

Integrated Silicon Photonic Crystals Toward Terahertz Communications

Withawat Withayachumnankul, Masayuki Fujita,* and Tadao Nagatsuma

The terahertz frequency range locates between 0.1 and 10 THz. This range accommodates atmospheric windows with staggering absolute bandwidth. It holds a potential for point-to-point wireless communications with an aggregate capacity reaching terabit per second in a range up to a kilometer. This unique capability is envisaged for backhauls between base stations and for local area networks. To this end, efficiency and compactness of the transceivers are crucial for successful large-scale adoption. However, state-of-the-art terahertz front ends are based on radio-frequency or photomixing technologies that are inefficient, bulky, or complicated. In principle, as a neighbor of the microwave and optics domains, the terahertz band can leverage technologies from both sides to overcome those challenges. Recently, low-loss integrated circuits based on photonic crystal waveguides are developed for routing terahertz waves. Here, a progress report on core components, including waveguides and diplexers, is presented. Additionally, the interfacing of the platform with electronic sources and detectors on one end, and with antennas for free-space coupling on the other end, is discussed. Currently, the platform can support terahertz communications at a data rate over 10 Gbit s⁻¹. Challenges and opportunities are discussed in the light of future development in this area.

aggravated by high-quality multimedia with gigantic data volume. This situation has put pressure on already congested microwave and millimeter-wave channels that have to be shared among a number of applications. As an upper neighbor of the millimeter-wave range, the terahertz spectrum band, loosely defined between 0.1 and 10 THz, has been identified as potential untapped resources for wireless links with vast bandwidths. According to the Shannon–Hartley theorem, the maximum channel capacity C in bits per second is proportional to the bandwidth B , as $C = B \log_2(1 + \text{SNR})$, subject to the signal-to-noise ratio (SNR).^[1] Thus, a large bandwidth at the terahertz band could be translated to a large data rate. It is estimated that a terahertz channel can support wireless data transfer up to 1 Tbit s⁻¹ with distance reaching a kilometer. To put this into perspective, a single uncompressed 4K-resolution video channel takes up only 6 Gbit s⁻¹. This capability can be discussed against competing free-space optical (FSO) communications with carriers at much higher frequencies and thus wider absolute bandwidth. However, potential hurdles for FSO include eye-safe power limit, ambient noise, atmospheric scattering, scintillation, and more stringent alignment.^[2]


1. Introduction

Wireless communication has become a new norm for high-speed data transfer in the last decade. The demand has been

Indeed, terahertz communications has its own set of challenges, predominantly in relation to various power losses. This issue could lower the signal quality, i.e., SNR, and thus compromising the channel capacity. In particular, operation at terahertz frequencies involves three major types of loss, including atmospheric loss, free-space path loss, and material losses. Atmospheric loss becomes relatively strong due to the presence of ambient water vapor that possesses rotational modes in the terahertz frequency range.^[3] Nevertheless, this issue can be largely subdued with the knowledge of atmospheric windows,^[4] where water-vapor absorption is minimal. On the other hand, free-space path loss scales quadratically with frequency. This large attenuation can be compensated by using high-directivity antennas, to be discussed in Section 5. Ohmic loss unavoidably exists in metal-based transmission lines and passive components, which are common to microwave and millimeter-wave technologies. This factor exacerbates in resonant structures and at higher frequencies, where the conductivity drops and the skin depth is shallower. Dielectric loss is nonnegligible due to a limited number of dielectric materials suitable for

Dr. W. Withayachumnankul
School of Electrical and Electronic Engineering
The University of Adelaide
Adelaide, SA 5005, Australia

Dr. W. Withayachumnankul, Prof. M. Fujita, Prof. T. Nagatsuma
Graduate School of Engineering Science
Osaka University
1–3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan
E-mail: fujita@ee.es.osaka-u.ac.jp

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/adom.201800401>.

© 2018 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

The copyright line of this paper was changed on 20 July 2018 after initial publication.

DOI: 10.1002/adom.201800401

microfabrication.^[5] As a workaround, existing transceiver chains either generate terahertz waves at the point of radiation and/or use bulky components such as lenses and hollow waveguides to avoid strong confinement.^[6] Such implementations increase the complexity and cost and restrict the compactness and functionality of terahertz platforms.

A new design paradigm is crucial for functional systems to reach simplicity and efficiency. In general, a platform for routing terahertz waves must be low loss, broadband, integrated, and economical for deployment in large scale. It must be able to accommodate basic processes including filtering, modulation, and multiplexing. This will enable multilevel modulation schemes and multiplexing schemes to maximize spectral efficiency. Since the terahertz band is at the crossroad between the electronics and photonics domains, this allows to leverage and integrate existing techniques from both worlds. While electronic sources are self-contained, metal-free photonic guiding structures yield low dissipation, suitable for routing terahertz waves for complex processing. This concept has led to a development of 2D photonic crystal waveguides made of only silicon as a platform for terahertz circuits. Dissipation in this platform is exceptionally low due to negligible absorption of high-resistivity silicon at this frequency range. Unlike its optics counterpart, these terahertz waveguides are self-supporting and thus require no substrate that could impose extra losses. They are fully compatible with standard planar fabrication technologies. The platform has a potential to integrate with various passive and active devices for advanced functions, as an example in **Figure 1**. This progress report provides an overview on recent developments in this area.

2. Photonic Crystal Waveguides as Terahertz Platform

Photonic crystals were originally conceived in the optical regime as a means to prohibit propagation modes of light.^[8] A crystal is typically a periodic combination between two low-loss dielectric materials, one of which could be air. The index contrast of the two materials must be sufficiently large and the period in the order of a wavelength in order to establish stop-bands or the so-called photonic bandgaps that are void of a propagation mode. By introducing a local defect into the periodicity, discrete photonic modes can exist therein with strong wave confinement that is suitable for sensing applications.^[9] Likewise, a line defect in the periodicity can create a waveguiding structure known as a photonic crystal waveguide. Since this type of waveguide can be purely made from dielectric materials, the structure is scalable subject to material availability, and ohmic loss can be eliminated. Thus, photonic crystal waveguides are a promising candidate for routing terahertz waves with high efficiency. Diverse designs of waveguides based on this concept have been realized across the terahertz spectrum.^[10] A prominent example includes nonplanar photonic crystal-cladded fibers made of cyclo-olefin copolymer (COC) that demonstrate the attenuation less than 0.1 dB cm^{-1} at 0.6 THz .^[11]

For compact routing of terahertz waves, photonic crystal waveguides can be implemented in the planar form. **Figure 2** shows an example for this realization.^[12] A hexagonal array of



Withawat Withayachumnankul received a PhD degree in electrical engineering with a commendation from the University of Adelaide, Australia, in 2010. From 2010 to 2013, he held an Australian Research Council Postdoctoral Fellowship at his alma mater, where he is currently a Senior Lecturer and Postgraduate Coordinator. He is a leader of

the Integrated Terahertz Laboratory. His research interests include terahertz technology, metamaterials, plasmonics, and antennas. He is an IEEE Senior Member and currently serving as a Chair of the IEEE South Australia Joint Chapter on Microwave Theory and Techniques and Antennas and Propagation.



Masayuki Fujita is an associate professor at the Graduate School of Engineering Science, Osaka University, Japan. He received his PhD degree from Yokohama National University on ultrasmall and ultralow-threshold microdisk lasers. Subsequently, he joined Kyoto University and initiated research on photonic crystals. Next, he moved to Osaka

University and was appointed the research director of the strategic basic research program CREST, "Development of terahertz integrated technology platform through fusion of RTDs and photonic crystals" of the Japan Science and Technology Agency. His research interests include terahertz materials and devices, photonic nanostructures and microstructures, and their applications.



Tadao Nagatsuma joined NTT Laboratories after receiving PhD degree from Kyushu University in 1986. Since 2007, he has been with Osaka University, where he is currently a Professor with the Division of Advanced Electronics and Optical Science, Department of Systems Innovation, Graduate School of Engineering Science,

and a Director of Co-Creative Education Division, Office for Industry-University Co-Creation. His research interests include millimeter-wave/terahertz electronics and photonics, and their applications to communications, sensing, and measurement. He is a Fellow of IEEE, a Fellow of IEICE, Japan, and a Fellow of the Electromagnetics Academy of USA.

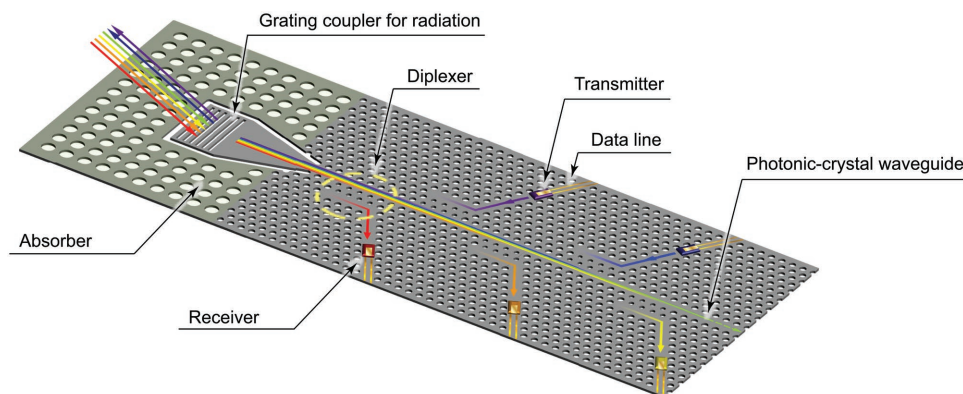


Figure 1. Example of silicon photonic crystal integrated circuit for terahertz communications with frequency-division diplexing. All necessary terahertz components can be built into this platform. Reproduced with permission.^[7] Copyright 2016, The Optical Society.

air thru-holes is developed into a silicon wafer to form photonic crystal cladding alongside the guiding channel. This clad provides the bandgap effect that results in wave confinement in the in-plane dimensions. In the vertical dimension, total internal reflection prevents radiation leakage into free space.

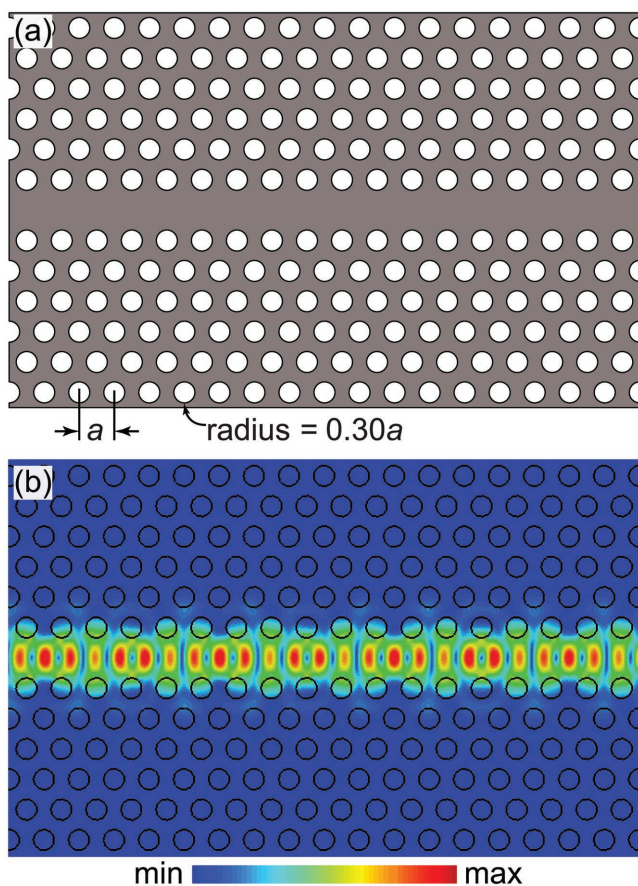


Figure 2. Photonic crystal waveguide for terahertz waves. a) Top-view diagram and b) corresponding field distribution at 330 GHz. The entire waveguide is made of a perforated silicon wafer with a thickness of 200 μm . The lattice constant a equals 240 μm . Since crystalline silicon is rigid, the platform is self-sustaining. The indicated dimensions are for the operation within 300–400 GHz.

The field distribution in Figure 2b reveals the fundamental transverse-electric mode (the electric field is parallel to the slab plane) inside this waveguide. Float-zone intrinsic silicon with a resistivity in the order of tens of kilo-Ohms is an ideal candidate for this purpose. Owing to minimum free carriers and impurities, this type of silicon is among the lowest loss materials for terahertz waves with the extinction coefficient less than 0.01 cm^{-1} below 1 THz.^[13] On top of that, silicon has a moderate refractive index of 3.4, resulting in a wide photonic bandgap.^[14] In terms of fabrication, necessary feature sizes down to one hundredth of a wavelength can be readily developed into crystalline silicon via standard deep reactive ion etching.

The performance of silicon-based photonic crystal waveguides was characterized by using a continuous-wave electronic system.^[12] As seen in Figure 3a, the transmittance of a 1 cm waveguide is exceptionally high across the range of 315–340 GHz. In particular, between 326 and 331 GHz, the loss is less than 0.1 dB cm^{-1} . Compared with metal-based transmission lines, this waveguide exhibits two orders of magnitude lower loss in the same frequency range. Metallic microstrip lines and grounded coplanar waveguides exhibit attenuation as high as 10 dB cm^{-1} around 300 GHz, even though low-loss COC was used as a dielectric spacer.^[15] For the photonic crystal waveguide, the photonic bandgap is not present below 301 GHz, and this results in the cutoff of the waveguide mode such that no transmission occurs below 315 GHz. Above 340 GHz, a higher-order mode coexists in this waveguide, and the fundamental mode is above the air light line. Hence, a fraction of energy can leak by means of coupling with the other mode or into free space. In theory, photonic crystal waveguides can accomplish tight bending with low loss. For this waveguide design, it is possible to achieve 60° corner with a minimum bending loss of 0.2 dB per bend between 320 and 330 GHz.

As can be seen in Figure 3b, the group delay is strongly dispersive near the waveguide mode cutoff around 315 GHz, where the propagation mode starts to develop inside the waveguide and thus the direction of the wave vector varies rapidly with frequency. At higher frequencies, the group delay becomes relatively flat. In principle, dispersion limits the transmission bandwidth. As shown in Figure 3c, around 330 GHz where the transmission loss is extremely low, the available bandwidth is

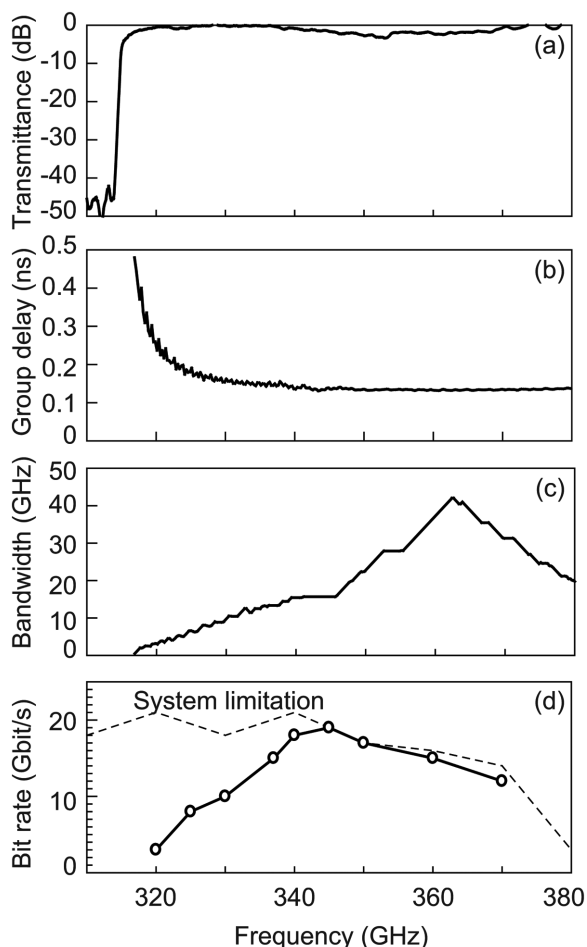


Figure 3. Characteristics of photonic crystal waveguide in relation to data transfer. The waveguide length is 1 cm. a) Propagation loss. b) Simulated group delay. c) Bandwidth determined from the group delay dispersion. d) Measurable bit rate for error-free communications with on–off keying. The system limitation is dictated by the output terahertz power of a UTC-PD and the response speed of an SBD detector. Reproduced with permission.^[14] Copyright 2017, The Laser Society of Japan.

up to 10 GHz. At 360 GHz where the propagation loss is up to 3 dB cm⁻¹, the bandwidth reaches its maximum of 40 GHz due to the low dispersion. In order to observe the effect of

dispersion on the communications, this waveguide platform was experimentally characterized for its maximum transmission bit rate at different carrier frequencies. On the transmitter side, a beating optical signal from two continuous-wave laser diodes was amplitude-modulated by a pseudorandom bit stream, and then converted to a terahertz signal via a unitraveling-carrier photodiode (UTC-PD) that detects the beat envelope. This terahertz signal was transmitted across the photonic crystal waveguide before being detected by a Schottky barrier diode (SBD). As can be seen in Figure 3d, the bit rate increases gradually until reaching the system limitation. At 340 GHz, the maximum error-free bit rate equals 19 Gbit s⁻¹.

3. Frequency-Division Multiplexing

Frequency-division multiplexing is an important function to capitalize full benefits of a vast terahertz spectral band. Particularly, this multiplexing scheme allows to modulate multiple carriers at a low speed that does not exceed the bandwidth of modulators and detectors, while maintaining a high aggregate transmission capacity potentially up to terabit per second. In addition, with multiplexing, multiple individual channels can share the same terahertz frontend to reduce the overall size and complexity. This capability is readily integrable in the photonic crystal circuit in the form of compact diplexers. A diplexer can be designed based on the concept of a directional coupler that is constructed from two photonic crystal waveguides running close by in parallel. In this setting, a single propagation mode degenerates into odd and even modes with different wavenumbers, controlled by the coupling strength between the two waveguides. The phase difference between the two modes thus depends on the coupling strength, coupling length, and frequency, and it determines energy balance between the two output ports. Therefore, a directional coupler can function to completely transfer energy from one waveguide to the other within a specific frequency band. The frequency dependence of the coupler suggests that it can work as a diplexer to separate or combine signals in two spectral bands.

Figure 4a shows an implementation of two photonic crystal diplexers in tandem to function as a triplexer, with the resulting spectral responses in Figure 4b. Specifically, the first diplexer forwards the frequency components around 325 GHz to

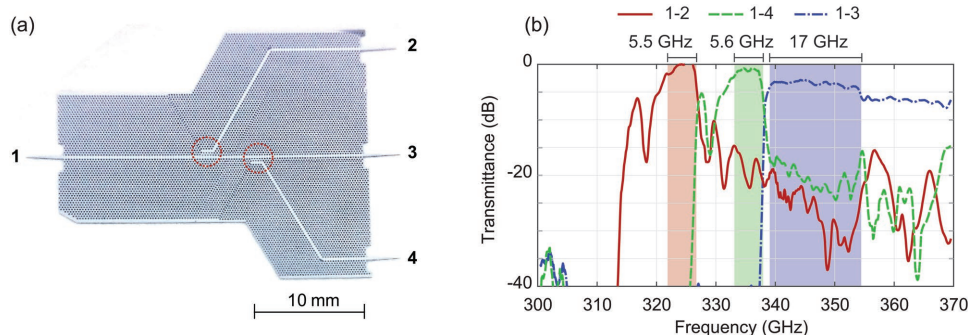


Figure 4. Frequency-division triplexer realized on the photonic crystal platform. a) Fabricated sample showing two diplexers connected in series. The sharp tails are used for coupling to hollow rectangular waveguides of the measurement system. b) Frequency-dependent transmittance profiles for the three output ports excited by Port 1. The bandwidth is marked at 3 dB transmission.

Port 2, while the second diplexer forwards the components around 335 GHz to Port 4. Other frequency components supported by the guided mode remain on the waveguide and exit at Port 3. Each diplexer requires a short coupling length of about one wavelength or four times the lattice constant only, and the bandwidth is around 1.6%, which is relatively large for such a diplexer. This can be achieved by optimizing the coupling strength, or in other words the spacing and air hole radii between the two parallel waveguides.^[7,16] The frequency selectivity of the diplexer can be improved by exploiting the frequency-dependent nature of the photonic crystal waveguides. As can be seen from Figure 4b, the isolation between ports is 15 dB or higher. The insertion loss is low, owing to low dissipation of the waveguides. Based on similar diplexer designs, multichannel data transmission has been demonstrated.^[7,16]

4. Integration of Active Components

Active components underpin a myriad of functionalities, including terahertz signal generation, external modulation, frequency multiplication, and homodyne and heterodyne detection. Many active components in the form of compact epitaxial semiconductors can be integrated with the photonic crystal platform. An incidental benefit is that the platform can be an excellent thermal sink due to the high thermal conductivity of silicon. A recent progress on this front focuses upon integration of terahertz sources and detectors, or more specifically resonant-tunneling diodes (RTDs).^[17] A key challenge lies in mode and impedance matching between the device and the waveguide for maximum coupling efficiency. As an example, an RTD-based detector has been integrated with a high-*Q* photonic crystal cavity to realize a compact thin-film sensing platform.^[18] As shown in Figure 5, an RTD chip was mounted directly onto a photonic crystal waveguide, where evanescent coupling takes place with a coupling efficiency of less than 0.1%. Nevertheless, the measurable *Q* factor of the cavity above 10 000 at 318 GHz highlights the exceptionally low dissipation and high spectral

resolution of the platform. For terahertz communications, an RTD detector was attached to the waveguide to demonstrate error-free data rate of 3 Gbit s⁻¹ at 300 GHz.^[19] A more complex configuration is a terahertz transceiver that involves two RTDs, one as transmitter and the other as receiver at different frequency bands.^[20] The transmission was successfully demonstrated despite low coupling efficiency. With the aid of a planar tapered antenna,^[21] the simulated coupling efficiency between an RTD and a photonic crystal waveguide was improved to more than 50% with a 3 dB bandwidth of 67 GHz.^[22]

5. Antennas for Free-Space Coupling

Antennas are vital for coupling guided waves in the photonic crystal waveguide with free-space waves. For terahertz wireless communications, an antenna together with its feed has to be designed around unique requirements in relation to several factors including bandwidth, efficiency, radiation gain, and compactness. One consideration for terahertz antennas is the broadband capability to capitalize vast bandwidth available in this spectral range for high-speed data transfer. As an example, an antenna operating across an atmospheric window spanning 200 and 300 GHz must have a relative bandwidth of at least 40%, over which the radiation pattern should remain reasonably stable. From the fabrication perspective, it is appealing to create a planar terahertz antenna from the same silicon wafer used to build the photonic crystal waveguide. This approach ensures compactness and integrability. Importantly, an antenna created from such a low-loss dielectric material can circumvent notorious ohmic loss that is accentuated in resonant systems and thus detrimental to the radiation efficiency. Thus, unconventional antenna designs are crucial in order to fulfill the requirements specific to terahertz wireless applications.

The radiation gain of antenna is another important aspect in terahertz communications.^[23] Typically, for wireless communications, an omnidirectional antenna is preferred over a directional one, owing to the extent of signal coverage and the ease of alignment. However, such a scenario is not applicable to terahertz links, due to the limited power available from terahertz sources and the increasing free-space path loss at this high-frequency range. This situation is best formulated via the simplified Friis transmission equation that relates the transmitted power P_t and received power P_r via^[24]

$$P_r = \left(\frac{\lambda}{4\pi R} \right)^2 G_t G_r P_t$$

Here, G_t and G_r are for the absolute gain of transmitting and receiving antennas, R for the distance between the transmitter and receiver, and λ for the operation wavelength. The equation assumes that the antenna pair is impedance-matched and polarization-matched. The term $(4\pi R/\lambda)^2$ is related to the free-space path loss. At 300 GHz or 1 mm wavelength, for wave propagation over the distance of 10 m, this loss makes up a majority of the link budget with 100 dB. Every order of magnitude increment in the distance incurs an additional 20 dB of loss. Provided the limited transmitted power P_t , this loss results

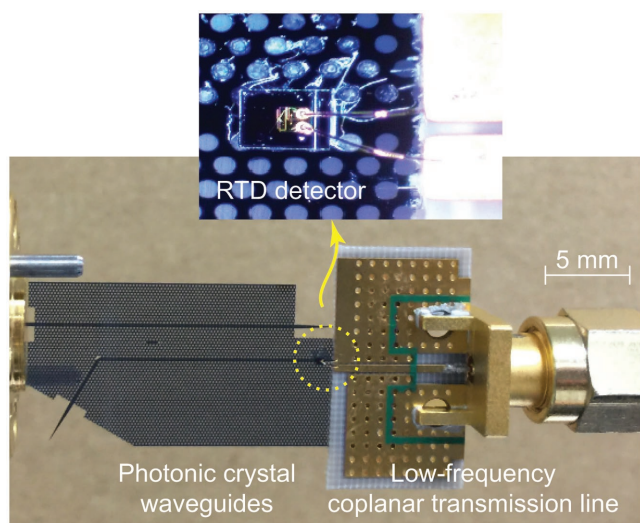


Figure 5. Integration of RTD with photonic crystal waveguide. Reproduced with permission.^[18] Copyright 2017, Springer Nature.

in a low SNR at the receiver, and thus a low channel capacity. High-gain antennas are therefore necessary to counterbalance the path loss at the cost of stringent point-to-point alignment.

So far different types of silicon-based antennas and scatterers have been implemented to serve the photonic crystal platform. They have been inspired by concepts originating either in the optics or microwave domain. An earliest implementation adopted a grating coupler that is widely used in optics. Also seen from Figure 1, a flaring photonic crystal waveguide was decorated with a series of grooves with a period close to a guide wavelength. This periodic loading results in scattered waves that are constructive in an oblique direction. A thru-hole grating yielded coupling efficiency of only 5%, while an optimized blind-hole design could reach the efficiency of 60%.^[20] The remaining energy was either unscattered, reflected, or projected into the bottom-half space. Common to diffraction gratings, the radiation is subject to beam squint, i.e., frequency-dependent radiation angle, owing to the phase-matching condition. This spatial dispersion of the beam limits the relative bandwidth at a fixed angle to a few percent. While such a small relative bandwidth translates to a large absolute bandwidth at optical frequencies, this bandwidth is far below most requirements at terahertz frequencies.

Other terahertz antennas designed for the photonic crystal waveguide perform end-fire radiation, i.e., in the same direction as the guided waves. One design involves the concept of dielectric resonator antenna (DRA) that originated from the microwave community.^[25] In contrast to metallic resonator antennas, DRAs rely on oscillating displacement currents in a low-loss dielectric material for their operation.^[26] For this particular implementation, the antenna was made of silicon in a cylindrical shape that terminates the waveguide. The maximum radiation gain was 10.6 dBi, and the impedance bandwidth was around 6%. Although the antenna footprint is compact, the relative bandwidth is not satisfactory for broadband operation. This issue is partly due to the resonance nature of this antenna type. As an alternative, nonresonant traveling-wave antennas become a viable solution. A dielectric rod antenna falls into this category since the antenna is tapered to gradually leak a guided mode into free space. Again this type of antenna can be purely made of silicon and integral to the waveguide. A large effective aperture for high radiation gain can be formed by either extending the rod length or to combine multiple rods in an array. Here, the latter choice was preferred to preserve mechanical integrity. As shown in Figure 6, this rod array attained over 20 dBi absolute gain across 315–390 GHz in the end-fire direction.^[27] This level of gain is close to 22 dBi of a standard horn antenna.

6. Outlook

The terahertz integrated platform based on photonic crystals is still in its infancy. Much work is yet to be done in relation to its performance and functionality toward practical applications. With regard to the waveguides themselves, although dissipation loss is negligible with silicon, radiation and mode-conversion losses need to be addressed. Dispersion is another factor that precludes ultra-high-speed transmission. Both the losses and

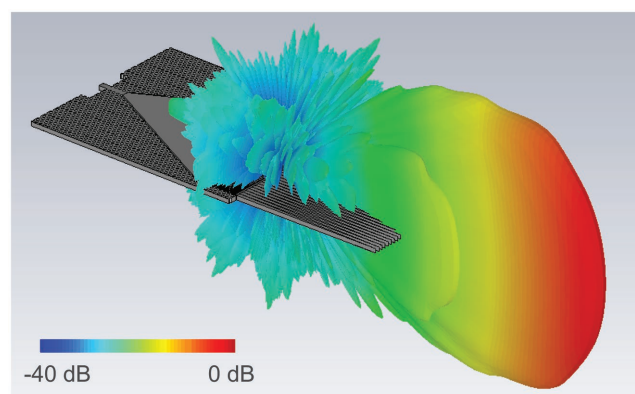


Figure 6. Normalized radiation pattern of dielectric rod antenna array. The radiation pattern is at 330 GHz, where the maximum absolute gain equals 22 dBi.

dispersion could be solved by engineering photonic crystals. For duplexers, their bandwidth, isolation, and insertion loss could be improved via optimization. Currently, data modulation is carried out at the source. Migrating modulation to the platform can lead to greater functionality and compactness. Silicon lends itself to modulation via carrier injection, but the response rate is limited by the carrier recombination time. Trap-assisted recombination can result in a faster modulation speed. RTDs are presently used as integrated detectors, and maximizing coupling efficiency is a goal of current research. Integration of RTDs as terahertz sources needs more careful consideration due to external feedback that could interfere with their stability.^[28] Mixers could be integrated in order to perform modulation and heterodyne detection on the platform. Dynamic or nonlinear responses could be attained by integration of some tunable materials such as phase-change materials or liquid crystals. As for antennas, radiation toward the broadside direction with enhanced gain is desirable for many applications, and this could be realized with 2D antenna arrays. On top of that, polarization diversity of antennas is vital to increase channel capacity via polarization multiplexing. Finally, multilayer platforms enabled by advanced fabrication can add degrees of freedom to control electromagnetic waves.^[29]

7. Conclusion

In summary, we have discussed silicon-based photonic crystal waveguides as a future integrated platform for terahertz communications. The guiding mechanism involves the photonic bandgap effect that yields strong field confinement and thus compactness of the platform. The waveguides are created only from float-zone silicon that has very low dissipation for terahertz waves and is fully compatible with planar fabrication technologies. Hence, the efficiency and cost of the platform are competitive compared with other conventional approaches. In addition to routing broadband terahertz waves with high efficiency, the platform is able to accommodate a myriad of integrated components for various functionalities. To this end, we have discussed the integration of duplexers, active components, and high-gain broadband antennas. Reaching practicality requires further

improvement in the performance of the waveguides and auxiliary components, and development of additional components including filters, oscillators, modulators, and isolators. An ultimate system will be able to perform sophisticated processes to increase spectral efficiency in terahertz communications. In addition to being radio-frequency front ends, the platform can also complete a last-mile link by direct interfacing with radio-over-fiber technology. The applicability of this platform extends beyond terahertz communications. Near-field and far-field sensing can enjoy the same benefits in relation to efficiency and compactness. Importantly, the platform is readily scalable to higher terahertz frequencies to capitalize larger absolute bandwidth there.

Acknowledgements

The authors would like to thank Mr. M. Yata, Mrs. A. Suminokura, and Mr. K. Tsuruda of Osaka University, and Mr. D. Ohnishi, Mr. T. Mukai, and Dr. J. Kim of Rohm Co. Ltd. for their technical supports and fruitful discussions. This work was supported in part by the Core Research for Evolutional Science & Technology (CREST) program of Japan Science and Technology Agency (JST; #JPMJCR1534), Grant-in-Aid for scientific research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (#17H01764), and Australian Research Council Discovery Projects (ARC DP180103561).

Conflict of Interest

The authors declare no conflict of interest.

Keywords

antennas, diplexers, photonic crystal waveguides, terahertz, terahertz communications

Received: March 28, 2018

Revised: May 16, 2018

Published online: June 25, 2018

- [1] J. G. Proakis, M. Salehi, *Communication Systems Engineering*, Prentice-Hall, New Jersey, USA **2002**.
- [2] T. Nagatsuma, K. Oogimoto, Y. Inubushi, J. Hirokawa, *Nano Commun. Netw.* **2016**, 10, 1.
- [3] W. Withayachumnankul, B. M. Fischer, D. Abbott, *Proc. R. Soc. A* **2008**, 464, 2435.
- [4] ITU-R, *Recommendation ITU-R P.676-10, Attenuation by atmospheric gases*, **2013**.
- [5] a) D. Headland, P. Thurgood, D. Stavrevski, W. Withayachumnankul, D. Abbott, M. Bhaskaran, S. Sriram, *Opt. Mater. Express* **2015**, 5, 1373; b) S. Walia, C. M. Shah, P. Gutruf, H. Nili, D. R. Chowdhury, W. Withayachumnankul, M. Bhaskaran, S. Sriram, *Appl. Phys. Rev.* **2015**, 2, 011303.
- [6] a) G. Ducournau, K. Engenhardt, P. Szriftgiser, D. Bacquet, M. Zaknoute, R. Kassi, E. Lecomte, J. F. Lampin, *Electron. Lett.* **2015**, 51, 915; b) T. Nagatsuma, G. Ducournau, C. C. Renaud, *Nat. Photonics* **2016**, 10, 371.
- [7] M. Yata, M. Fujita, T. Nagatsuma, *Opt. Express* **2016**, 24, 7835.
- [8] a) E. Yablonovitch, *Phys. Rev. Lett.* **1987**, 58, 2059; b) S. John, *Phys. Rev. Lett.* **1987**, 58, 2486.
- [9] a) T. Yoshie, L. Tang, S. Y. Su, *Sensors* **2011**, 11, 1972; b) S. Kawakami, A. Mori, K. Nagashima, S. Hashimoto, M. Haraguchi, *Bull. Chem. Soc. Jpn.* **2016**, 89, 385; c) H. Inan, M. Poyraz, F. Inci, M. A. Lifson, M. Baday, B. T. Cunningham, U. Demirci, *Chem. Soc. Rev.* **2017**, 46, 366; d) J. Hou, M. Li, Y. Song, *Angew. Chem., Int. Ed.* **2018**, 57, 2544.
- [10] S. Atakaramians, S. Afshar V, T. M. Monro, D. Abbott, *Adv. Opt. Photonics* **2013**, 5, 169.
- [11] K. Nielsen, H. K. Rasmussen, A. J. Adam, P. C. Planken, O. Bang, P. U. Jepsen, *Opt. Express* **2009**, 17, 8592.
- [12] K. Tsuruda, M. Fujita, T. Nagatsuma, *Opt. Express* **2015**, 23, 31977.
- [13] a) J. M. Dai, J. Q. Zhang, W. L. Zhang, D. Grischkowsky, *J. Opt. Soc. Am. B* **2004**, 21, 1379; b) R. Kakimi, M. Fujita, M. Nagai, M. Ashida, T. Nagatsuma, *Nat. Photonics* **2014**, 8, 657.
- [14] M. Fujita, *Rev. Laser Eng.* **2017**, 45, 752.
- [15] E. Peytavit, C. Donche, S. Lepilliet, G. Ducournau, J. F. Lampin, *Electron. Lett.* **2011**, 47, 453.
- [16] M. Yata, M. Fujita, T. Nagatsuma, presented at *2014 Int. Topical Meeting on Microwave Photonics (MWP) and the 2014 9th Asia-Pacific Microwave Photonics Conf. (APMP)*, IEEE Xplore, Sendai, Japan **2014**, pp. 40–43.
- [17] M. Asada, S. Suzuki, *J. Infrared Millim. Terahertz Waves* **2016**, 37, 1185.
- [18] K. Okamoto, K. Tsuruda, S. Diebold, S. Hisatake, M. Fujita, T. Nagatsuma, *J. Infrared Millim. Terahertz Waves* **2017**, 38, 1085.
- [19] A. Suminokura, K. Tsuruda, T. Mukai, M. Fujita, T. Nagatsuma, presented at *2014 Int. Topical Meeting on Microwave Photonics (MWP) and the 2014 9th Asia-Pacific Microwave Photonics Conf. (APMP)*, IEEE Xplore, Sendai, Japan **2014**, pp. 419–422.
- [20] M. Fujita, T. Nagatsuma, *Proc. SPIE* **2016**, 9856, 98560O.
- [21] K. Urayama, S. Aoki, S. Suzuki, M. Asada, H. Sugiyama, H. Yokoyama, *Appl. Phys. Express* **2009**, 2, 044501.
- [22] X. Yu, R. Yamada, J.-Y. Kim, M. Fujita, T. Nagatsuma, in *4th Int. Symp. on Microwave/Terahertz Science and Applications (MTSA 2017)*, Okayama **2017**.
- [23] D. Headland, Y. Monnai, D. Abbott, C. Fumeaux, W. Withayachumnankul, *APL Photonics* **2018**, 3, 051101.
- [24] C. A. Balanis, *Antenna Theory*, John Wiley & Sons, Hoboken, NJ **2005**.
- [25] W. Withayachumnankul, R. Yamada, C. Fumeaux, M. Fujita, T. Nagatsuma, *Opt. Express* **2017**, 25, 14706.
- [26] L. F. Zou, W. Withayachumnankul, C. M. Shah, A. Mitchell, M. Klemm, M. Bhaskaran, S. Sriram, C. Fumeaux, *IEEE Photonics J.* **2014**, 6, 4600110.
- [27] W. Withayachumnankul, R. Yamada, M. Fujita, T. Nagatsuma, *APL Photonics* **2018**, 3, 051707.
- [28] L. D. Manh, S. Diebold, K. Nishio, Y. Nishida, J. Kim, T. Mukai, M. Fujita, T. Nagatsuma, *IEEE Trans. Terahertz Sci. Technol.* **2018**, <https://doi.org/10.1109/THZ.2018.2842209>.
- [29] A. Michaels, E. Yablonovitch, *Opt. Express* **2018**, 26, 4766.