background

EO polymers possess a large electro-optic coefficient (r) of 100 pm/V or higher and a refractive index (n) of approximately 1.6. The figure of merit (n^3r) for ultra-high-frequency and terahertz electric-field detection using EO effect is larger than that of inorganic EO crystals. Therefore, EO polymers, with the excellent ultra-high-frequency response, are promising for highly efficient terahertz electric-field detection. EO polymers also exhibit a small difference in refractive indices between the optical waves and terahertz wave, resulting in small velocity mismatch between optical wave and terahertz wave propagating through the material. While inorganic EO crystals have a limited detectable terahertz

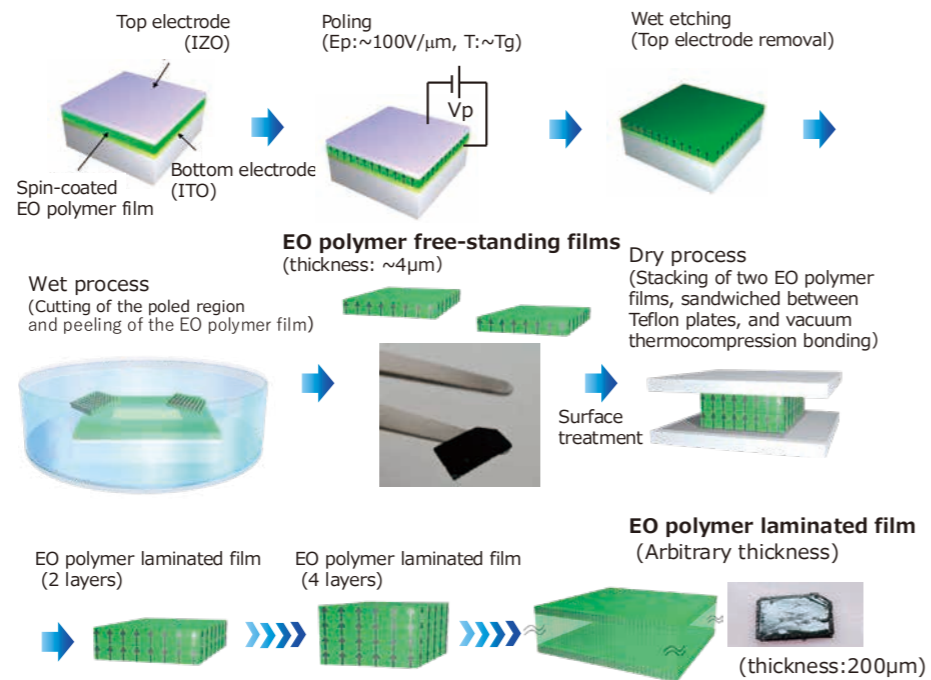


Figure 1 Schematic of the fabrication method for EO polymer free-standing and laminated films

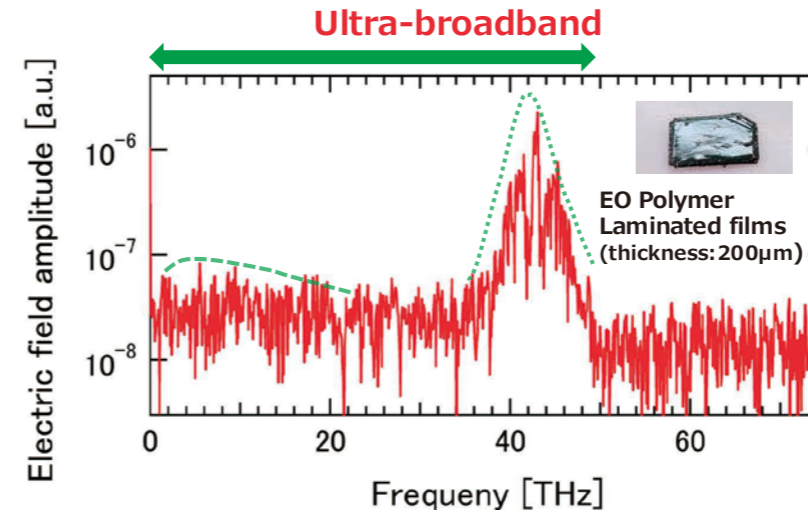


Figure 2 Fourier-transformed electric-field amplitude spectrum
Ultra-broadband electric-field detection using an EO polymer laminated film (200 μm thick)

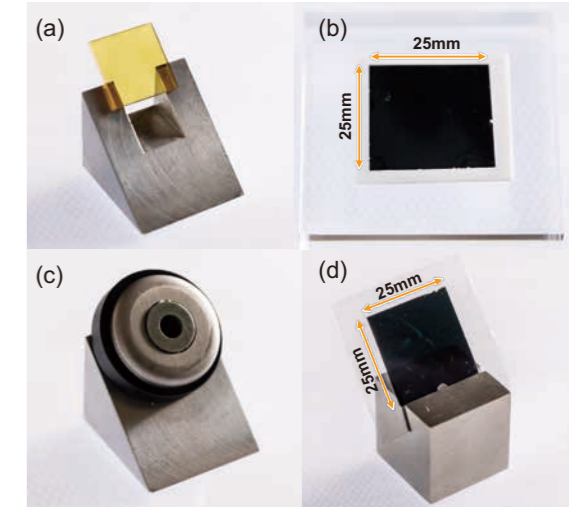


Figure 3 (a) EO polymer transferred film, (b) EO polymer free-standing film (25 mm square), (c) EO polymer laminated film (200 μm thick), (d) EO polymer carrier film (25 mm square)

frequency range due to terahertz wave absorption by crystal lattice vibrations, EO polymers, being amorphous materials (solids in which atoms and molecules are arranged randomly without a regular periodic structure), have a relatively small absorption coefficient over a wide terahertz frequency range, which is suitable for ultra-broadband terahertz electric field detection.

To exhibit the EO effect of EO polymers, we perform poling—a process in which EO molecules are aligned so as to have the polar orientation using an applied electric field. In the poling, transparent conductive electrodes such as ITO and IZO are used. Specifically, the temperature is raised to near the glass transition temperature (T_g) of the EO polymer, and a relatively high electric field for poling (E_p : approx. 100 V/μm) is applied to align the dipoles of the EO molecules. The temperature is then lowered while maintaining the applied electric field to freeze the aligned orientation.

Since electrodes used in the poling strongly absorb and reflect terahertz waves, electrodes used in the poling prevent terahertz applications of EO polymers. We developed a method to transfer the poled EO polymer film onto a substrate that is transparent in the terahertz frequency range, and performed broadband terahertz electric field detection using electrode-free EO polymer transferred substrates.

EO Polymer Free-Standing and Laminated Film Fabrication

As shown in the schematic in Fig-

ure 1, we further developed a fabrication technique for EO polymer free-standing and laminated films. We developed a new process for fabricating poled EO polymer free-standing films and stacking them while aligning the poling directions. After poling, the top electrode is removed, and the laminated EO polymer films are fabricated using wet and dry processes, including peeling technology of EO polymer film, surface treatment, and vacuum thermocompression bonding. For fabrication, EO polymers with excellent thermal stability and robustness capable of withstanding these processes are selected.

Ultra-Broadband Electric Field Detection using EO Polymer Laminated Films

In electro-optic sampling—a terahertz electric field detection method that utilizes the electro-optic effect—the detection efficiency is proportional to the figure of merit (n^3r) and the film thickness d . Using the method shown in Figure 1, a lot of poled EO polymer free-standing films were fabricated and laminated with their poling directions aligned to produce an EO polymer laminated film (thickness d : approx. 200 μm). Using terahertz time-domain spectroscopy with a femtosecond laser at a wavelength of 1.56 μm, the waveform of the terahertz electric-field generated from a DAST crystal was detected using the EO polymer laminated film. Figure 2 shows the electric-field amplitude spectrum obtained by Fourier transforming the measured electric-field waveform (i.e., decomposing a complex electric-field wave-

form into a superposition of the amplitude of single-frequency waves). In addition to the frequency range from 0.1 to 20 THz, an infrared light electric field with a peak around 40–42 THz was observed, demonstrating successful ultra-broadband electric-field detection.

Future Prospects

We are advancing technology development for producing large-area EO polymer free-standing films and for fabricating a carrier film structure for EO polymers. As of March 2026, as shown in Figure 3, we are now able to fabricate EO polymer free-standing films with 25 mm square. By cutting large-area EO polymer free-standing films into appropriately sized pieces to produce a lot of EO polymer free-standing films, the efficiency of fabricating multilayer laminated films can be significantly improved. Large-area EO polymer free-standing films are also expected to be applicable to the fabrication of waveguide-type devices, such as EO polymer optical modulators and EO polymer optical phased arrays. Furthermore, we believe that a carrier film structure—where an EO polymer free-standing film is sandwiched between a low-tack film and a release film—will contribute to making EO polymer free-standing films commonly used. Since the poling of EO polymers is technically difficult, we aim to contribute to the advancement of this field by making EO polymer free-standing films commonly used.

Development of EO Polymer Optical Phased Array toward its Application to New 3D Display



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After completing his doctoral course, he became a JST-CREST researcher in 1996. Dr. YAMADA joined Communications Research Laboratory (currently NICT) in 1999. Engaged in research on the development of electro-optic polymer materials and their evaluation techniques, optical modulation devices, and terahertz wave detection techniques. Ph.D. (Engineering).



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After completing graduate school, he joined NHK in 1997. Since then, he has been engaged in research on plasma displays, three-dimensional imaging devices, and optical phased arrays for spatial image reproduction displays.

We are engaged in research and development on optical phased arrays (OPAs)* based on EO polymer (EOP) for applications such as free-space optical communications, LiDAR, and 3D displays. An optical phased array is a device that can control the propagation direction and convergence/divergence of a light beam by exploiting optical interference, and is characterized by having no mechanical moving parts, making it compact and lightweight. In particular, EO polymer optical phased arrays (EOP-OPAs) enable ultra-fast, low-power light beam control, and are expected to serve as emitter units for the various applications mentioned above.

Background

We are engaged in research and development of ultra-fast temporal and spatial optical modulation technology using EO polymers, one application of which is the optical phased array. As shown in Figure 1,

an optical phased array consists of an optical beam splitter that divides the input light, optical phase shifters whose refractive index is modulated through the electro-optic (EO) or thermo-optic effect, and an optical output part (end-faces of waveguides or gratings connected to them). By applying control signals to each optical phase shifter in the array and controlling the wavefront, the propagation direction and convergence and divergence of the light beam can be flexibly controlled as shown in Figure 1.

Comparison of Optical Phase Shifter Materials and Device Properties

Light beam control speed, power consumption, applicable wavelengths, and other characteristics depend on the material and operating principle of the optical phase shifter employed. Figure 2 shows a comparison between EO polymer optical phased arrays (EOP-OPAs), silicon-based optical phased arrays (Si-OPAs), and liquid crystal on silicon spatial light modulators (LCOS-SLMs). LCOS-SLMs utilize

Device	Operating mechanism	Optical beam control speed	Power Consumption	Wavelength in use (1.55μm)	Wavelength in use (visible light)
LCOS-SLM (Reflective type)	Molecular orientation change	~10kHz	Low	○	○
Si-OPA (Waveguide type)	Thermo-optic effect	~100kHz	High	○	×
EOP-OPA (Waveguide type)	EO effect	~100GHz	Low	○	○

Figure 2 Comparison of the properties of EOP-OPAs, Si-OPAs, and LCOS-SLMs

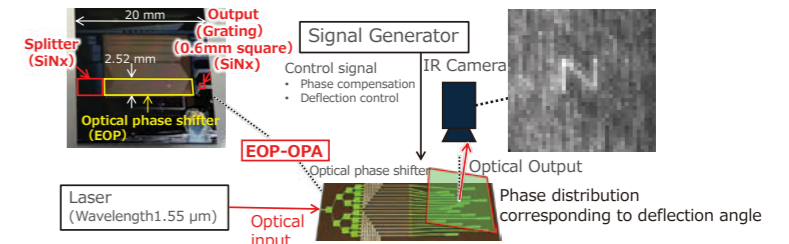


Figure 3 Two-dimensional beam deflection and pattern display using a 64-channel EOP-OPA device at a wavelength of 1.55 μm

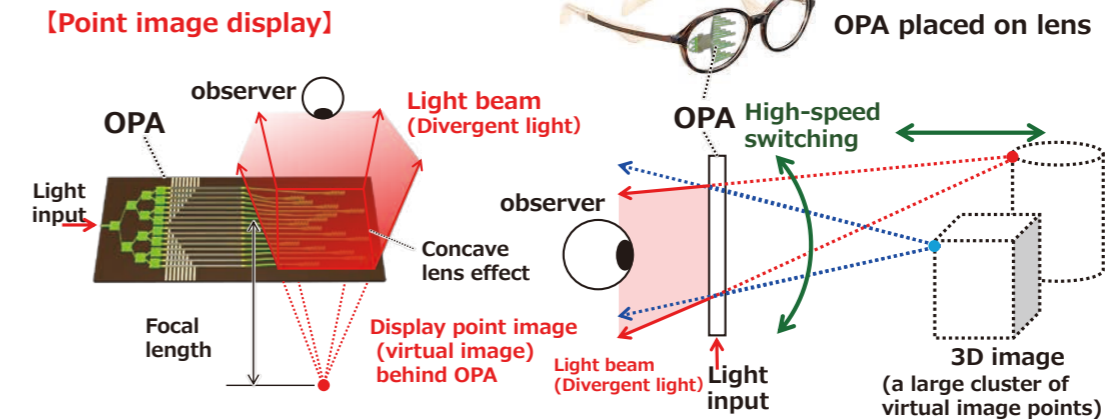


Figure 4 Schematic of a novel 3D display technology and glasses-type 3D display application

changes in the molecular orientation of a liquid crystal to modulate the refractive index, resulting in a relatively slow light beam control speed of approximately 10 kHz. Si-OPAs utilize the thermo-optic effect to change the refractive index, resulting in a light beam control speed of approximately 100 kHz and higher power consumption. Furthermore, silicon is transparent at a wavelength of 1.55 μm and can therefore be used at this wavelength, but it cannot be used at visible wavelengths. In contrast, EOP-OPAs utilize the EO effect based on electron response to modulate the refractive index, enabling light beam control at up to 100 GHz with low power consumption, and are expected to deliver superior performance in both beam control speed and energy efficiency. We have also developed EOP materials applicable not only at 1.55 μm but also in the visible wavelength range (red, 630 nm). Using these EOP materials, we fabricated optical modulators and demonstrated high-performance optical modulation, and the applicable wavelength range is expanding into the visible wavelength region.

Two-Dimensional Optical Beam Deflection and Pattern Display via Optical Phase Control using EOP-OPA

Figure 3 shows the configuration of a 64-channel EOP-OPA device operating at a wavelength of 1.55 μm, together with the corresponding evaluation setup. The input

light is divided by the optical beam splitter, passes through the optical phase shifters that allow the control of optical phase, and is emitted from the optical output part (grating). By applying control signals for phase compensation and deflection control to each optical phase shifter, a phase distribution corresponding to the deflection direction is generated at the optical output part. The letter “N” was drawn by performing vector scanning—moving the light beam directly along the shape of the desired pattern. Using the EOP-OPA, we achieved the world’s first two-dimensional optical beam deflection and pattern display based solely on optical phase control.

Novel Three-dimensional Display Technology and Applications

This technology can be extended to a novel three-dimensional (3D) display technology, as illustrated schematically in Figure 4. The essence of optical control using an OPA lies in controlling the optical wavefront. By controlling the wavefront, a point image (virtual image) can be formed behind the OPA. By using a single OPA to rapidly switch and display point images at different positions in three-dimensional space, a large cluster of virtual image points (3D image) can be displayed. Since the point images reproduce the light emitted from the optical image (virtual image) of an object, a natural 3D image can be observed. The applicable wavelength range of

the EOP-OPA is expanding into the visible wavelength region, and the high-speed light beam control using the EOP-OPA is expected to enable its application to glasses-type 3D displays using the novel 3D display technology.

Future Prospects

To develop novel 3D display technologies, increasing the number of channels in EOP-OPAs and the associated research and development of driving electronics will be crucial. We aim to demonstrate the superior ability of light beam control of the EOP-OPA and, in parallel, advance R&D of EOP materials applicable across the entire visible wavelength range, toward the development of full-color 3D display technology.

* optical phased arrays (OPAs)
A device that individually and electrically controls the optical phase of numerous light beam sources branched from a single light beam source, thereby manipulating the light beam propagation direction and its convergence/divergence.

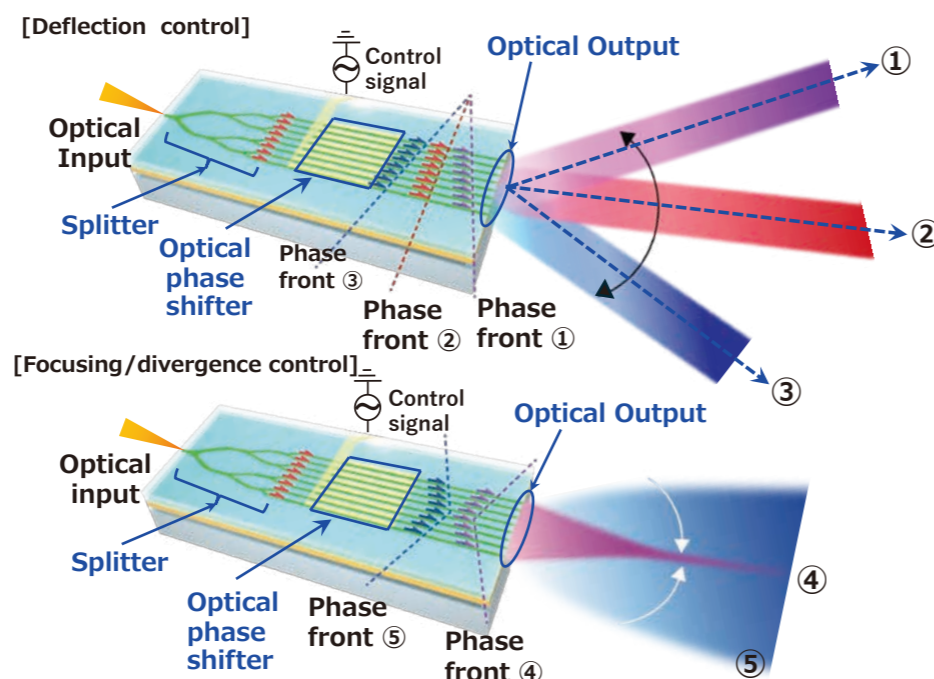


Figure 1 Configuration of optical phased array and light beam control

The Engineers Supporting the Nano-scale Functional Assembly ICT Laboratory



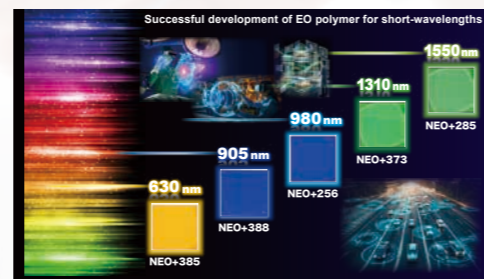
Right alongside the researchers working at the forefront of their fields are the research engineers. From materials analysis to equipment fabrication, their daily contributions are indispensable to research. In this issue, we focus on three research engineers who support research and development at NICT, offering a glimpse of the appeal and fulfillment of their work as well as the expertise they bring to the field.

Research Engineer



YAMADA Chiyumi

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I perform physical property evaluation of EO chromophores and polymers synthesized in the laboratory. I collect various physical property data—such as UV absorption spectra, glass transition temperatures, and EO coefficients—and determine whether they are suitable for use in devices. For polymers that achieve a certain level of performance, I conduct more detailed measurements of the long-term stability and capabilities required when actually incorporated into devices, such as thermal relaxation of molecular orientation and opti-

cal propagation loss. Conducting experiments under conditions that fully bring out the maximum performance of each polymer is critically important. If experimental conditions are not properly optimized and the polymer fails to demonstrate its full potential, it may lose the opportunity for practical application. Therefore, based on experience, I consistently strive to obtain results under optimal conditions.

Challenges, appeal, and fulfillment of this work

Research rarely goes smoothly, and problems arise frequently, but the sense of accomplishment when overcoming them is all the greater for it. Although findings are later presented to the world in papers and at academic conferences, during the research process I experience a feeling of pride in knowing I was the first person in the world to discover that fact. There are even times when I look forward to Mondays because I am eager to see the results. Simply put, I love experiments.

What I am glad about having joined NICT

NICT has professionals in a wide range of specialized fields who conduct research while fully applying their expertise. Being surrounded by highly motivated people who strive to reach even greater heights, in an environment filled with stimulating conversations, naturally stirs in me the desire to keep working hard as well.

A word to students aspiring to become engineers

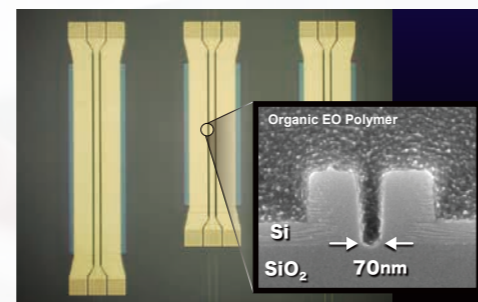
You do not need to be an all-rounder. It is fine if there is just one thing you are strong at. When I first joined NICT, I was overwhelmed by the knowledge and skills of the people around me, but I made up my mind to do my best at what I could do. By steadily building up my work, I was able to acquire skills essential for research. Effort bears fruit, and that strength will in turn come to your aid.

Research Engineer



YOKOHAMA Hideo

Research Engineer
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I fabricate and evaluate optical modulators using optical waveguides made from materials with different properties, including organic EO polymers and inorganic materials. I aim to optimize the device structure to leverage the performance of both EO polymers and inorganic materials such as silicon, and to establish the device fabrication process. Following fabrication, I conduct measurements and evaluations, and feed the results back into subsequent device development.

Challenges, appeal, and fulfillment of this work

The device fabrication process I am responsible for comprises more than 100 steps, including pre-processing. These steps are carried out in a clean room using process equipment, and at each stage I inspect the device under an optical microscope. However, unexpected situations frequently arise, and I often find myself glued to the microscope, unable to look away. In such cases, I consider countermeasures and, when necessary, implement recovery steps to complete the device. The joy of measuring a finished device and seeing its characteristics gradually improve after dealing with each problem one by one is truly special.

What I am glad about having joined NICT

I feel very fortunate to be able to conduct experiments at the cutting edge within well-maintained and well-equipped research facilities. New equipment is thoroughly characterized through

repeated verification of operating conditions, and only after being verified in combination with the preceding and subsequent processes can it be incorporated into the device fabrication process. In this regard, we are able to proceed efficiently because we have an environment where accumulated experimental results and appropriate advice from colleagues are readily available.

A word to students aspiring to become engineers

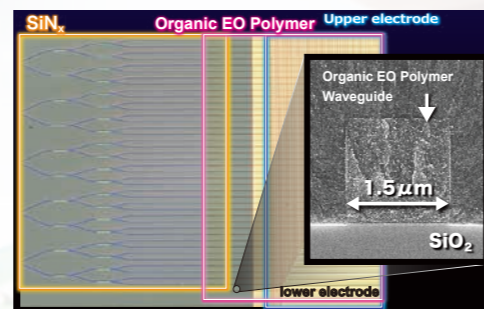
Research related to device fabrication can be pursued from a variety of perspectives, such as a creative approach focused on developing new devices, a manufacturing-oriented approach that emphasizes process technology, and a craftsmanship-driven approach that deeply explores a specific field. NICT also has a broad range of research fields, and provides an environment in which you can readily get involved in areas of interest, allowing you to expand your opportunities to contribute.

Research Engineer



UEDA Rieko

Research Engineer
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I mainly fabricate devices that include optical waveguides. An optical waveguide is a structure that serves as a pathway for light. After depositing organic EO polymers synthesized in the laboratory by spin coating, the structures are formed through etching using a reactive ion etching (RIE) system. I fabricate optical waveguides to measure optical propagation loss, and I also fabricate devices such as optical modulators using organic EO polymer films whose molecular orientation has been aligned by a process known as poling.

Challenges, appeal, and fulfillment of this work

There are many challenges in conducting research. What is particularly difficult is establishing the process flow. Device fabrication involves many steps, and it takes time and perseverance to determine optimal conditions. Since fabrication precision directly affects propagation loss, I carefully verify the processing conditions. For example, the order of processing steps and the internal condition of the reactor in the equipment also affect fabrication precision. The equipment is maintained with the cooperation of all users. I feel a sense of fulfillment when structures such as waveguides, and electrodes are fabricated exactly as designed, without deviation, or when optical emission can be confirmed. For devices that split a single waveguide into 64, I feel relieved when output from all channels is confirmed.

What I am glad about having joined NICT

What I value most is the opportunity to be involved in cutting-edge research. Since joining NICT, I have acquired a wide range of knowledge and technical skills. To keep up with the rapid advances at the forefront of research and avoid falling behind, I continue to make dedicated efforts daily.

A word to students aspiring to become engineers

Study voraciously, focusing on what interests you. I believe there are things you can only experience during your student years, so seize every opportunity and take on challenges proactively. Failures are also valuable experiences. The knowledge, skills, and experience you gain in this manner will be useful someday, somewhere.



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