Press release

March 11, 2022
Keio University

High-Speed Silicon On-Chip Optical Switch Based on a Graphene Microheater

Applications anticipated in next-generation high-capacity optical communication technologies, optical integrated circuits, and quantum chips.

By integrating a microheater using the atomically thin material, graphene[1], with silicon photonics[2], Professor Hideyuki Maki and his colleagues at the Department of Applied Physics and Physico-Informatics in the Faculty of Science and Technology at Keio University have fabricated a high-performance on-chip optical switch[3]. This technology is expected to have applications for new optical devices on silicon chips such as devices that require high-speed path switching for optical communications, optical integrated circuits, and photonic chips.

An optical switch is a device that can re-route an optical signal without converting it into an electrical signal. In the field of optical communications, they are utilized to select the output port of the optical path and are indispensable in supporting high-speed communications. While at present there are a variety of optical switch types under development, for efficient next-generation compact switches, experts are looking to optical switches that have optical waveguides integrated onto silicon chips. Typical optical switches within this category employ a mechanism which changes the refractive index of a material using the thermo-optic effect. However, current switches that use such metal heaters face limitations in their performance related to speed and efficiency.

This research study focused on fabricating a new type of optical switch that uses graphene, a material known for its thermal properties, instead of conventional metals. The researchers were able to form a graphene-based microheater directly on the silicon photonics device. As a result, even while using the same basic structure of optical switches that employ conventional metal-based heaters, the researchers were able to significantly improve the switches' performance, drastically shortening the rise and fall response times to a few mere microseconds. This technology has demonstrated that graphene, a two-dimensional material, is extremely promising for optical switches in silicon photonics. It is expected to be applied in various on-chip integrated optical device technologies, including next-generation high-capacity optical communications chips, optical interconnects, optical integrated circuits, and quantum chips, etc.

This research was conducted in collaboration with Associate Professor Yasuaki Monnai (affiliated with the Faculty of Science and Technology at Keio University at the time of this study) of the Research Center for Advanced Science and Technology (RCAST) at the University of Tokyo.

The results of this research were published in the online edition of *ACS Nano* of the American Chemical Society (ACS) on February 14, 2022.

1. Main Points of Research

- A new type of on-chip optical switch was fabricated that replaces conventional metal heaters with a microheater that uses graphene, a material known for its thermal properties, formed directly on the silicon waveguide.
- The fabricated graphene-based microheater optical switch demonstrated rise and fall response times of a mere few microseconds, a significant improvement over conventional

metal heaters in optical switches that utilize the thermo-optical effect.
- This technology is expected to have wide applications across next-generation high-capacity optical communication chips, optical integrated circuits, and quantum chips.

2. Background of Research

The rapid development of the information age has led to an era where various services and electronics are operated via the internet and optical communications. An essential device in supporting the infrastructure of high-capacity communications is the optical switch. Optical switches take optical signals (light) and reroute them without needing to convert them to electric signals. Within the optical communications infrastructure and optical communication networks, they are an indispensable technology to the optical paths used when transferring data. There are a variety of switch types used in modern technology such as mechanical switches, MEMS (micro-electro-mechanical systems) switches, and switches with waveguides on glass substrates. However, these switches operate at relatively low speeds of around 1-10 milliseconds. For next-generation high-speed switches, researchers have turned their attention to silicon photonics based optical switches that use on-chip waveguide structures, reporting speeds in the order of tens of microseconds. Most optical switches of this variety are made with a localized metal heater that uses the thermal modulation of the refractive index of a material (the thermo-optical effect).

However, while research development has already made various discoveries related to optical switches that rely on metal-based heaters, they cannot measure up to the even higher speeds and efficiency that will be necessary for chips in next-generation high-capacity communications, optical interconnects, optical integrated circuits, quantum chips, and other new optical integrated devices. Instead, completely new technological innovations will need to be introduced.

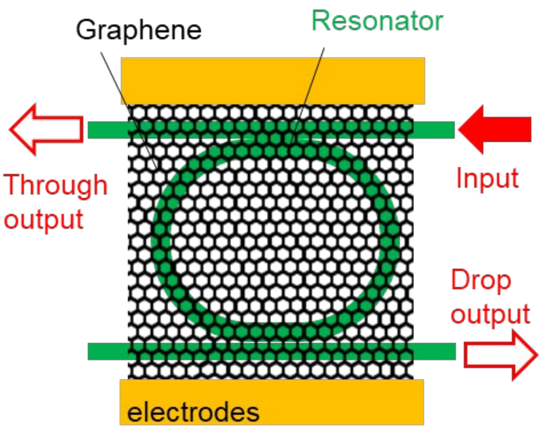
3. Content of Research and Results

This research study, focused on creating new technology for on-chip optical switches, was the first to replace conventional metal heaters with a graphene-based microheater, leading to an optical switch that can be formed directly on a silicon photonics device and operate at incredibly high speeds. Graphene is an atomically thin carbon material that is known for its great thermal properties due to its monolayer thickness. This same group of researchers has previously explored graphene's capability of up to GHz order of temperature modulation.[4] Based on those results, the team went on to make use of graphene's thermal properties by incorporating it into a microheater, achieving vastly improved speeds to switches that rely on conventional metal-based heaters. The team designed the optical switch's structure with an add/drop-type racetrack resonator and two output waveguides (the through and drop ports) and placed the graphene microheater directly on the resonator (Figure 1). Applying a bias voltage to the graphene device induces Joule heating in the resonator, modulating the refractive index of the resonator through the thermo-optical effect. This allows for electrical control over light-coupling through the resonator and thereby creates a reliable optical switch that can alternate between through and drop output ports (Figure 2). Furthermore, the researchers measured that the graphene-based optical switch achieved real-time high-speed operation at 100 kHz and verified modulation rise and fall response times of 1.2 and 3.6 microseconds respectively. This switching speed is up to tens of times faster than that of a metal-heater optical switch using the same mechanism, indicating that the properties of the optical switch can be significantly improved simply by replacing the metal with graphene. Finally, the research team theoretically investigated the mechanism of this high-speed operation by using a heat conduction simulation and theoretically demonstrated that graphene's thermal properties were what enabled such high-speed modulation.

4. Future Developments

Integrated device technology used to undergird the infrastructure of the information age is reaching the uttermost limits of simple electronic circuits in terms of speed, limited power consumption, and compactness. As a result, integrated optical devices such as silicon photonic options are attracting attention as a way to break through these limitations and form the backbone of next-generation device technology. The graphene-based high-speed optical switch technology demonstrated in this study enables high-speed modulation of optical paths, and thus can be applied in chips for next-generation high-capacity optical communications. Silicon photonics technology also has likely applications outside of long-distance optical communications such as optical interconnects and optical integrated circuits that can replace traditional wiring between and within machinery. Likewise, the research findings of this study have potential for quantum computing chips, quantum cryptography chips, and various other up-and-coming optical technology. Nanocarbon materials such as graphene and carbon nanotubes have been reported to be used not only for optical switches as demonstrated in this study, but also for new on-chip optical device applications such as light sources on silicon chips or even quantum light sources.[5] They are also expected to aid in the development of nanocarbon integrated optical devices.

This work was partially supported by Grants-in-Aid for Scientific Research (KAKENHI), (16H04355, 23686055, 18K19025, 20H02210); the Japan Science and Technology Agency (JST) Adaptable and Seamless Technology Transfer Program through Target-driven R&D (A-STEP) Industry-Academia Collaboration, (JPMJTR20R4); the Kanagawa Institute of Industrial Science and Technology (KISTEC) Strategic Research Seeds Development Project; the Spintronics Academic Research Base and Collaboration Network; and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) Nanotechnology Platform Project (Nanofabrication).



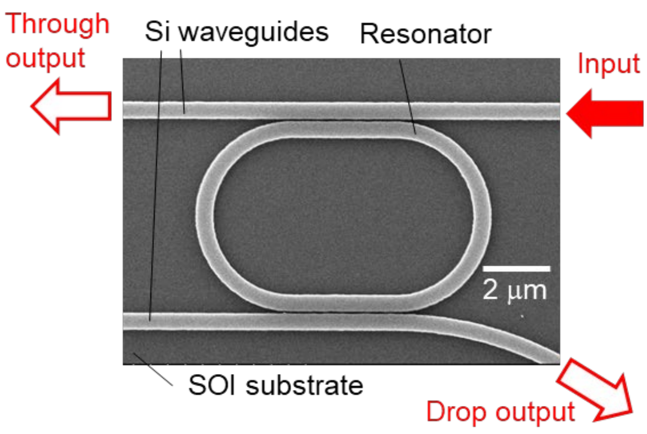


Figure 1 Left: Schematic of the graphene optical switch.
Right: Scanning electron microscope image of the area surrounding the resonator of the fabricated optical switch.

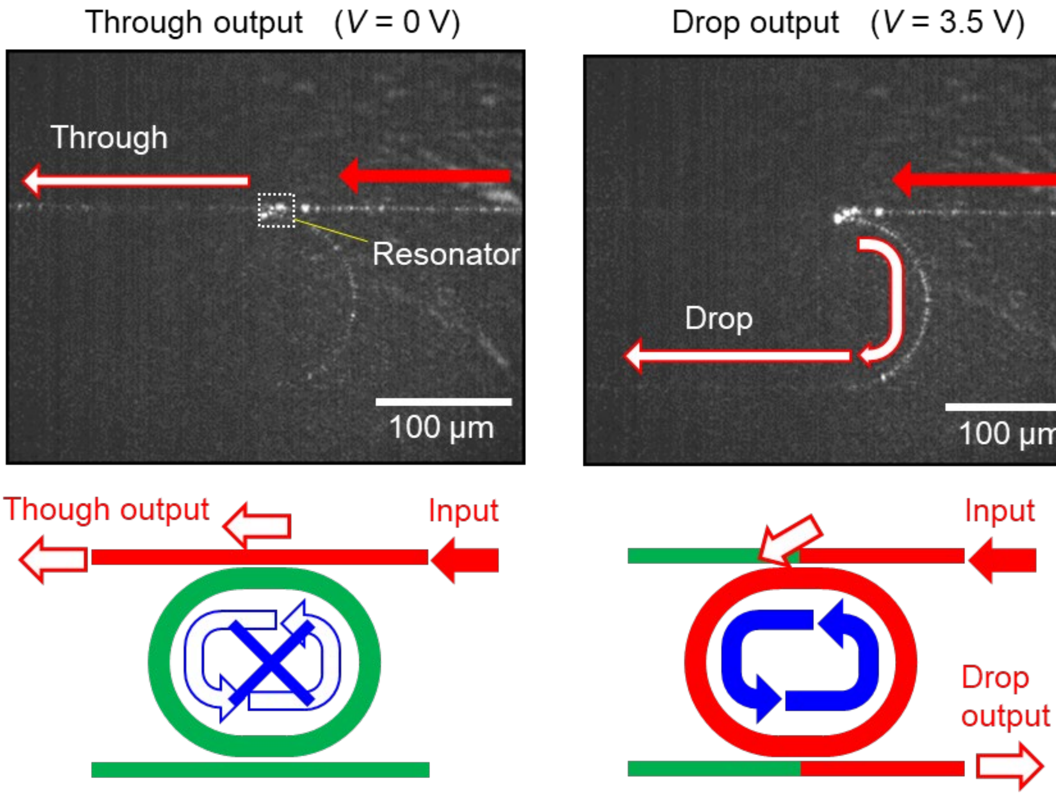


Figure 2 Above: The Optical Switch
Nonresonance condition (left) Resonance condition (right)
Below: Optical Switch Device Operation
Because the refractive index of the resonator changes based on whether a bias voltage is introduced to the graphene, it is possible to control light coupling in the resonator. This means that it is possible to make the device switch outputs between through (left) and drop output (right) ports.

Details of Journal Article :
"High-Speed and On-Chip Optical Switch Based on a Graphene Microheater"
Shoma Nakamura, Kota Sekiya, Shinichiro Matano, Yui Shimura, Yuuki Nakade, Kenta Nakagawa, Yasuaki Monnai, Hideyuki Maki
ACS Nano, https://doi.org/10.1021/acsnano.1c09526

Glossary and References

1: Graphene

A nanomaterial. When monolayers of graphene are stacked together, they form graphite, a material used in pencil lead.

2: Silicon Photonics

The study of optical devices that use microfabrication on silicon chips to fabricate new highly integrated optical technology. Conventional integrated circuits use electronic devices integrated on silicon semiconductor chips to send/receive signals and perform operations, but there are limits to improving both their speed and power consumption. As such, experts are trying to convert to optical technology for parts of next-generation hybrid devices.

3: Optical Switch

In optical communications, an optical switch is a device that can directly re-route an optical signal without converting it into an electrical signal. This is an indispensable device in high-speed communication because it maintains the signal speed.

4: Press Release
*(Released March 30, 2018)
"Development of Graphene High-Speed Optical Devices for use on Silicon Chips: a new path to on-chip integrated optical devices" (Japanese language only)
https://www.keio.ac.jp/ja/press-releases/2018/3/30/28-43298/

5: Press Releases
*(English Version Released January 28, 2020)
"Pure and Efficient Single-photon Source Based on Carbon Nanotubes for Quantum Cryptography"
https://www.keio.ac.jp/en/press-releases/2020/Jan/28/49-67070/
*(Released August 13, 2020)
"Highly Efficient and Linewidth Carbon Nanotube Optical Devices Integrated into a Silicon Optical Circuit: Driving communication wavelengths opens doors for applications in optical integrated circuits and quantum cryptography chips" (Japanese language only)
https://www.keio.ac.jp/ja/press-releases/2020/8/13/28-74127/

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