Athermal Broadband Graphene Optical Modulator with 35 GHz Speed

Hamed Dalir,†,# Yang Xia,†,# Yuan Wang,† and Xiang Zhang*,†,‡,⊥

†NSF Nano-scale Science and Engineering Center (NSEC), University of California at Berkeley, 3112 Etcheverry Hall, Berkeley, California 94720, United States
‡Material Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States
⊥Department of Physics, King Abdulaziz University, Jeddah, 21589, Saudi Arabia

Supporting Information

ABSTRACT: Optical modulators with ultrahigh speed, small footprint, large bandwidth, robust athermal operation, and complementary metal-oxide semiconductor (CMOS) compatibility are important devices for optical communication and computing applications. Compared to the conventional optical modulators, graphene modulators have attracted great interest due to their large optical bandwidth with an ultracompact footprint. However, their practical applications are limited by the trade-off between speed and optical bandwidth, with a critical issue of temperature tolerance. In this work, we experimentally demonstrate an athermal graphene optical modulator with a 140 nm bandwidth in the entire optical communication regime (1500−1640 nm), with robust high-temperature operation. The device is based on a planar structure with double-layer graphene, leading to the high modulation speed, up to 35 GHz through reduction of the total resistance, and capacitance (9 fF). We observe speed stability in a wide range of temperatures (25−145 °C). The ultracompact footprint (18 μm²) of the device promises the next generation of on-chip optical interconnections for efficient communication.

KEYWORDS: graphene modulator, broadband, athermal operation, ultrahigh speed, double-layer

To boost the development of future supercomputers and data centers, ideal optical modulators are demanded with ultrahigh speed, small footprint, large optical bandwidth, athermal operation, and complementary metal-oxide semiconductor (CMOS) compatibility. Modulators are classified into two operational categories: electrorefractive and electroabsorptive. For the refractive approach, the modulation is typically achieved by varying the plasma dispersion effect and free carrier absorption in silicon to control the real part of material permittivity. However, for a single-pass two-beam interference like Mach−Zehnder’s, such a change is typically poor. Hence, a device several hundreds of micrometers long must be employed to manipulate the relative phase of the interfering beams for output power control.1−3 This results in a large footprint and a high capacitance, which consequently raises the power consumption. Other refractive modulator designs with multiple-pass single-beam interference, such as resonators, require a large quality factor (>10⁵) or a narrowband modulation (<0.1 nm), which results in a stringent fabrication process. In addition, a precise temperature stabilization to keep the device on resonance is indispensable, causing an increase in the total power consumption.3,5 In contrast, absorptive modulators (such as germanium-based devices) utilize the changes of the imaginary part of the material permittivity by applying an electrical field through the structure, mostly with a reverse bias voltage on a p−i−n-like structure.

The electroabsorption effect of germanium has offered a high modulation speed but with a limited optical bandwidth due to finite band gap.6,7 As a result it cannot cover the entire optical communication regime (1525−1565 nm (C band) and 1570−1610 nm (L band)). Furthermore, CMOS-compatible applications require special processes (such as epitaxial growth, wafer bonding, or die bonding), which limits the thermal stability of the final devices.5−9

Graphene, a monolayer of carbon atoms formed in a honeycomb lattice, is appealing for optical modulation4,10−13 applications due to its unique electrical and optoelectronic properties. Among these are (1) ultrastallation speed (several hundreds of GHZ), thanks to its high carrier mobility of more than 200 000 cm²/(V·s);14−18 (2) broadband operation with a constant absorption of εc/ℏc = 2.293%, where ℏ and c are the Plank constant and speed of light in a bulk material, which covers a broad range from visible to infrared wavelengths;19,20 (3) CMOS compatibility with the demonstrated wafer-scale integration on silicon in past few years;21 and (4) unique temperature stability related to its exceptional thermal conductivity.13 With all of these merits,
graphene is expected to be integrated with silicon photonics for the next generation of short-reach optical interconnects.\textsuperscript{\textbf{15,22}}

Here we report the experimental demonstration of a graphene-based electroabsorption modulator with a 35 GHz modulation speed, while absorption is actively controlled by tuning the Fermi level through electrical gating of a graphene double layer. A 2 dB modulation depth within the range of optical communication wavelengths (1500–1640 nm), under ambient conditions, was obtained. More importantly, we show that the modulation performance of our device remains immune to a large range of changes in the temperature (25–145 °C). This is crucial for practical interconnections and communication systems.

\section*{EXPERIMENTAL METHODS}

To facilitate high-speed and broadband operation, a planar structure is developed by relocating the double-layer graphene underneath the waveguide. This new design allows us to achieve a 10 times thicker spacer layer between the graphene layers compared to the previous work to reduce the device capacitance.\textsuperscript{\textbf{11}} The contact resistivity has been improved using rapid thermal annealing (RTA). These lead to a more than 1-order enhancement of the modulation speed. In order to fabricate the double-layer graphene optical modulator, wet thermal oxidation and atomic layer deposition (ALD) were employed to form a 1 μm silica and a 20 nm thick Al\textsubscript{2}O\textsubscript{3}, respectively, which prevents the leakage of the optical mode underneath the waveguide. This new design allows us to achieve a 10 times thicker spacer layer between the graphene layers compared to the previous work to reduce the device capacitance.\textsuperscript{\textbf{11}}

Due to the larger overall tangential electric field integration underneath the waveguide, the absorption of the TM mode is as large as 0.1 dB/µm, and a 3 dB modulation depth is expected from the current device geometry.\textsuperscript{\textbf{11}} The contact resistivity has been improved using rapid thermal annealing (RTA). These lead to a more than 1-order enhancement of the modulation speed. In order to fabricate the double-layer graphene optical modulator, wet thermal oxidation and atomic layer deposition (ALD) were employed to form a 1 μm silica and a 20 nm thick Al\textsubscript{2}O\textsubscript{3}, respectively, which prevents the leakage of the optical mode underneath the waveguide. This new design allows us to achieve a 10 times thicker spacer layer between the graphene layers compared to the previous work to reduce the device capacitance.\textsuperscript{\textbf{11}}

The top graphene layer was then transferred, forming a capacitor structure (Figure S1f). Similar procedures to those for the bottom graphene layer were performed to allow the active tuning of graphene layers (Figure S1f–h). The Raman spectroscopy data indicate good-quality graphene for both top and bottom layers (Figure S2). A layer of 270-nm-thick, amorphous silicon (a-Si) was deposited by PECVD (Figure S1i). Eventually a 600 nm × 30 µm (width × length) silicon waveguide, with both ends connected to a pair of grating couplers (period = 870 nm, optimized for transverse magnetic (TM) mode with λ = 1550 nm) was fabricated via e-beam lithography and transformer coupled plasma (TCP) etching (Figure S1j). We carried out a two-dimensional finite element method (FEM) simulation using COMSOL Multiphysics. The calculation results indicate that the absorption of the TM mode (0.1 dB/µm) is greater than the transverse electric (TE) mode due to its better overlap with graphene, and a 3 dB modulation depth is expected from the current device geometry shown in Figure 1b. Figure 1c and d show the false-color SEM image including the waveguide, input/output couplers, and Cr/Pd/Au metallization. Top and bottom graphene layers (red colors) overlap well with the modulator waveguide.
■ MEASUREMENT RESULTS
To study the dynamic response of the double-layer graphene modulator, an unmodulated RF signal with $-7$ dBm from the calibrated Anritsu 37397D vector network analyzer (VNA) was combined with a bias direct current (dc) voltage of 25 V through an SHF BT-110 bias-tee and applied between the bottom and top layers of graphene. The coaxial cable was connected to the device with a GGB model 40A-GS microwave probe. Losses from the cabling, bias-tee, and probe were subtracted. A distributed feedback (DFB) laser at 1550 nm was used to externally generate the light into the modulator. The radiofrequency (RF)-modulated signal was then transferred to the VNA via the BPDV3120R u’t photodiode cascaded with a UA1L65VM broadband postamplifier. We measured small-signal RF ($S_{21}$: ratio between the optical amplitude modulation and the RF signal). Figure 2 illustrates the $S_{21}$ results, while a

![Figure 2](image.png)

**Figure 2.** Radio frequency response of the device. The 3 dB cut-off frequency of 35 GHz was obtained with an RF power of $-7$ dBm biased at $V_{DC} = 25$ V. Speed performance is limited by device RC time constant. An estimation of the geometric capacitance of the measured device is 9 fF, while our measurement indicates that a high series resistance ($\sim 500 \Omega$) mainly arises from the contact resistance between the graphene layer and metal electrode, limiting the current speed performance.

bandwidth of 35 GHz limited by the RC time constant of our fabricated modulator is obtained. The RC is restricted by the dimension of the capacitor, graphene sheet resistance, and contact resistance. An estimation of the measured device’s geometric capacitance is 9 fF, while our measurement revealed that the high series resistance ($\sim 500 \Omega$) mainly came from the contact resistance between the graphene layer and palladium electrode (pad), which is the key issue for the current speed limitation. Using the state-of-the-art process, the series resistance of the device can be considerably reduced to below 50 ohm,$^{2,4}$ which combined with a microstrip electrode design terminated with a matched impedance$^{25}$ can significantly increase the speed of the modulator.

Typically, interference-based silicon devices such as resonators or Mach–Zehnders are highly sensitive to high-temperature operation due to the large thermo-optic coefficient effect in silicon. To study the temperature dependence of the operating characteristics, we tested the 30-$\mu$m-long waveguide modulator throughout a large temperature range of 25–145 °C. We studied the slope of the RF response ($S_{21}$) at 1550 nm throughout a large temperature range of 25–145 °C (raw data plotted in Figure S3). As shown in Figure 3, the slope virtually remains unchanged as the temperature rises, which denotes a robust speed performance. In addition, a 1.9 dB modulation depth at a high temperature of 145 °C with the same swing voltage was obtained, indicating less dependency on the temperature change. The robust athermal operation in modulators is critical to optoelectric interconnection and communication systems for ultrafast efficient modulation.

![Figure 3](image.png)

**Figure 3.** Robust athermal operation of the graphene modulator under a large temperature range. The slope of the RF response $S_{21}$ under different temperatures remains virtually the same. At a high temperature of 145 °C a modulation depth of 1.9 dB is obtained, indicating a robust athermal operation of the device, which is a key factor for practical approaches.

The static results on the transmission of the graphene waveguide modulator with various bias voltages were measured at the standard communication wavelength of 1550 nm (Figure 4a). While most of the transmission loss comes from the two gratings couplers ($-13.5$ dB for both couplers), the minimum transmission of the waveguide is $-16.4$ dB, at which 2 dB modulation depth with TM mode excitation was obtained for a 30-$\mu$m-long waveguide modulator. An extremely low insertion loss of $-0.9$ dB was measured by comparing the output of two identical waveguides with and without graphene layers. Applying a voltage swing of 25 V to the modulator is required to turn the modulator from the OFF to ON state and vice versa, which corresponds to a power consumption of 1.4 pJ/bit.

The absorption of graphene is adjusted by the electrical gating. The band structure of graphene is composed of two bands that are degenerate at the so-called Dirac points. Due to the nature of the monolayer (low density of states), the position of the Fermi level can be modified readily by changing the accumulation charge. Considering an undoped monolayer graphene (Figure 4 region II), the Fermi level is at the Dirac point. Under the illumination of photons with an energy of $\hbar \nu$ (where $\hbar$ and $\nu$ are the Plank and light frequency, respectively), the transmission would be attenuated. However, when the graphene sheet is either hole- or electron-doped (Figure 4 regions I and III), its Fermi level drops or rises, respectively. When the charging is sufficient to raise (or drop) the Fermi level by the photon’s half energy above (or below) the Dirac point, the interband transition is considerably suppressed, and hence higher transmission is allowed. In our device, when a positive voltage is applied to the top layer (bottom layer is effectively negatively biased), a less positive voltage is needed to suppress the absorption compared with the negative voltage case. This is because the absorption is mainly from the top layer graphene, which is closer to the waveguide mode, and that layer is initially p-doped. We examined the optical bandwidth of our double-layer graphene device in a large range of optical communication wavelengths. A uniform modulation depth under different optical wavelengths (1500–1640 nm) was

DOI: 10.1021/acsphotonics.6b00398
observed with a constant swing voltage (Figure 4b). Such a broadband functionality in a modulator is important to boost the capacity of optical short-reach interconnects. A comparison of performances between our modulator and established modulation techniques is provided in Table S1.

**CONCLUSION**

In conclusion, we have experimentally demonstrated a planar double-layer graphene modulator with an ultrafast operation up to 35 GHz. A uniform modulation depth of 2 dB for the entire optical communication wavelengths (1500−1640 nm) was obtained with an ultracompact footprint of 18 μm². Robust thermal operation of the modulator with no noticeable change in speed performance of the device at a high temperature up to 145 °C was presented, critical for the next generation of optical communication and computing.

**ASSOCIATED CONTENT**

*Supporting Information*

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsphotonics.6b00398.

Additional information (PDF)

**AUTHOR INFORMATION**

*Corresponding Author*

E-mail (X. Zhang): xiang@berkeley.edu.

**Author Contributions**

H. Dalir and Y. Xia contributed equally to this work.

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The experiment of this research was supported by the Office of Naval Research (ONR) MURI program under Grant No. N00014-13-1-0678; the simulation was supported by the ‘Light-Material Interactions in Energy Conversion’ Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-AC02-05CH11231.

**REFERENCES**


