# Organic and Inorganic Hybrid Devices (Photonics Technologies)

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We report the fabrication and device applications of the nonlinear photonic crystals (PhCs) which combines PhC functions for controlling the light dispersion characteristics and highly nonlinear optical organic materials. We reveal a direct relationship between the observed nonlinear optical responses and the corresponding photonic band dispersion nature such as a slow light in the nonlinear PhCs, and we show experimental evidence that the performance of nonlinear optical applications such as the optical switch, wavelength conversion and two-photon absorption devices are dramatically improved in this structure. Moreover, we report on the design and experimental demonstration of an integrated Mach-Zehnder electro-optic (EO) modulator based on the silicon PhC waveguides combined with an EO polymer exhibiting large electro-optic properties.

## 1 Introduction

As epitomized by the spread of smartphones and cloud computing, the ways in which telecommunications networks are being used are further diversifying, and photonic information and communications technology (photonic ICT), connecting the world with light, has become a vital fundamental technology today on which all kinds of social infrastructures are based. At the same time, problems with power consumption and heat generation by the massive telecommunications systems themselves are beginning to surface with the increase in traffic and size of datacenters. Long distance transmission of optical signals using optical fibers was put into practical use a long time ago, but the signal processing part at the core of the telecommunications system still relies on electronic circuits. Traditional electronic technology based on silicon LSIs are already close to their limit, while the speed and traffic of telecommunications networks are accelerating, and social demand for minimizing power consumption has been rising. In order to answer to these mutually opposing demands in performance, we must use light not only as the medium for long distance transmissions, but also make use of essential optical technology in the field of advanced signal processing. For example, signal delays and the amount of heat generated per unit volume are becoming serious problems in high-end servers and supercomputers due to many-core CPUs and the high density of electrical interconnections, and the replacement of metal interconnections with short distance, intra- and inter chip optical interconnects is progressing rapidly[1][2].

In this way, the development of photonic materials and devices is growing increasingly important. Photonics has evolved towards device miniaturization with the ultimate goal of integrating many optical components onto a compact chip, producing photonic integrated circuits with high degrees of functionality. However, in conventional optics, miniaturization of structures in photonic manipulations is restricted by the diffraction limit. Therefore, photonic devices are generally much larger than conventional electronic devices. The main issue is how to build a photonic device on the same kind of miniature scale as electronic devices in order to realize an optical integrated circuit such as that required for on-chip optical communication. Given this situation, a growing amount of research has been carried out in recent years on photonic crystals and silicon photonic devices as a new optical element technology to overcome that which has been considered difficult to achieve in photonic devices, such as downsizing and integration. Silicon is the material that forms the basis of electronic devices, but traditionally, it was considered unsuitable for use in optical modulation, detection and light emitting devices. For a long time it was mostly ignored for its unsuitability in photonic devices. However, serious research into its use in photonic devices began in the 2000s initiated through national projects or led by industries, and silicon photonics quickly entered the mainstream of practical technology for its low cost, fusing electronic and optical circuits. Along with the optimization of device structures and advances in nanofabrication technology, silicon photonic devices were developed one after another for high-speed, silicon-based optical devices and silicon-germanium photodetectors achieving speeds in excess of 40 Gbits$^{-1}$[1][3]–[6]. The opto-electronic integrated circuit integrating optical and electronic circuits on the same chip is on the verge of being realized.

These integrated photonic devices have evolved through the clever application and use of established semiconductor processes, nanofabrication technology, and facilities known as CMOS foundries. In other words, semiconductors and inorganic materials such as Si, $SiO_2$, InP, GaAs, etc., had until now been the main materials used in photonic devices. However, this research and development into hard materials such as silicon is currently close to peaking or practical use. It has become necessary to go beyond the boundaries of existing materials and develop new organic $\pi$ conjugated molecules and polymers (soft materials) that are different from inorganic and semiconductor materials in that they are flexible and have highly nonlinear optical functions, to address the issue of responding flexibly to the increasingly diverse ways in which light is being utilized.

Organic nonlinear optical materials consisting of a polymer matrix doped with $\pi$ conjugated nonlinear molecules are overwhelmingly superior to inorganic and semiconductor materials due to the delocalization of $\pi$ conjugated electrons at the microscopic level, and they are characterized by their extremely large nonlinear optical constants ($r_{33}$> 100 pm/V) and ultrafast nonlinear response speeds (within several tens of fsecs), among other outstanding properties[7]–[9]. However, organic materials have low refractive indexes making devices extremely bulky (normally around 10 cm in polymer modulators), and they were thought to be unsuitable for use in optical integrated circuits. This was the obstacle to free research into optical integrated circuits and nanophotonic devices making use of the outstanding optical functionality of organic materials. On the other hand, silicon has a high refractive index, making it advantageous in integration, but most of these silicon devices rely on free-carrier dispersion effects in the *p-n* structures, because no $\chi^{(2)}$ nonlinearity is present in pure silicon because of its centrosymmetry. Therefore, the bandwidths of these modulators are usually limited by the free carrier dynamics. This means that silicon integrated circuits, due to the properties of the material, cannot be used to create ultrafast electro-optic modulators achieving speeds of over 100 GHz. We are currently working to break this barrier through research and development into nanophotonic devices that make full use of the slow light effect through hybrid technology combining organic materials with silicon photonics, and the structure of the organic photonic crystal. By fusing the outstanding nonlinear optical characteristics of organic $\pi$ conjugated materials with the merits of silicon photonics and photonic crystal technology, we believe it will become possible to integrate ultrafast light controlling devices or develop various new on-chip optical technologies that were not possible with traditional photonic devices. In this paper, we report the fabrication and device applications of the nonlinear photonic crystals (PhCs) which combines PhC functions and highly nonlinear optical organic materials. We reveal a direct relationship between the observed nonlinear optical responses and the corresponding photonic band dispersion nature such as a slow light in the nonlinear PhCs, and we show experimental evidence that the performance of nonlinear optical applications such as the optical switch, wavelength conversion and two-photon excited fluorescence devices are dramatically improved in this structure. And moreover, we report on the design and experimental demonstration of extremely small and high efficiency Mach-Zehnder electro-optic (EO) modulator at potentially ultrafast modulation speeds based on EO polymer/silicon hybrid PhC waveguides.

## 2 Developing an organic photonic crystal

Photonic crystals are materials composed of dielectric structures with periodicity on the optical wavelength scale. The ability of a photonic crystal to control the light dispersion relation (i.e., photonic band structure) with a high degree of freedom is an issue of scientific and practical importance. Tailoring of the band dispersion in photonic crystal systems can give rise to anomalous dispersion characteristics including photonic band gap and extremely slow group velocities (a phenomenon known as “slow light”) that cannot be achieved in homogeneous materials and conventional waveguides. These characteristics have opened up unprecedented and exciting possibilities in a wide range of photonics with multiple applications in photonic information and communication technologies, integrated optoelectronics, and nonlinear optics. If it were possible to create such a structure based on organic

$\pi$ conjugated materials, it would become possible to massively enhance the interaction between light and matter, which could boost the performance of devices that make use of enhanced nonlinear optical effects, or could lead to the realization of organic optical active integrated circuits through the miniaturization of devices.

The main reasons why there had been few quantitative experimental studies carried out on photonic crystal devices using organic $\pi$ conjugated materials were because the nanofabrication technology was undeveloped in organic $\pi$ conjugated materials, unlike in well-established semiconductor processing technology. It was difficult to fabricate high precision device structures, and massive optical scattering had made quantitative discussions based on device performance measurements difficult. The refractive indexes of organic materials are low too, with little difference between the refractive index of the clad region, making it difficult to confine light at the nanoscale, and there was also the problem of serious damage as the result of nanolithography. To overcome these problems we have been developing nano fabrication technology for nonlinear optical polymer materials, and new device structures.

In order to carry out precise processing under a wavelength order maintaining the high aspect and high perpendicularity necessary for two-dimensional photonic crystals, anisotropic dry etching of inductively coupled plasma (ICP) for example is generally used[12]. However, this leads to a dramatic drop in the performance of optically functional molecules within the polymer due to damage during etching. In order to overcome this problem, we structurally separated the two-dimensional photonic crystal slab layer and nonlinear optical polymer layer into upper and lower layers, and proposed a unique vertical hetero device structure in which the layers are coupled in terms of their optical mode, proving that it is possible to fuse the nonlinear optical polymer with outstanding nonlinear characteristics, with photonic crystal functions, without damaging them[13][14]. Furthermore, even when organic materials with low refractive indexes are used, a clad layer that has a high light confining effect is indispensible in order to make the organic materials function effectively as photonic crystals. In a $SiO_2$ clad most often used, the difference in refractive index is insufficient, causing light to leak out, but using silver as the clad for the organic photonic crystal slab, we proved that it is possible to achieve sufficient confinement of light through plasma reflection[15]. By making use of the properties of flexible organic $\pi$ conjugated materials, we also succeeded in directly imprinting organic two-dimensional photonic crystal devices using the nano imprinting method suitable for practical application (Fig. 1)[16]. We not only succeeded in creating a high precision device free of damage, but by using the nano imprinting method we also achieved a much higher throughput relative to current semiconductor lithography technology, and there are high expectations for it to become technology that is low in cost because it uses organic materials.

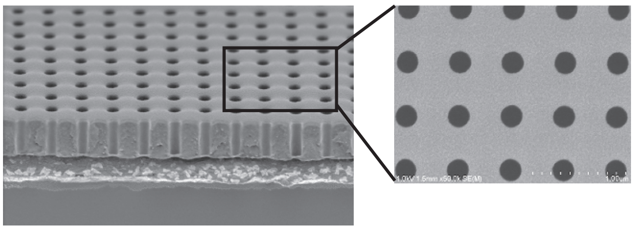

**Fig. 1** Scanning electron microscopy (SEM) micrograph of the fabricated organic nonlinear optical polymer two-dimensional photonic crystal

There is potential to largely enhance the nonlinear optical response of organic $\pi$ conjugated materials by making use of the slow light effect and photonic band dispersion control through photonic crystals, but in applying these effects appropriately to actual devices, what is important is how precisely the photonic band can be measured and manipulated to achieve the desired optical dispersion state. However, the modes under the light line normally do not couple with external free photons, so until now no one had directly examined the structure of the photonic band in waveguide mode. To solve this problem, we proposed and demonstrated a new method for the direct determination of the photonic band structure of waveguiding modes below the light line in organic two-dimensional photonic crystals by angle-resolved attenuated total reflection spectroscopy measurements using a prism coupling arrangement over a wide frequency range[17]. The measured photonic band structure is in good agreement with theoretical calculations (Fig. 2). The accurate shape of the experimental band structure provides direct information on light dispersions and the propagating (both linear and nonlinear) properties of two-dimensional photonic crystals. This information is crucial for understanding and designing the anomalous optical behavior of many photonic applications using photonic crystal system with a many degrees of freedom.

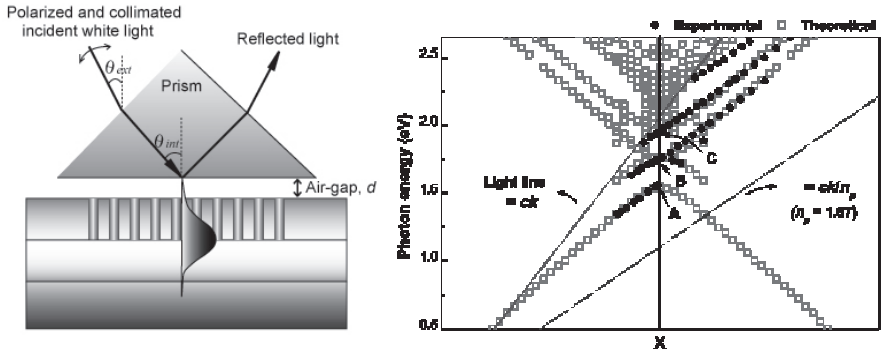

**Fig. 2** Schematic diagram showing the experimental geometry of angle-resolved attenuated total reflection spectroscopy using a coupling prism, and the obtained experimental photonic band structure under the light line of the two-dimensional photonic crystal waveguide (closed circles), compared with the theoretical band structure calculated by the 3D finite-difference time-domain method (open squares)

## 3 Enhancing the performance of nonlinear photonic devices by using slow light technology

In this Section, we discuss the exciting possibilities of an organic photonic crystal in nonlinear light-matter interactions and their device applications. Photonic band structure features and large group velocity dispersion characteristics in photonic crystals are expected to find use in new active and novel high-efficiency nonlinear optical applications such as high-efficiency optical switching, frequency conversion devices, and others, in combination with organic nonlinear optical polymer materials. These applications are possible with photonic crystals because an extremely slow group velocity, originating from anomalous band dispersions at the band edge and/or a very flat band, produces a strong enhancement in the electromagnetic field of the excitation wave. We will briefly show dramatic improvements in the performance of nonlinear optical devices and the exciting possibilities of an organic photonic crystal in nonlinear optics.

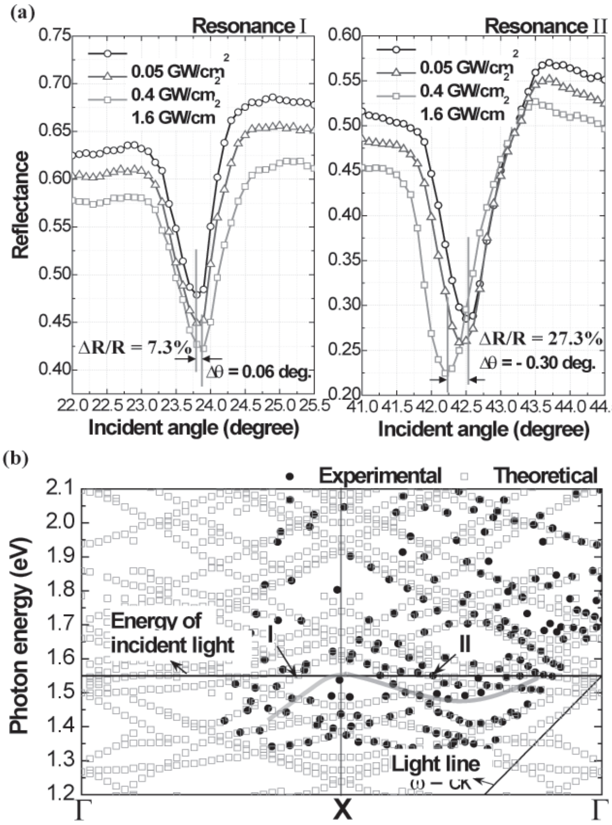

**Fig. 3** (a) The large nonlinear changes based on optical Kerr effect in the angle-dependent reflectivities of the two-dimensional photonic crystal waveguide; (b) Corresponding experimental and theoretical photonic band structure

### 3.1 All optical switching device

The third-order nonlinear optical process (optical Kerr effect), which changes the refractive index in proportion to the light intensity, can be used in ultrafast optical switching of over a terabit ($10^{12}$ bits$^{-1}$), and great expectations are held for its use in the future as a fundamental principle in ultrafast all optical signal processing. However, the optical Kerr nonlinearities of conventional nonlinear materials are usually very weak, so the biggest issue in realizing a practical all-optical switching was to produce large nonlinearities and minimize the power requirements for switching processes. In our research, we aimed to realize an all-optical switching device using an organic nonlinear two-dimensional photonic crystal waveguide, and we evaluated and analyzed the properties of optical switching by the optical Kerr effect. The two-dimensional photonic crystal waveguide was made by using a guest-host nonlinear optical polymer of PMMA doped with Disperse Red 1 (DR 1). By probing the resonances between a photonic band and an external laser field and their nonlinear changes in angle-resolved reflectivity, we show experimental evidence that the nonlinear optical changes in a two-dimensional photonic crystal waveguide with a Kerr nonlinearity are critically dependent on the dispersion nature and the group velocity of the photonic bands[13]. The results agree well with the behavior predicted from band structures, indicating that the design of nonlinear optical properties of material systems is realistically possible by band dispersion and group velocity engineering (Fig. 3). We demonstrated for the first time in observing novel and unusual nonlinear phenomena, exhibiting differences in sign and quantity of the nonlinear angular shifts at the resonances. We also demonstrated the enhancement of the nonlinear optical changes based on Kerr effect by the slower group velocity in organic nonlinear photonic crystals. Although $c/v_g$ is limited to the order of 1 in conventional waveguides, $v_g$ in two-dimensional photonic crystal waveguides can be designed with a much greater degree of freedom. The enhancement of the nonlinear optical changes resulting from the slower group velocity, such as demonstrated in this research, should lead to dramatic improvements in the performance of all-optical switching devices and will open up new possibilities in applications such as highly efficient dynamic dispersion management devices. Furthermore, the agreement between the observed nonlinear responses and the band dispersion characteristics means we can begin to engineer the nonlinear optical properties of organic photonic crystal systems by controlling the photonic crystal configuration.

## 3.2 Wavelength converter

Recently, high-efficiency compact ultraviolet (UV) coherent light sources are of great interest for numerous applications in fields such as high-density optical data storage, bio-agents detection, water sterilization, and medicine. Second harmonic generation (SHG) and sum-frequency mixing (SFM) in combination with a photonic crystal structure composed of highly nonlinear optical materials are the most attractive and promising methods to create a high-efficiency coherent radiation from existing laser systems and to access the short wavelength range towards the UV region. The ability to control the light dispersion relation (photonic band structure) with a great degree of freedom in photonic crystal systems has opened up unprecedented and exciting possibilities in nonlinear optics, in particular, which can produce lager nonlinearities and minimize the power requirements for nonlinear applications such as wavelength conversion processes. This arises from the anomalous dispersion characteristics of photonic crystals, which enhance the electromagnetic field due to their slow group velocities at the band edge and/or a very flat band as compared with conventional uniform materials[18][19]. In this work, we reported, for the first time, fabrication and observation of second-harmonic and sum-frequency radiation in the UV and blue regions of a two-dimensional photonic crystal waveguide mainly composed of the nonlinear optical polymer (DR1/PMMA). We demonstrated the large enhancement (170 times) of the SHG wavelength conversion efficiency at the wavelength of 368 nm arising from the resonant coupling between an external laser field and the photonic band mode (Fig. 4). We found a good agreement between the SHG enhancements and the photonic band structure features, which means that active manipulation of these nonlinear wavelength conversion processes is a realistic possibility through the band dispersion control, and further work may lead to the progressive development in nonlinear optical applications such as a high-efficiency compact coherent light sources in the deep ultraviolet (200 to 350 nm), mid-far infrared (2 to 10 μm), and even terahertz ranges.

## 3.3 Two-photon excited fluorescence device

Two-photon excitation (TPE) processes have attracted considerable interest because of their potential to be applied to diverse fields, including three-dimensional fluorescence imaging, high-density optical data storage, lithographic microfabrication, and photodynamic cancer

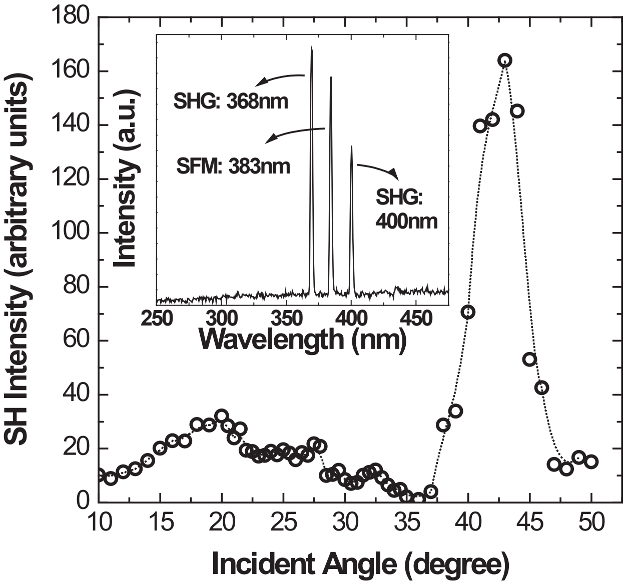

**Fig. 4** The large enhancement of second-harmonic generation at 368 nm and an incidence angle of 45 degrees for the nonlinear optical polymer two-dimensional photonic crystal waveguide. A large SHG enhancement of approximately two orders of magnitude was achieved. The inset shows SHG and SFM spectrum in the UV region.

therapy. From the viewpoint of such applications, a third-order nonlinear TPE process has two important advantages over a single-photon excitation process: the ability to generate excited states using photons with half the linear excitation energy and a quadratic dependence on laser intensity. These advantages can increase the light penetration depth in absorbing media and provide a high three-dimensional spatial resolution under tight-focusing conditions, without being restrained by the diffraction limit. Unfortunately, the majority of known organic molecules (and most inorganic materials) have very small nonlinear absorption cross sections ($\sigma$), typically $\sigma \sim 1$ GM ($=10^{-50}$ cm$^4$ s photon$^{-1}$ molecule$^{-1}$). Consequently, very high laser powers are required, making the widespread use of two-photon excited fluorescence (TPEF) impractical.

However, the combination of a photonic crystal structure and highly nonlinear materials can produce large nonlinearities, thus reducing the power requirements for TPE processes. In this work, we have identified the nonlinear optical polymer of poly(methyl methacrylate) (PMMA) doped with a bis(styryl)benzene derivative as one of the most promising candidates for TPEF materials to use in two-dimensional photonic crystals. This derivative of bis(styryl)benzene is a nonlinear optical molecule that exhibits a very large TPE cross section $\sigma$ (as high as 900 GM) due to a large delocalized $\pi$-electron system, and has very high fluorescence quantum yields. We have successfully demonstrated enhancement (> 100 times) of the TPEF in a highly nonlinear optical polymer two-dimensional photonic crystal waveguide, arising from resonant coupling between the external laser field and a photonic band mode (Fig. 5). Good agreement was obtained between the TPEF enhancements and features of the photonic band structure obtained by angle-resolved reflectivity measurements and the theoretical photonic band structure generated by three-dimensional finite-difference time-domain calculations[14], indicating that active manipulation of these nonlinear TPE processes is a realistic possibility through engineering the band dispersion and band group velocity characteristics. This enables nonlinear light – matter interactions to be enhanced due to the enhancement of the electromagnetic field of the excitation wave. The result of enhancing the TPE efficiency is 90,000 GM, which is an extremely large value as TPE cross section $\sigma$. Future work in this direction should lead to dramatic improvements in the performance of TPE applications.

## 4 Organic-silicon hybrid on-chip electro-optic (EO) modulator

Today, fiber optic communication links has become ubiquitous, but conventional networks consist of electronic core systems (including electronic switches and routers). Making progress in converting information processing to high-speed digital optical processing requires the

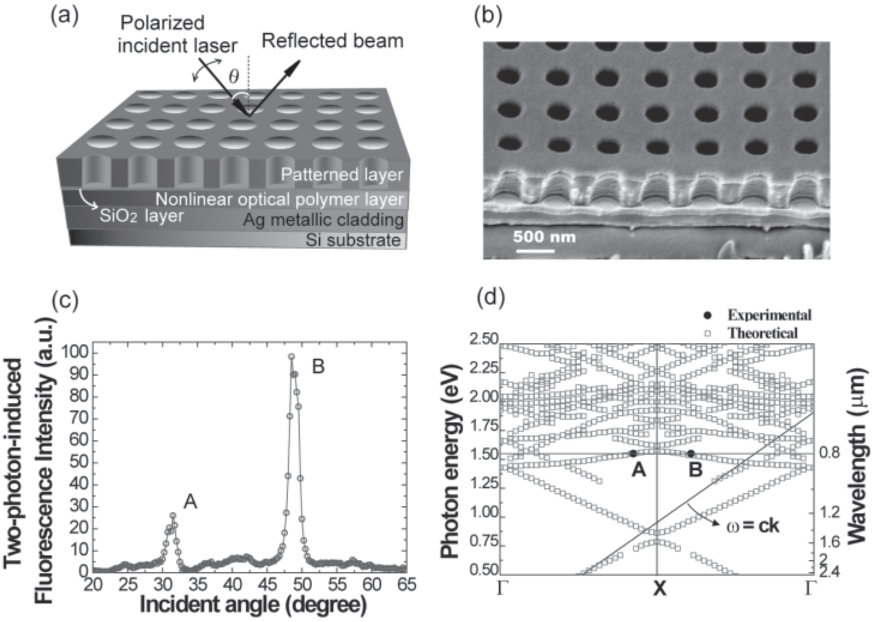

**Fig. 5** (a) Schematic showing sample structure; (b) SEM micrograph showing cross section of fabricated two-dimensional photonic crystal waveguide; (c) Incidence-angel dependence of the two-photon excited fluorescence (TPEF) intensity at 486 nm; (d) The corresponding photonic band structure of the device.

development of technology to fuse integrated electronic circuits that can handle complicated logical processes with integrated optical circuits that are fast and low power consumption. The electro-optic (EO) modulators encode electrical signals onto high-speed digital optical signals, but currently it is the modulator that uses lithium niobate (LN) crystals that has been put to practical use. However, the device is over a few centimeters in size, making it unsuitable for on-chip integration. This has led to intense research and development all over the world in recent years into optical modulators based on silicon photonics. Various silicon-based optical modulators have already been developed that are suitable for integration to enable optical interconnects and cost reductions, fabricated using CMOS compatible nanofabrication technologies. Most of these silicon devices rely on free-carrier dispersion effects in the *p-n* structures, because no $\chi^{(2)}$ nonlinearity is present in pure silicon because of its centrosymmetry. Therefore, the bandwidths of these modulators are usually limited (< several tens of GHz) by the free carrier dynamics[2]. For this reason, a new photonic device design is needed to realize an ultrafast, new-generation integrated on-chip optical network of over 100 Gbits$^{-1}$ per channel.

Hybrid technology combining organic EO polymers with ultra high-speed (> 100 GHz) and high EO coefficients ($r_{33}$ > 100 pm/V), with silicon photonics, is extremely promising technology for realizing ultrafast EO modulators that are highly integrated and low power consumption. EO polymers have much bigger EO coefficients than LN, making it possible to lower drive voltage of devices, and their refractive index dispersion between the telecommunications wavelength and RF range is extremely small, making ultrafast optical modulation in the range of 100 GHz to THz possible. Furthermore, the creation of a hybrid silicon structure makes it possible to attain a sufficient refractive index difference even with organic materials that have small refractive indexes. This enables light propagation by confining light within nano-scale areas. Therefore, a fusion of the merits of both technologies upon the development of organic material and silicon photonics hybrid technology could lead to ultrafast integrated EO modulators, which are impossible to create with inorganic and semiconductor devices.

In general, light propagates the core area of high refractive index, so an organic material with a low refractive index relative to Si becomes a clad area leading to the electric field distribution of the propagation mode being concentrated in the Si area. This means that in order to make use of the EO activity of the organic $\pi$ conjugated material in an organic-Si hybrid structure, it is necessary to make it so that light propagates itself through the organic clad. The most typical structure for achieving this is the slot waveguide. An extremely narrow slot is etched into the center of the Si waveguide and filled with organic material. Doing this enables the confinement of the main electric field in a slotted area even within the organic area with a low refractive index. The Si slotted two-dimensional photonic crystal has a structure that has been further developed from this. A slot section is created in the center of the line-defect waveguide within a two-dimensional photonic crystal and filled with organic material to propagate light in a slotted area. Figure 6 shows the schematic diagram of the actual structure we fabricated. This not only enables the localized propagation of light

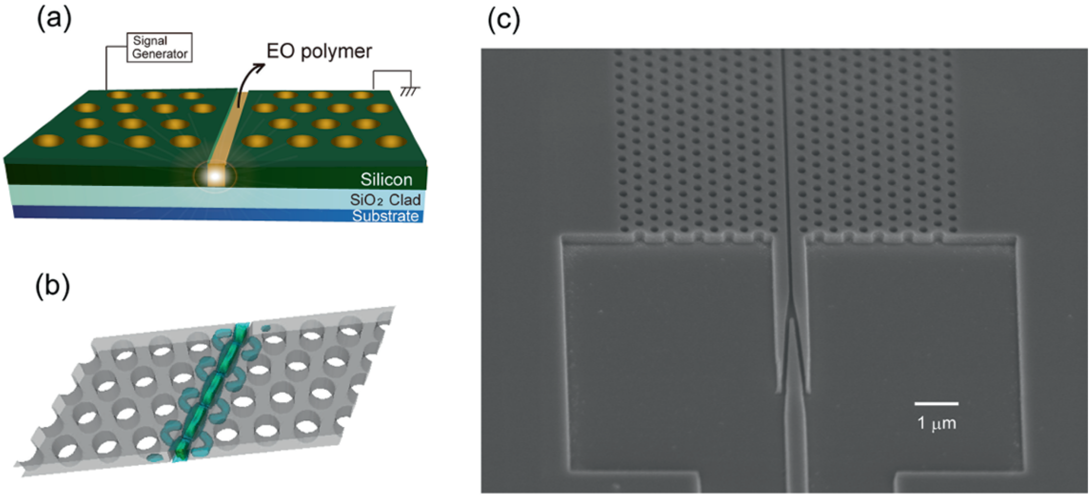

**Fig. 6** (a) A schematic diagram of an organic EO polymer and Si slotted two-dimensional photonic crystal hybrid device; (b) The optical mode profile in nano-slot waveguide; (c) SEM micrograph of the fabricated Si slotted photonic crystal waveguide.

within a slot with a width of around 50 to 250 nm, but the photonic crystal effect also greatly delays the group velocity. The phase change in accordance with EO modulation is greatly enhanced due to this slow light effect, so the EO modulation efficiency is greatly improved.

We designed a Mach-Zehnder (MZ) interferometer EO modulator using a Si slotted two-dimensional photonic crystal with an SOI substrate and a nanoslot filled with organic EO polymer. We then numerically evaluated the properties of the slot mode that propagates in a localized area within the nanoslot, by three-dimensional photonic band structure and 3D-FDTD calculations. As a result, by making appropriate use of the increase in slow light phase difference ($\Delta\Phi \propto \Delta k$) and the electric field concentration effect by the nanoslot (in other words, the Si nanoelectrode gap), we numerically proved that it is possible to achieve EO modulation of low operating voltage (half-wave voltage of $V_\pi = 0.75$ V) and ultrafast operating speed (operating frequency $f_{3\mathrm{dB}} = 121$ GHz) despite being an extremely short device with an MZ interference arm of only 50 μm[10]. In this way, the Si slotted two-dimensional photonic crystal is extremely effective in boosting the performance of EO modulators, but it is necessary to carry out electric field poling of the organic EO polymer through the Si nanoelectrode gap. The problem with this process was that the leakage current between the nano Si electrodes caused the serious reduction of the poling efficiency of the organic EO polymer within the slot.

In order to overcome this problem, we propose a MZ EO modulator that is a hybrid between an organic highly nonlinear EO polymer and a silicon one-dimensional photonic crystal nanobeam waveguide. We will not delve into the details, but an EO polymer / Si hybrid one-dimensional photonic crystal nanobeam has a structure similar to general waveguides which are characterized by their suitability for EO polymer poling, and it shows outstanding poling properties that are not inferior in bulk states on a Si platform. Using this kind of process, we established a processing technique for precision fusing organic EO polymer with silicon photonics. As a result of making an asymmetric MZI device (L = 100 μm) of this structure, and evaluating its EO modulation properties, a clear improvement in the EO modulation efficiency was attained due to the slow light effect, and we achieved low voltage driving of 0.73 $V_\pi$-cm and an extremely large effective EO coefficient ($r_{33\ \mathit{eff.}} = 343$ pm/V) in the actual device[11]. This is approximately one thousandth of the size, and the equivalent of over ten times the performance (the effective $r_{33}$ value in device) of lithium niobate (LN) modulators, indicating that our EO polymer/silicon hybrid photonic crystal nanobeam platform effectively enables EO modulation using a simple geometry and an extremely small device footprint at potentially ultrafast modulation speeds.

## 5 Conclusions

In this paper, we showed that the organic and inorganic hybrid technology that combines highly nonlinear optical organic materials with photonic crystals and silicon-integrated photonics is promising technology that lead directly to the realization of extremely small and ultrafast nonlinear optical devices with low operational power. These technologies make use of optical functionality which is unique to organic materials and is not found in semiconductors or inorganic materials. It will be applicable in a variety of optical technologies that were impossible to achieve through traditional photonic devices, such as the development of ultrafast electro-optic (EO) modulators of over 100 $\mathrm{Gbits}^{-1}$ and on-chip opto-electronic integrated circuits. It will also have applications in all-optical signal processing, optical buffer, and ultrasensitive sensors, as well as in biophotonics and other wide-ranging ripple effects extending to fields in photonic devices and optical ICT technology. Organic nonlinear optical materials have been improving dramatically in recent years in terms of their performance, low-loss properties, and thermal stability, and interest has grown rapidly in organic-silicon hybrid photonics. We have expectations for the further development of this field in organic-inorganic hybrid photonic devices through the linking up between advances in research in both organic materials science and device technology, including stability and reliability tests in working toward putting the devices into practical use.

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