Topical Review

Review of graphene modulators from the low to the high figure of merits

Jiamin Liu\textsuperscript{1,2}, Zia Ullah Khan\textsuperscript{1}, Cong Wang\textsuperscript{2}, Han Zhang\textsuperscript{2}\textsuperscript{*} and Siamak Sarjoghian\textsuperscript{1}\textsuperscript{*}

\textsuperscript{1} School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, United Kingdom
\textsuperscript{2} Collaborative Innovation Center for Optoelectronic Science and Technology, International Collaborative Laboratory of 2D Materials for Optoelectronics Science and Technology of Ministry of Education, College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, People’s Republic of China

E-mail: hzhang@szu.edu.cn and s.sarjoghian@qmul.ac.uk

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Abstract

In this paper, the basic physics of modulator are discussed and traditional silicon modulator in the early years is involved as a comparison. Fifty-seven research articles about graphene modulators are reviewed in detail. All the figure of merits including modulation depth, modulation speed, footprint, modulation bandwidth, operation bandwidth, and insertion loss of these modulators are well studied. The challenges and problems for graphene modulators are addressed by analyzing the first twenty-five references while the last thirty-five references of graphene modulators are reviewed to address the higher figure of merits that are still developing. Physics of other 2D materials are also mentioned as a comparison, especially a modulator by black phosphorus. We believe this review will give a good roadmap to develop better graphene modulators that solves the challenges and problems in this field.

Keywords: graphene modulator, figure of merit, 2D materials

(Some figures may appear in colour only in the online journal)

1. Introduction

1.1. Overview

Among most of the passive devices, a modulator is a very common device and has been reported by numerous papers [1–60]. Before the development of graphene fabrication technology, the modulators were suffering from a large footprint, high-energy consumption, low operation speed, narrow bandwidth, and low modulation depth because of the lower fundamental limits of traditional materials such as silicon. Modulators based on traditional materials [1–3] have also been developed to very near their performance limits. It is 2011 when the first graphene modulator was reported [4]. Since then many papers [5–60] have reported different graphene modulators with different structures, and their figure of merits (FOMs) have been improved. The structures of graphene modulators can be a monolayer graphene-coated on the top of the semiconductor wafer [4, 5], double-layer sandwiched by an insulator material such as Al\textsubscript{2}O\textsubscript{3} [6–8], four [9] or more [10] graphene layers on wafer, graphene-coated cylindrical dielectric wire [11–13], dielectric-loaded plasmon waveguide [14], and Mach–Zehnder (M–Z) interferometer [5, 10], for optical modulator [4–14] and THz modulator [15, 16].

In this section, firstly we will talk about the basic physics of modulator to address what is a modulator and its function. In section 2, several examples have been discussed to address the challenges and problems in this field. State-of-the-art values in this field have been documented in this paper by studying graphene modulators reported in references [4–25] and traditional silicon modulators in references [1–3] as a comparison. In section 3, some examples of graphene modulators have also been given to address further challenges.
and problems. And FOMs from references [26–57] have been recorded to address the higher FOMs developed by graphene modulators. Suspended graphene modulators [58–60] with higher FOMs and near fundamental limits design have been presented in section 4. Section 5 is about the physics of other 2D materials and the comparison of modulators by black phosphorus (BP) and graphene. In the end, the future perspectives are discussed, and the conclusion is drawn in section 6.

1.2. The basic physics of modulator

In electronics and telecommunications, a modulator is used as a device to vary one or more properties of the carrier waves by the electronic or optical signal. According to the different varying properties of the carrier waves, the modulator can be divided into amplitude modulator (AM), frequency modulator (FM), and phase modulator (PM). In this review, amplitude modulators only in the optical and THz ranges are considered.

1.2.1. Types of modulator. According to different signal types, a modulator can be divided into electro-optical, magnetic-optical, and all-optical. Electro-optical modulators are divided into two further types: electro-absorptive and electro-refractive. The modulator enabled by the change of imaginary part of the mode index is defined as the electro-absorptive modulator, and the one enabled by the change of real part of the mode index is defined as the electro-refractive modulator. The electro-refractive modulator is often used as a Mach–Zehnder (M–Z) interferometer.

1.2.2. FOMs of modulator. For the amplitude modulator, the FOMs include modulation depth, modulation speed, foot-print, modulation bandwidth, operation bandwidth, and figure of merit (FOM).

The modulation depth is defined as the change in the amplitude of the carrier waves when modulation is operated. In the modulation, the amplitude of the carrier wave changes as the information signal changes, and the highest change in the amplitude is defined as the modulation depth. It can be written as:

\[ h = \frac{m(t)}{A}, \]

where \( m(t) \) is the amplitude of the information signal wave, \( A \) is the amplitude of the carrier wave. For a realized transmission-based modulator, the modulation depth can also be obtained as [6]:

\[ M = \frac{T_{\text{on}} - T_{\text{off}}}{T_{\text{on}}}, \]

where \( T_{\text{on}} \) is the on-state transmittance, \( T_{\text{off}} \) is the off-state transmittance. The normalized modulation depth can also be defined as the extinction ratio given by [14]:

\[ \text{extinction ratio} = \Delta \alpha = \alpha_{\text{off}} - \alpha_{\text{on}}, \]

where \( \alpha_{\text{off}} \) is the off-state loss of the modulator, \( \alpha_{\text{on}} \) is the corresponding on-state loss.

The modulation speed is defined as the frequency of the information signal when 3-dB modulation amplitude is applied to the modulator. The equivalent circuit of a modulator can be simplified as a voltage source applied to a resistance and a capacitor, as shown in figure 1.

At higher modulation frequency, most of the applied voltage will appear across the resistance \( R \) due to the low resistance of the capacitor and the modulator cannot be operated efficiently. Hence, when the modulator is operating, enough energy should be applied to the capacitor and the modulation speed should not be too high. We have a relation of:

\[ R = \frac{1}{\omega C}, \]

when half of the total energy is applied to the modulator. Then we get the 3-dB modulation speed of:

\[ f_{\text{3dB}} = \frac{1}{2\pi RC}. \]

In the graphene modulator, \( R \) includes the contact resistance between electrodes and graphene, and the graphene sheet resistance. \( C \) is related to the footprint of the modulator. The footprint of a modulator is defined as the active modulation area. In a waveguide-based modulator, it is the beam width multiply by the interaction length. There is also a limit of the modulation speed which is related to the interaction length, and it can be obtained as:

\[ f_{\text{limit}} = \frac{c}{4nL}, \]

where \( c \) is the velocity of light in vacuum, \( n \) is the effective refractive index of the mode, and \( L \) is the interaction length. This limit is to ensure the electric field in the material is a fixed value when the electromagnetic wave is transmitting in the modulator. The modulation bandwidth is often the same as the modulation speed because the lowest possible modulation speed is zero. The operation bandwidth is the bandwidth of the carrier waves, which shows that more channels of the signal can be carried in the modulator if it is higher.

The insertion loss is the lowest loss of the modulator which cannot be tuned, and it can be calculated as:

\[ \alpha = -10\log[T_{\text{max}}]. \]

The figure of merit (FOM) is defined as the ratio between modulation depth and insertion loss, which can be an index...
of the fundamental limits of the modulator. The FOM can be calculated as:

\[ FOM = \frac{\Delta \alpha}{\alpha}. \] (8)

The fundamental limit of the modulator is a relation between insertion loss and modulation depth, as described in reference [61].

2. The graphene modulators part I: research trend of FOMs

2.1. Examples of graphene modulators

The first graphene-based modulator was reported in 2011 [4], where monolayer graphene is coated on the semiconductor wafer, as shown in figure 2(a). The voltage is applied between graphene and the Si. The Al$_2$O$_3$ layer is acting as the insulator. For the low thickness of Al$_2$O$_3$ (only 7 nm), the applied voltage on this modulator is very low, which is in the scale of $-5 \text{ V to } 5 \text{ V}$. The footprint of this modulator is 25 $\mu$m$^2$, where the interaction length is 40 $\mu$m. The transmission is measured as a function of the drive voltage, as shown in figure 2(c). The physics of this modulator is to switch the interband transition threshold. Based on their measurement results, the normalized modulation depth can be 0.1 dB $\mu$m$^{-1}$.

The 3D transmission spectrum as functions of drive voltage and operating wavelength is further obtained, which shows a sharper change of transmission at the threshold points as seen red dashed line in figure 2(d). For this modulator, the highest modulation speed is only 1.2 GHz which is caused by the high contact resistance and graphene sheet resistance. Another problem is the low light-graphene interaction for the highest field amplitude is not happening at the position of graphene, as clear from figure 2(b).

This modulator can also be used as a Mach–Zehnder modulator, as reported in [5]. In this work, the authors found the real part of the mode index has a significant change as a function of the chemical potential. The variation of the real part of the mode index ($\Delta N_{\text{eff}}$) can be about 0.015, which is very good for the Mach–Zehnder modulator.

As shown in figure 3, two arms of the waveguides are used in the Mach–Zehnder modulator, one arm is biased by a fixed voltage to make the chemical potential of graphene fixed at 0.4 eV, and the other arm is biased by a changeable voltage (chemical potential). The transmission of this modulator will depend on the chemical potential of the modulation arm, and can be calculated as [5]:

\[ T(\Delta \mu_c) = \frac{1}{4} \times [\exp(-\alpha_0 L) + \exp(-\alpha_1 L) + 2 \exp(-\frac{\alpha_0 L + \alpha_1 L}{2}) \cos(\Delta \phi)], \] (9)

where $\Delta \phi = \frac{2\pi}{\lambda} \Delta N_{\text{eff}} L$, and $\alpha_0$ and $\alpha_1$ is the mode power attenuation (MPA) of the reference arm and the modulation arm, respectively. The problem of this modulator is that the footprint is very large, and $\Delta N_{\text{eff}}$ is still very low.
A higher modulation speed is reported in [7] at 150 GHz where one bus and one ring waveguide are used to couple with each other.

The double graphene layers are coated on the ring waveguide as shown in figure 4(b) and detailed in figure 5(a). Due to the lossy nature of the ring waveguide during the interband transition of graphene, much less mode power will be coupled to the ring waveguide and hence transmittance in the bus waveguide will be very high. Otherwise, if only the intraband transition takes place, the ring waveguide will be transparent, and much more mode power will be coupled to the ring waveguide which makes the transmittance in the bus waveguide very low.

In the fabrication, a very thick (65 nm) Al$_2$O$_3$ layer is deposited between two graphene layers, and the voltage is applied between these two graphene layers. The capacitance of this modulator is very small due to the very thick insulator, which enhances the modulation speed (30 GHz realized bandwidth and 150 GHz possible speed). However, the applied voltage should be much higher (up to 50 V) because of the thicker insulator, which shows lower modulation efficiency. Therefore, the contradiction between modulation speed and modulation efficiency shows a challenge.

The high-$\kappa$ dielectric material has been used as an insulator in the sub-wavelength thickness graphene modulator [17], as shown in figure 6.
In this work, a very thick high-κ gate material (Ta₂O₅) acts as an insulator between the upper graphene layer and the low metal electrode, for perpendicular incidence (the wavelength is \( \lambda = 1.55 \mu m \)). The metal electrode also acts as a reflector. The modulation is enabled by the interband transition of graphene, as clear from the band structure in figure 6.

The thickness of the insulator is very high (~225 nm), however, the modulation area is also very large. Therefore, the modulation speed is limited to 100 MHz. Moreover, the light-graphene interaction is extremely low because the interaction length is only two of the thickness of the monolayer graphene, which makes the modulation depth very low (on the scale of ~4%).

The first THz graphene transmission modulator [15] is fabricated using single-layer graphene-coated on the top of the SiO₂/p-Si substrate shown in figure 7(a). The conductivity is measured as a function of applied voltage, as shown in figure 7(c). As the voltage increases, the conductivity decreases, which says the Dirac point happens at a higher voltage, and 50 V is closer to the Dirac point.

Figure 7(b) is the multiple-layer THz graphene modulator with several graphene pairs, which was not demonstrated by [15]. In the pairs of graphene, if one is n-doped, the other one will be p-doped, as shown in the band structure. When the graphene is at the Dirac point, the density of state (DOS) for the interband transition is extremely low. The photon energy of THz wave is very low, so the interband transition can only happen near the Dirac point. In this way, the intraband transition will dominate the absorption mechanism. However, at the Dirac point, there is also no DOS for the intraband transition. The transmittance will be very high when the graphene layers are at the Dirac point. When the graphene layers are biased to be away from the Dirac point, the intraband transition will take place and the absorption will be larger to make the transmittance lower. Therefore, the THz graphene modulator is enabled by the intraband transition of graphene.

Figures 7(d) and (e) show that the transmittance is higher at 50 V than at 0 V. And there shows a modulation depth of ~15%. Due to the very high natural doping of graphene from the substrate, the Dirac point happens at 50 V instead of 0 V.

Another THz modulator was demonstrated by the same group, in [16]. This modulator is based on reflection, as shown in figure 8.

Monolayer graphene is coated on the SiO₂/p-Si substrate with a metal mirror at the bottom, as clear from figure 8(a). The bottom metal mirror acts both as an electrode and a reflector. The THz wave incidents at the perpendicular direction of the modulator and interact with the monolayer graphene. The modulation is also enabled by the intraband transition. However, due to the Fabry–Perot etalon, the light-graphene interaction is much higher at the resonance thickness of the substrate, as clear from figure 8(b), which shows a modulation depth of 95%. The power of the mode is the peak at the position of graphene at the resonance condition. However, the very high
Fig. 7. THz graphene modulator based on transmission. Reprinted by permission from Springer Nature: Nature Communications [15] (2012). (a) The structure of single-layer graphene; (b) is the multiple-layer graphene and the band structure of different states; (c) is the measured conductivity of graphene as a function of applied voltage; (d) is the measured transmittance as a function of carrier THz wave frequency at different applied voltage 50 V (red) and 0 V (blue); (e) is the corresponding transmittance when the substrate effect is removed.

Fig. 8. (a) Structure of the THz reflection modulator; (b) calculated power reflectance of the modulator as a function of the substrate optical thickness; (c) measured normalized modulation amplitude as a function of modulation frequency. Reprinted with permission from [16]. Copyright (2012) American Chemical Society.

The capacitance of the modulator makes the modulation speed of the THz modulator very low, about 4 kHz [16] as shown in figure 8(c) and 20 kHz [15]. The reason for this high capacitance is the large footprint of this modulator.

2.2. State of the arts of graphene modulators (part I)

To analyze the start of the arts of graphene modulators, twenty-five references [1–25] have been studied for the first time published in the years from 2004 to 2016, including electro-optical modulators, all-optical modulators [11–13], THz modulators [15, 16], and Mach–Zehnder modulators [1, 5, 10]. State-of-the-art values of all those modulators are recorded in table 1 in terms of modulation depth, modulation speed, footprint, modulation bandwidth, operation bandwidth, and insertion loss. These references are very selective and representative for this part I which was finished before 2016, since they contribute good results for FOMs research trend analysis.

2.3. Supplementary information of table 1

(a) Liu et al [1–3] are silicon modulators which are for comparison; [4, 6–9, 14, 17–25] are electro-optical graphene modulators; [11–13] are all-optical graphene modulators; [15, 16] are THz graphene modulators; [5, 10] are Mach–Zehnder graphene modulators.
Table 1. State-of-the-art values of graphene modulator (part I).

| Reference, and year | Where | If measured | Operation frequency | Modulation depth | Modulation speed | Footprint | Modulation bandwidth | Operation bandwidth | Insertion loss |
|---------------------|-------|-------------|--------------------|------------------|------------------|-----------|--------------------|--------------------|--------------|
| [1], 2004           | Nature| yes         | 1.55 μm            | Maximized        | 1 GHz            | 0.03 mm²  | 1 GHz              |                    | 15.3 dB       |
| [2], 2005           | Nature| yes         | 1.5 μm             | 15 dB            | 60 GHz           | 5.4 μm²   | 60 GHz             |                    | 16 dB         |
| [3], 2011           | OE    | yes         | 1.55 μm            | 10 dB            | 1.2 GHz          | 60 μm²    | 120 GHz            |                    | 2.5 dB        |
| [4], 2011           | Nature| yes         | 1.53 μm            | 4 dB             | 1 GHz            | 2.5 μm²   | 1 GHz              |                    | 34.7 THz       |
| [5], 2012           | NL    | yes         | 1.537 μm           | 6.4 dB           | 1 GHz            | 80 μm²    | 1 GHz              |                    | 10 dB         |
| [6], 2012           | APL   | no          | 1.55 μm            | 5.2 dB           | 100 μm²          | 1 MHz     | 100 GHz            |                    | 0.3 dB        |
| [7], 2012           | OE    | yes         | 1.55 μm            | 7 DB             | 120 GHz          | 60 μm²    | 120 GHz            |                    | 2.5 dB        |
| [8], 2012           | OE    | yes         | 1.55 μm            | 3 DB             | 100 GHz          | 0.07 μm²  | 100 GHz            |                    | 3 dB          |
| [9], 2012           | OE    | yes         | 1.55 μm            | 0.2 DB           | 0.1 GHz          | 10 mm²    | 0.1 GHz            |                    | 0.3 dB        |
| [10], 2012          | Nature C| yes       | 0.6 THz            | 0.8 dB           | 20 kHz           | 2.25 cm²  | 20 kHz             | 100 GHz           | 0.2 dB        |
| [11], 2012          | NL    | yes         | 0.63 THz           | 4.4 dB           | 4 kHz            | 1 cm²     | 4 kHz              | 60 GHz            | 2 dB          |
| [12], 2012          | OE    | no          | 1.55 μm            | 30 DB            | 10 μm²           | 100 GHz   | 100 GHz            |                    | 0.5 dB        |
| [13], 2012          | APL   | no          | 1.55 μm            | 35 DB            | Fast             | 120 μm²   | larger             |                    |              |
| [14], 2013          | LPL   | yes         | 1.06 μm            | 13 DB            | 1 MHz            | 100 μm²   | 1 MHz              | 13.35 THz         | 0.1 dB        |
| [15], 2013          | NanoT | yes         | 1.55 μm            | 16.8 DB          | 0.045 μm²        | 15 THz    | 13.5 dB            |                    |              |
| [16], 2013          | NL    | yes         | 1.57 μm            | 10 DB            | 1 GHz            | 0.5 μm²   | 300 GHz            |                    | 1.3 dB        |
| [17], 2013          | OE    | no          | 1.55 μm            | 34 DB            | 100 GHz          | 5 μm²     | 100 GHz            |                    |              |
| [18], 2014          | OE    | yes         | 1.55 μm            | 16 DB            | 0.67 GHz         | 0.67 GHz  | 225 THz            |                    | 3.3 dB        |
| [19], 2014          | APL   | no          | 40 THz             | 10 DB            | 15 THz           |          |                    |                    |              |
| [20], 2014          | NL    | yes         | 1.55 μm            | 4.4 DB           | 4 GHz            | 90 μm²    | 3 GHz              | 500 GHz           |              |
| [21], 2014          | NL    | yes         | 1.55 μm            | 2.1 DB           | 200 GHz          | 28 μm²    | 200 GHz            |                    |              |
| [22], 2014          | LPR   | no          | 40 THz             | 21.5 DB          | 15 THz           |          |                    |                    |              |
| [23], 2015          | Nature P| yes      | 1.55 μm            | 28 DB            | 150 GHz          | 45 μm²    | 30 GHz             |                    |              |
| [24], 2015          | NL    | yes         | 1.55 μm            | 3.2 DB           | 1.2 GHz          | 0.5 μm²   | 1.2 GHz            | 600 GHz           |              |
| [25], 2016          | Optica| yes         | 1.55 μm            | 3 DB             | 200 GHz          | 15 μm²    | 200 GHz            | 73.5 THz          |              |

1. The references are recorded in the order as the paper publishing year increases (2004 to 2016).
2. The quality factor of a modulator is defined as $Q = \frac{\lambda}{\Delta \lambda}$, where $\lambda$ is the operation wavelength and $\Delta \lambda$ is operation bandwidth. The $Q$ factor in [1] is 39 350. This is not recorded in the table.
3. The modulation efficiency of the Mach–Zehnder modulator is defined as $\eta = \frac{V}{\pi L}$, where $V$ is an applied voltage which should be enough for the $\pi$-phase shift, $L$ is the interaction length of the two arms of Mach–Zehnder modulator [1, 5, 10]. When the applied voltage for the $\pi$-phase shift is smaller and the interaction length is lower, the modulation efficiency should be higher, for low energy consumption, and low insertion loss. This is not recorded in the table.
4. The figure of merit $\Delta \alpha$ is not recorded in the table, but the insertion loss $\alpha$ is recorded.
5. The modulation controls the modulation depth: when the interaction length is larger, the modulation depth should be higher. The modulation depth is also called a modulation index or extinction ratio.
6. The footprint of the THz modulator is much larger due to the diffraction limit of the THz wave.
7. Larger the electric field at the graphene, larger will be the modulation depth and this phenomenon is related to light–matter interaction.
8. The insertion loss is an important parameter of the modulator.
9. (j) 10. The smaller footprint ensures the lower applied voltage, the higher the modulation speed, and the lower energy consumption.

2.4. The results from table 1

(a) The number of papers published in each year is plotted as a function of the year, as shown in figure 9(a). Silicon modulators were reported in 2004 [1] and 2005 [2] respectively. It is worthwhile to note that graphene is firstly fabricated in 2004 while the graphene modulator was reported for the first time in 2011. The reason for mentioning [1] and [2] from 2004 and 2005, respectively is to show the research delay and time gap between the graphene fabrication and the first reported graphene modulator.

It has been noted that research on graphene modulator was on the peak from 2012 to 2014, (8 references) were published in 2012, (4 references) in 2013, and (6 references) in 2014. However, the trend decreased from 2014 to 2016, which may show that the research on graphene modulator became less as the research problems on graphene modulators may be less. However, there are still some problems need to be solved, and new structures of graphene modulator are demanded.
silicon modulator is included), and Applied Physics Letters (three references). The number of papers as a function of different journals is shown in figure 9(b). All these are high impact factor (above three) journals.

(c) The number of papers as a function of if measured is shown in figure 9(c). Most of the papers (16 references) are measured while only nine papers are pure theory research. More theory researches on this topic should be done to balance the number of papers.

(d) Most of the papers are focusing on the optical modulator which operating at wavelength $\lambda = 1.55$ $\mu$m. Only two papers are about the THz graphene modulator at this stage.

(e) The modulation depth as a function of paper number is shown in figure 10(a). The paper number is in the order of paper published year increasing. The vertical line in the left down corner of figure 10(a) is the boundary line to separate Si modulator from the graphene modulator. It can be noted in figure 10(a), the modulation depth of the graphene modulator was lower than that of the tradition Si-based modulator in the year 2011. However, it increased as the year passed, and can be much higher than that of Si-based modulator. The highest modulation depth of the graphene-based modulator was first increasing then decreasing as the year passed. The highest value happened in the year of 2013 [10], which was 35 dB. Moreover, there was no 100% modulation depth recorded at this stage.

(f) Figure 10(b) shows the modulation speed (modulation bandwidth) as a function of the paper number (in the order of the publishing year). It can be seen that the highest modulation speed was increasing with the passing of years. The modulation speed of the graphene-based modulator can be much higher than that of the Si-based modulator. The highest value can be 200 GHz (a not realized possible value). The theory value is 150 GHz, which happened in 2015 [7]. As clear from figure 10(b), there are five much lower values for the modulation speed, where two values are from graphene THz modulators. The very high modulation speed is caused by the high mobility of graphene which makes the total resistance very low, and hence the small footprint which makes the capacitance of the modulator very low.

(g) The footprint of the graphene-based modulator can be very small. The smallest can be $\sim0.054$ $\mu$m$^2$ reported in 2013 [14]. The footprint (the large sizes of Si-based modulator and THz modulator are not included) as a function of the paper number is shown in figure 10(c). We can see all the sizes of graphene optical modulator are on the scale of $\mu$m$^2$. The highest values also decreased with the passing of time.

(h) The operation bandwidth of the graphene-based modulator can be very high $\sim73.5$ THz [13] as shown in figure 10(d). Most values are around 15 THz, indicating that many channels of carrier waves can be processed in these modulators. This is because of the broadband high tunable absorption loss of graphene.

(i) In figure 10(e), it is noted that the insertion loss of the graphene modulator can be much lower than that of the Si-based modulator. Most of the values are below 4 dB, and the lowest insertion loss can be 0.1 dB [11] in 2013. However, for most of the cases, the insertion loss is large, and the lowest value can still be improved.

2.5. Challenges and problems for graphene modulators

The challenges and problems for the research gap of graphene modulator are clearly shown as discussed above. Research topics can come from to address these challenges and problems as listed below.

(a) The light-graphene interaction remains low for most of the cases of graphene modulators. If the light-graphene interaction is enhanced, all the FOMs of the graphene modulator will be improved.

(b) There is a contradiction between modulation speed and modulation efficiency. If the modulation speed is enhanced, the modulation efficiency will be lost. Researchers can have other designs of the graphene modulator to reduce this contradiction.

(c) The insertion loss is still very large for most of the cases.

(d) The energy consumption is still very high.

(e) The modulation speed is highly limited because of the high contact resistance between the electrode and graphene, and
Figure 10. Modulation depth (a) and modulation speed (b) as a function of paper number in the order of publishing time increases (the first two data are from the Si-based modulator). (c) Footprint of graphene modulator as a function of the paper number in the order of published time increases (only the footprints of optical graphene modulators are considered). (d) Operation bandwidth as a function of the paper number (only the graphene modulators are considered). (e) Insertion loss of modulators as a function of the paper number (the first two values are from Si-based modulators).

(f) For the graphene Mach–Zehnder modulator, the variance of the real part of the mode index is still very low. The highest value is only 0.028 in [10], which makes the \( \pi \)-phase shift arm length very high, and it can only be 27.57 \( \mu m \) [10].

(g) The 100% modulation still needs to be realized, even though there may be some works that have realized it.

(h) The FOM of the graphene modulator is still low, \( \sim 72 \) [14], and still needs to be improved.

3. Review of graphene modulators part II: addressing higher FOMs

3.1. Graphene modulators (part II)

To the best of our knowledge, the first suspended graphene modulator is reported by [26]. The structure is shown in figure 11.

A big part of the structure is suspended in the air, the slot is between two top silicon waveguides. The monolayer graphene is transferred to the top of the slot. In our opinion, this structure is complex and hard to fabricate. The mode is confined in the slot, the light-graphene interaction is a function of the slot width.

When the slot width is lower, the light intensity is larger but the interaction area between the graphene layer and propagating light will be lower. When the slot width is larger, the interaction area will be larger, however, the light intensity is lower. Therefore, there is a tradeoff between light intensity and interaction area to enhance the light-graphene interaction. Even though the light-graphene interaction is larger than the rib waveguide, it is still very low.

The change of wave vector \( k \) and optical loss of slot waveguide are much larger than those of rib waveguide [26]. The change of wave vector \( k \) of slot waveguide can be 0.0653 \( \mu m^{-1} \), namely, it is only 0.0161 for the change of refractive index (\( \Delta N_{eff} \)), which is still a very low value.

Two arms of this slot waveguides were used to form a M–Z modulator and the normalized transmission as a function of the applied voltage was calculated by using equation (9) and is shown in figure 12.

Experimental verification of electro-refractive phase graphene modulation was reported in 2015 [27] and the fabricated device structure is shown in figure 13.
Figure 11. Schematic of the (graphene-on-silicon) GoS-suspended vertical slot waveguide. (a) Three-dimensional view. (b) Cross-sectional view. Reproduced from [26]. © IOP Publishing Ltd. All rights reserved.

Figure 12. M–Z modulators based on the GoS slot waveguide. Reproduced from [26]. © IOP Publishing Ltd. All rights reserved.

Figure 13. Graphene based electro-refractive phase modulator. Reproduced from [27]. CC BY 4.0.

Two kinds of graphene waveguides are formed as two arms of the Mach–Zehnder interferometer (MZI): one is the self-biased double graphene layer waveguide as the modulation arm, the other is a not-biased single graphene layer waveguide as the reference arm. The relative difference between the lengths of two MZI arms is 91 µm. TE-polarized light was coupled in by using grating couplers optimized for 1530–1570 nm. The authors measured the transmission at a different stage of the fabrication and the change of effective refractive index (∆N_{eff}) of the mode.
Figure 14. Simulation results: (a) mode field, (b) $N_{\text{eff}}$ and absorption of the modulator as a function of chemical potential of graphene. Reproduced from [27]. CC BY 4.0.

Figure 15. (a) Optical micrograph of the MZI modulator. (b) Cross-section of the GPM in the section A–A' of (a). Reprinted by permission from Springer Nature: Nature Photonics [28] (2018).

The waveguide structure was also simulated and shown in figure 14.

It can be seen that the graphene layer is located in the evanescent field of the Si waveguide and it is far away from the mode amplitude center. The chemical potential of each graphene layer is changed electro-statically by biasing the two graphene sheets with respect to each other. Therefore, the effective refractive index of the modulation MZI arm is changed which causes a shift in phases of each light beam in the MZI arms.

In figure 14(b), for this case of structure, the light-graphene interaction is very low and both the change of effective refractive index ($\Delta N_{\text{eff}}$) and the change of the absorption are still very low, which will cause very long $\pi$-phase shift length for electro-refractive modulation and low modulation efficiency for electro-absorption modulation.

Figure 15 shows another graphene phase modulator (GPM) which is reported in 2017 [28]. This is a compact device with a phase-shifter length of only 300 $\mu$m and a 35 dB extinction ratio. The GPM has modulation efficiency of 0.28 Vcm which is one order of magnitude larger than the state-of-the-art value in p-n junction Si phase modulators. The structure of each arm is a single graphene layer put on the silicon wafer. Even though their refractive index change is much larger than that in Si phase modulators, it is still a very low value because of very low light-graphene interaction, and a better graphene phase modulator with higher refractive index change is still demanded and not reported before this research.

In [29], a tunable graphene-based hybrid plasmonic modulator was reported for subwavelength confinement. There have two structures: one is an asymmetrical structure, as shown below in figure 16.

A silver cylindrical nanowire is put above a silicon-graphene-silica waveguide at a distance $h$, calling it as ‘graphene-based hybrid plasmonic modulator (GHPM)’. The mode field was simulated and it was found that the transmission energy is confined in the small dielectric gap. This hybrid mode can enhance light-graphene interaction. The modulation depth is a tradeoff between the mode field intensity and the distance of the graphene layer to the center of the mode field. However, from our point of view, there is a problem with their biasing of graphene. In order to further enhance the light-graphene interaction, a symmetrical structure was simulated as shown in figure 17.
structures are connected to the ground electrode. Due to this electrode, and the remaining two graphene layers in the two GOG layer in the upper GOG are connected to the signal electrode. The symmetrical structure of the four-layer configuration is shown in figure 16. This symmetrical structure can further enhance the light-graphene interaction.

A multilayer graphene electro-absorption optical modulator based on double-stripe silicon nitride waveguide was reported in [29]. Both graphene double-layer and four-layer structures were investigated, as shown in figure 18.

Before this research, almost all the presented Si$_3$N$_4$/graphene modulators are based on the single stripe Si$_3$N$_4$ waveguide. Comparing to the single stripe Si$_3$N$_4$ waveguide, double-stripe Si$_3$N$_4$ waveguide will have much more symmetrical mode field distribution and lower polarization dependence. Therefore, the light-graphene interaction will be enhanced.

The light-graphene interaction is much higher for TE mode and four-layer structure than TM mode and double-layer structure. This is due to the higher absorption of TE mode and the symmetrical structure of the four-layer configuration.

One graphene layer in the lower GOG and one graphene layer in the upper GOG are connected to the signal electrode, and the remaining two graphene layers in the two GOG structures are connected to the ground electrode. Due to this graphene layers co-electrode design, the series resistance of the modulator is reduced by 50%.

3.2. State of the arts of graphene modulators (part II)

The latest references focusing on graphene modulators are studied in this review as in part II and their start-of-the-art values of every FOM are tabulated in table 2. For this part, the references are supplementary. Since we cannot consider all the related references in the literature, this part II is not used for research trend analysis but just for addressing how the higher FOMs happen as a comprehensive research in the updated values.

As clear from the table, thirty-two articles [26–57] about graphene modulators are studied. The order of the references is strictly in the order of published year from 2012 to 2018. Among these [37, 48, 55], are about the all-optical graphene modulator [32], is about the magneto-optical graphene modulator, and electro-optic graphene modulator is reported in the remaining articles [31, 32, 37, 44, 50], are about THz graphene modulator; The operation (carrier) wavelengths of the rest references are at 1.55 µm.

The modulation depths can be 100% by [42]. For this 100% modulation, it is an optical reflection modulation using surface plasmon resonance in a graphene-embedded hybrid plasmonic waveguide. Their structure is shown in figure 19. In this modulator, when the light passes through the prism, it is totally reflected at the prism-Å interface and generates an evanescent wave. When the propagation constants of the evanescent wave and the hybrid plasmonic mode are matched, the evanescent wave couples to the hybrid plasmonic mode, resulting in a reflection dip at the incident angle for which the matching condition is satisfied.

The highest modulation speed is 1 THz reported in [36], and 850 GHz according to [34]. The footprint can be as low as 0.01 µm$^2$ [36]. The modulator structure presented in [36] is shown in figure 20. This is an ultra-compact optical modulator based on graphene-silica metamaterial. In figure 20, the carrier light is input from the left port of the multilayer graphene metamaterial, and output on the right side of the thin modulator. The carrier wave is squeezed and tunneled through the metamaterial channel. This device is sealed with a perfect electric conductor (PEC) wall for avoiding the leakage of the light energy. The thickness of the graphene-silica metamaterial is only 0.015 µm and with a height of 0.68 µm, which makes a footprint of only 0.01 µm$^2$. The extremely high carrier mobility ensures the resistance of this modulator to be very small. Meanwhile, the small device area also leads to a tiny capacitance $C$ (less than 0.1 fF). Thus, this modulator is estimated to have a modulation speed of more than 1 THz.

The state-of-the-art value of insertion loss is still very high. The lowest one is 6% reported in [42]. In this case which is shown in figure 19(a), the insertion loss is lower as the number of graphene layers is increased. This is caused by two factors: the increased resonant angle shift, and the lower loss of the hybrid plasmonic mode for $E_F = 0.6$ eV, owing to the reduced silver ($A_g$) thickness. In our opinion, this lower insertion loss can still be reduced significantly further.

In this case, two silver cylindrical nanowires were placed symmetrically on both sides of the silicon-graphene-silicon waveguide. It was called as ‘symmetrical graphene-based hybrid plasmonic modulator (SGHPM)’. One can easily find tighter modes confinement than which is shown in figure 16. This symmetrical structure can further enhance the light-graphene interaction.

![Figure 16. Structure and mode distributions of the designed GHPM. Reproduced from [29]. CC BY 4.0.](image1)

![Figure 17. Structure and mode distributions of SGHPM Reproduced from [29]. CC BY 4.0.](image2)
Figure 18. (a) Cross section of the double-stripe Si$_3$N$_4$ waveguide. (b) Graphene-on-graphene (GOG) structure. (c) Double graphene layers configuration. (d) Four graphene layers configuration. Reproduced with permission from [30].

Figure 19. (a) Schematic of the graphene-based optical modulator. Electric field distributions of the one-dimensional structure composed of Ag-SiO$_2$-graphene-Si-SiO$_2$ for (b) $E_F = 0.5$ eV, and (c) $E_F = 0.6$ eV. Reproduced with permission from [42].

The latest ultra-high-speed graphene optical modulator design based on tight field confinement in a slot waveguide is presented in [56] and the structure is shown below in figure 21.

In this work, the overlap of the two graphene sheets is suspended in the air slot. The partial graphene electrode overlap over the waveguide reduces the effective width of the capacitor and consequently, capacitance is reduced by more than one order of magnitude. The modulation speed is very high with lower overlap width, and it can be more than 800 GHz with the compromise of lower light-graphene interaction. The authors find when the overlap width is at 50 nm, the light-graphene interaction is enhanced to its maximum and the modulation speed can be 120 GHz. At this point, the contradiction between modulation speed and modulation efficiency is reduced significantly.

4. Suspended graphene modulators

In order to solve these problems and challenges in this field mentioned above, recently, three kinds of suspended graphene modulators [58–60] are reported. The suspended self-biasing graphene modulator has been designed very near to the fundamental limits of graphene [58]. For the suspended triple-layer graphene modulator, the light-graphene interaction is
layers. Reproduced with permission from [55].

Figure 20. (a) Multilayer graphene metamaterial modulator structure; (b) Metamaterial consists of graphene sheets and silica layers. Reproduced with permission from [36].

Table 2. State-of-the-art value of graphene modulator (part II).

| Reference, and year | Where | If measured | Operation f or λ | Modulation depth | Modulation speed | Footprint | Modulation bandwidth | Operation bandwidth | Insertion loss |
|---------------------|-------|-------------|------------------|------------------|------------------|-----------|---------------------|-------------------|---------------|
| [31], 2012          | ACS Nano | yes | 0.2–2 THz | 99% | | | 1.8 THz | | |
| [32], 2013          | PCCP | no | 0–14 THz | 15.7% | | | 14 THz | | |
| [33], 2013          | Nano Lett. | yes | 450 nm–2 μm | 35% | | | Broadband | | |
| [34], 2013          | Sci. Reports | no | 0.8–1.9 μm | 3 dB | 850 GHz | 0.7 μm | 850 GHz | 0.8–1.9 μm | |
| [35], 2014          | Nano Lett. | yes | 1.5 μm | 40% | 80 GHz | | 80 GHz | | |
| [36], 2014          | Opt. Lett. | no | 1.5 μm | 9.5 dB | 1 THz | 0.01 μm² | | 14–17 μm | – 0.27 dB |
| [37], 2014          | Sci. Reports | yes | 0.25–1THz | 94% | 200 KHz | 5 mm | 200 kHz | 0.75 THz | |
| [38], 2015          | Nanoscale | yes | 1.5 μm | 7 dB | | 10 μm² | | 6.2 nm | |
| [39], 2015          | Nature C | yes | 1.5 μm | 50% | 100 GHz | | | |
| [40], 2015          | OE | no | 1.5 μm | 12.5 dB | 133 GHz | 20 μm² | | 125.6 nm | |
| [41], 2015          | OE | yes | 1.5 μm | 2.5% | 2.5 MHz | | 2.5 MHz | | 10% |
| [42], 2015          | Opt. Lett. | no | 1.5 μm | 100% | | | | | 6% |
| [43], 2015          | J. Phys. D: Sci. Reports | no | 1.5 μm | 3 dB | | | 120 nm | | 62 THz |
| [44], 2015          | small | no | 0-10THz | 76% | 91 kHz | | | | 0.568 THz | 17% |
| [47], 2015          | Sci. Reports | yes | 1.5 μm | 22.5 dB | | | | | 2 dB |
| [45], 2015          | Nanotech | yes | 1.5 μm | 17.7 dB | 1.7 GHz | 1.3 μm² | | | |
| [46], 2016          | ACS Photonics | yes | 1.5 μm | 2 DB | 35 GHz | | | 35 GHz | 1.5–1.64 μm |
| [47], 2016          | Opt. Lett. | yes | 1.5 μm | 3 dB | | | 100 μm | | To 8.0 μm |
| [48], 2016          | Sci. Reports | yes | 1.5 μm | 9 dB | 0.5 THz | | | 0.5 THz | | 1 dB |
| [29], 2017          | Sci. Reports | no | 1.5 μm | 3 dB | 1.3 GHz | | 1.3 GHz | | |
| [49], 2017          | IEEE | yes | 1.5 μm | 5 dB | 2.5 GHz | | 2.5 GHz | | |
| [50], 2017          | Nanoscale | yes | 0.6–1.6 THz | 15% | | | | | 1 THz |
| [51], 2017          | OE | yes | 1.5 μm | 3% | 5 μm² | 5 μm² | | 900 nm–1.5 μm | 10% |
| [52], 2017          | OE | yes | 1.5 μm | 4.5 dB | 5 GHz | | 5 GHz | | 5 dB |
| [53], 2017          | OE | no | 1.5 μm | 3 dB | 30.6 GHz | | 50.48 μm | | 30 GHz |
| [54], 2017          | Opt. Lett. | yes | 1.5 μm | 1 dB | | | | | 30 dB |
| [55], 2018          | Opt. Lett. | yes | 1.5 μm | 3 dB | 0.48 THz | 3.6 μm² | 0.48 THz | | 0.32 dB |
| [56], 2018          | Nature P | yes | 1.5 μm | 35 dB | 5 GHz | | 300 μm | 5 GHz | |
| [57], 2018          | Appl.Phys. E | no | 1.5 μm | 3 dB | 120 GHz | | 120 GHz | | 1.5 dB |
| [58], 2018          | Sci. Reports | yes | 1.5 μm | 3 dB | | 40 μm | | 15 nm | |

Figure 21. (a) Three-dimensional schematic of the slot modulator design with the device length parameter L (not in scale). (b) Cross-section of the device with the equivalent RC circuit. (c) Mode profile of the device. Reproduced from [56]. © IOP Publishing Ltd. All rights reserved.
enhanced further with the lower contradiction between modulation speed and modulation efficiency [59]. A comparison between suspended double-layer graphene modulator and sub-wavelength graphene modulator shows a better quality of suspended modulator [60]. All the suspended graphene modulators are designed very near to the fundamental limits of graphene modulator [61].

By suspending the graphene sheets for these modulators, at least three distinctive advantages can be achieved: (i) The structure can be design-free for the middle silicon slab or insulator slab acting as a bus waveguide to confine the mode. If the right thickness of the middle slab is adopted, the light-graphene interaction can be enhanced to its maximum; (ii) The modulator can be very clean and can achieve high-quality devices. Moreover, the channel mobility reduction caused by graphene-dielectric interaction will be lower, and the graphene can achieve higher mobility; (iii) The modes in this structure will be totally symmetrical, so the insertion loss can be much lower, and the two graphene layers will be always under the same ambient, the doping degree can always be the same.

4.1. Suspended self-biasing graphene modulator [58]

The structure is shown in figure 22(a). For this modulator, two graphene sheets are sandwiched by a thick insulator and biased by each other. The possible way to fabricate this device is also shown in figures 22(c–f). The light-graphene interaction is enhanced significantly by this symmetrical structure. The insertion loss of this modulator is very low for the suspended symmetrical structure.

The electro-absorption modulation shows a FOM of 2076. The electro-refractive modulation shows one 100% modulation depth. The contradiction between modulation speed and modulation efficiency is reduced significantly and this design is very near the fundamental limits of graphene.

4.2. Suspended triple-layer graphene modulator [59]

The suspended triple-layer graphene modulator shows two modulation depths and high modulation speed. The three graphene layers are sandwiched by two insulator slabs, and the middle graphene layer is biased by the two side graphene layers. The structure and equivalent circuit are shown in figure 23. A possible way to fabricate this modulator is shown in figure 24.

These two modulation depths are caused by the two side graphene layers and the middle graphene layer separately. The light-graphene interaction is enhanced further for the middle graphene layer is always put in the mode centre where the
mode energy peak is always there. As the modulation performance of this modulator, the FOM of electro-absorption modulation can also be as high as 2105. There show several 100% modulations for electro-refractive modulation. The modulation speed can be 759.85 GHz with very low applied voltage and very low energy consumption. And the contradiction between modulation speed and modulation efficiency is reduced further.

4.3. Graphene suspended double-layer modulator (SDM) and sub-wavelength thickness modulator (STM) [60]

A comparison between suspended double-layer graphene modulator and sub-wavelength thickness graphene modulator was done by [60]. The structures for these two modulators and the possible way to fabricate the SDM are shown in figure 25. A leaky mode in the sub-wavelength thickness graphene modulator is found which should be avoided during the design process. The basic MPA for STM is very high, causing a very high insertion loss. The FOM of SDM can be ultrahigh (≈2480), however, for STM, it is only 1.28.

5. Review of modulators by other 2D materials

Other 2D materials such as transition metal dichalcogenides (TMDs) [62–87], h-BN [87–92], and Xenes [93–97] are important to fill the research gap of graphene. TMDs mainly include MoS$_2$ [66–80], WS$_2$ [81], and WSe$_2$ [82–86]; Xenes include phosphorene [93–95], and black phosphors (BP) [95–97]. These 2D materials are better than graphene in the applications of transistors [63, 66–69, 96], and even some cases of modulators [97].

5.1. The structures

The structures of these 2D materials are very simple and shown in figure 26. Graphene consists of a monolayer arrangement of carbon atoms in a hexagonal lattice, it is a real 2D material. Once before, the theory predicted that graphene should not be fabricated and realized to be in free space because of the unstable property may be caused by many factors such as thermal fusing. But the problem is overcome, and it is firstly fabricated by repeated peeling [98]. The structures are very...
similar to graphene for other 2D materials. The atoms of crystal are expanding in 2D. The TMDs consist of one transition metal atom sandwiched by two dichalcogenide atoms. h-BN is very like graphene, which is also called ‘white graphene’. For all kinds of Xenes, we will focus on BP. BP has a puckered layer structure, as seen in figure 27: n is the number of layers, the lattice constant is \(a_z\) which is equal to 1.07 nm (slightly larger than graphene).

Although the structures of other 2D materials are very simple, they were not discovered earlier. This is mainly because of: (1) the monolayer is in a very great minority; (2) 2D material crystals are not clearly seen in optical microscope on many substrates; (3) like graphene, they were not obvious to survive without the parent crystals [100].

5.2. Quantum physics
The absorption of photons by other 2D materials is controlled by two effects: (i) Quantum confined Franz-Keldysh effect
When the material is not doped, the Femi level is in the middle of the bandgap, as shown in figure 28(a). If the material is n-doped (figure 28(b)) or p-doped, the Femi level will move to the conducting band (n-doped) or valence band (p-doped) and the width of the bandgap will be narrower which causes the red-shift of the absorption edge. This is called as the QCFK. When the doping is very high, the Femi level will come to the conducting band (figure 28(c)) or the valence band.
band, which makes the bandgap wider. This is caused by that when the Femi level comes to the conducting band (n-doped, figure 28(c)), some lower states in the conducting band will have been filled, and the electrons should jump to higher states when they absorb photons. If the Femi level comes to the valence band (p-doped), some upper states in the valence band will have no electrons for the interband transition.

The conductivity of other 2D materials can also be calculated by the Kubo formula. In [97], the authors firstly calculated the conductivity of black phosphorus (BP), it is used to simulate a BP-based waveguide modulator which is shown in figure 29(a).

The monolayer BP is coated on the semiconductor wafer and capsuled by an aluminum oxide to protect the BP from degradation. The modulation depth of this modulator can be higher than that of the same waveguide made by graphene. According to the calculation in [97], the FOM is also slightly better with lower insertion loss. However, the mobility of other 2D material is much lower than graphene which causes the modulation speed lower than that of the graphene modulator. Also, their modulator operation bandwidth (the bandwidth of carrier waves) may be narrower due to the large bandgap [60].

6. Future perspectives and conclusions

6.1. Future perspectives

A modulator is frequently used in real applications. Before 2011, the traditional modulator was developed and investigated to very near the fundamental limits of the traditional materials such as silicon. Then graphene modulator was reported and subjected to extensive research in the following years. However, there are still a lot of challenges and problems, as mentioned earlier, to be studied in more detail.

The main purpose of researches on the graphene modulator is to develop a modulator closer to the fundamental limits of graphene. In some cases, higher light-graphene interaction can enhance the modulator closer to the fundamental limits of graphene. The condition is that the light interaction with other materials should be lower, so fewer materials in the fabrication of the graphene modulator can make the modulator better. In the cases of [16, 17], metal or other higher lossy materials are included in the active area, which definitely causes much higher insertion loss with lower modulation depth. For future perspectives, graphene and other 2D materials based modulators are analyzed to develop the higher FOMs.

6.1.1. Modulation depth. In [42], the modulation depth of electro-absorption modulation of graphene can be 100%. The higher coupling between different modes can enhance the modulation depth. In [16, 35], the resonant mode is used to enhance the modulation depth. By suspending the graphene structures [58–60], the modulation depth can be designed to the highest for these simpler structures with much fewer materials.

For future fabrications, the modulation depth of graphene modulators can be enhanced by (i) coupling between different modes; (ii) using resonant modes; (iii) suspending structures; (iv) designing for higher light-graphene interaction; (v) fabricating with fewer materials.

For electro-refractive modulation, the 100% modulations can be realized with a much lower π-phase shift length than that of silicon modulators. Higher light-graphene interaction can enhance the change of refractive index, which will cause even lower π-phase shift length. The π-phase shift length has been reduced to 11.3 μm by [59].

6.1.2. Modulation speed. The contradiction between modulation speed and modulation efficiency is always a problem that stops a better modulator. In order to get higher modulation speed, the capacitor of modulators should be lower, and the resistance caused by contact or graphene sheet should be lower. So higher modulation speed can be realized by (i) using thicker gate material; (ii) making the modulation area smaller; (iii) improving the mobilities of graphene by cleaning graphene sheets; (iv) lower the electrode-graphene contact area.

For the trade-off between modulation speed and modulation efficiency, methods (i) and (ii) may cause lower modulation efficiency. By designing the suspended graphene modulators [58–60], thicker gate material can be found which will enhance the light-graphene interaction simultaneously. In short, the suspended structures can be good candidates for future applications.

6.1.3. Footprint. For the graphene modulator, the footprint is much smaller than that of the traditional modulator which is because of much higher absorption of graphene with a small area. Different structures have different footprints. Higher light-graphene interaction can further enhance the footprint.

6.1.4. Operation bandwidth. Because of the broadband absorption of graphene, the operation bandwidth of the graphene modulator is always very high. Originally, the 3-dB bandwidth can be from visible light to near THz band. The waveguide-base modulator has very small wave-graphene interaction in THz ranges, so the 3-dB bandwidth may not reach THz ranges. The most interesting operation bandwidth for research is on a scale of 15 THz [14, 22].

6.1.5. Insertion loss. Fewer the materials in the modulator, much lower will be the insertion loss. The insertion loss of the suspended graphene modulator has been developed very near to the fundamental limits of graphene which is in the range of 0.002 dB [58–60].

6.2. Conclusions

In conclusion, a broad overview of graphene modulators has been presented, reviewing fifty-seven research articles published in the era of 2011 to 2019. Different types of graphene modulators are considered in this review, such as all-optical,
electro-absorption, electro-refractive, magneto-optical modulators, and THz modulators, among which electro-modulation is of great interest and studied intensively. For future research, the electro-optical modulator will show greater popularity.

Different structures are also included like mono-layer, double-layer, four-layer, and multi-layer graphene modulators, and suspended or slot graphene modulators or graphene-coated cylinder dielectric wires. Among these different structures, the suspended structures show great application prospects for much better FOMs.

For all kinds of graphene modulators, most are focusing on optical communication wavelength at 1.55 µm, and most are electro-optical modulators. All the figure of merits of the graphene modulators are much better than the traditional silicon modulators. In the first twenty-five references, state-of-the-art values have been addressed and the trend of research has been analyzed. The challenges and problems are also addressed. For the last thirty-five references about graphene modulators, we have addressed how the better FOMs happen and shown the near fundamental limits design.

These reported graphene modulators show how these are developed from low FOMs to high FOMs. The physics of other modulators, we have addressed how the better FOMs happen and shown the near fundamental limits design.

ORCID iDs

Siamak Sarjoghian https://orcid.org/0000-0002-5600-3820

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