# Calculations of spectral output of a novel graphene light source integrated with electrostatically actuated membrane

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**Abstract**—Calculations of spectral output of a graphene light source integrated with electrostatically actuated membrane were performed, taking into account the light source geometry and the deflection range of silicon membrane. Concept of miniaturized, tuneable light source operating in IR spectral range is presented. Maximum wavelength tuneability is discussed.

2D material-based light sources attracted considerable attention over the past decade, providing new functionalities that are difficult to achieve in the case of bulk materials [1]. Especially, the observation of bright visible light emission from electrically biased suspended graphene membranes [2, 3] paved the way for further research of graphene properties for optoelectronic applications. The emission wavelength of graphene's broadband hot carrier photoluminescence can be tuned by integration in photonic cavities, with out-of-plane heat transfer to hexagonal boron nitride [4]. Placing a near-field back-reflector layer behind multilayer graphene allowed for the demonstration of efficient mid-infrared emission [5]. Graphene thermal emitters were shown to be suitable for efficient coupling into silicon waveguides in photonic integrated circuits, which can be applied, e.g., in absorption spectroscopy systems for optical gas sensing [6].

Visible emission from a graphene membrane, though potentially interesting, creates some difficulties when it comes to practical realization. First of all, a considerably high membrane temperature, around 2700 K, is required, which increases the risk of device degradation. For this reason, stable operation of such a device is usually achieved in a vacuum [2]. From an applications point of view, however, it would be very interesting to develop a tunable source emitting in the IR. Such a source would operate at lower temperatures (compared to the visible light emitting one), which is beneficial as far as its reliability is concerned.

This Letter presents a concept of a tunable device based on thermal emission from graphene, integrated with an electrostatically actuated membrane. This concept stands out for its simplicity, miniaturized design, and wavelength tuning functionality. A prediction of the spectral output for such a source operating in the IR is given.

The concept of a novel tuneable light source is to combine the suspended graphene membrane and Micro-Electro-Mechanical Systems (MEMS) element in one integrated device [7]. MEMS play a significant role not only in scientific and industrial research, but also in many products used in everyday life [8, 9]. Interesting types of microsystems are devices based on membranes, where a thin layer of micrometer size is activated based on various physical mechanisms using electrostatic, thermal, or resistive phenomena [10].

Graphene membrane is suspended above a mirror membrane that is electrostatically positioned (Fig. 1), allowing its distance from the graphene layer $b$ to be precisely adjusted. In this way, the spectral output of the light source can be modulated due to the interference of the emitted and the reflected light by the electrically biased graphene. In order to enable an efficient operation in IR, the silicon membrane is covered with the reflecting layer (e.g., gold).

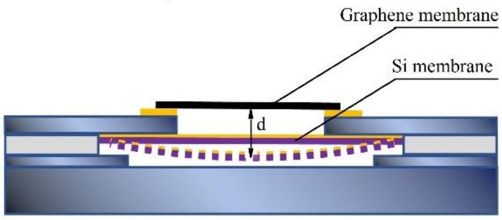


Fig. 1. Schematic of graphene light source integrated with electrostatically actuated Si membrane.

The emission spectra from graphene membrane deviate in the infrared from the well-known black-body radiation formula, and for the monolayer graphene can be written in the form [2]:

$$I_0(\omega) = \frac{\varepsilon\omega^3}{\left[exp\left(\frac{h\omega}{2k_BT}\right)+1\right]^2}, \tag{1}$$

where $\omega$ is the photon frequency, $\varepsilon$ is the emissivity of graphene, $k_B$ is the Boltzmann constant, $h$ is the Planck constant, $T$ is the absolute temperature.

Temperature dependence of graphene's thermal conductivity is:

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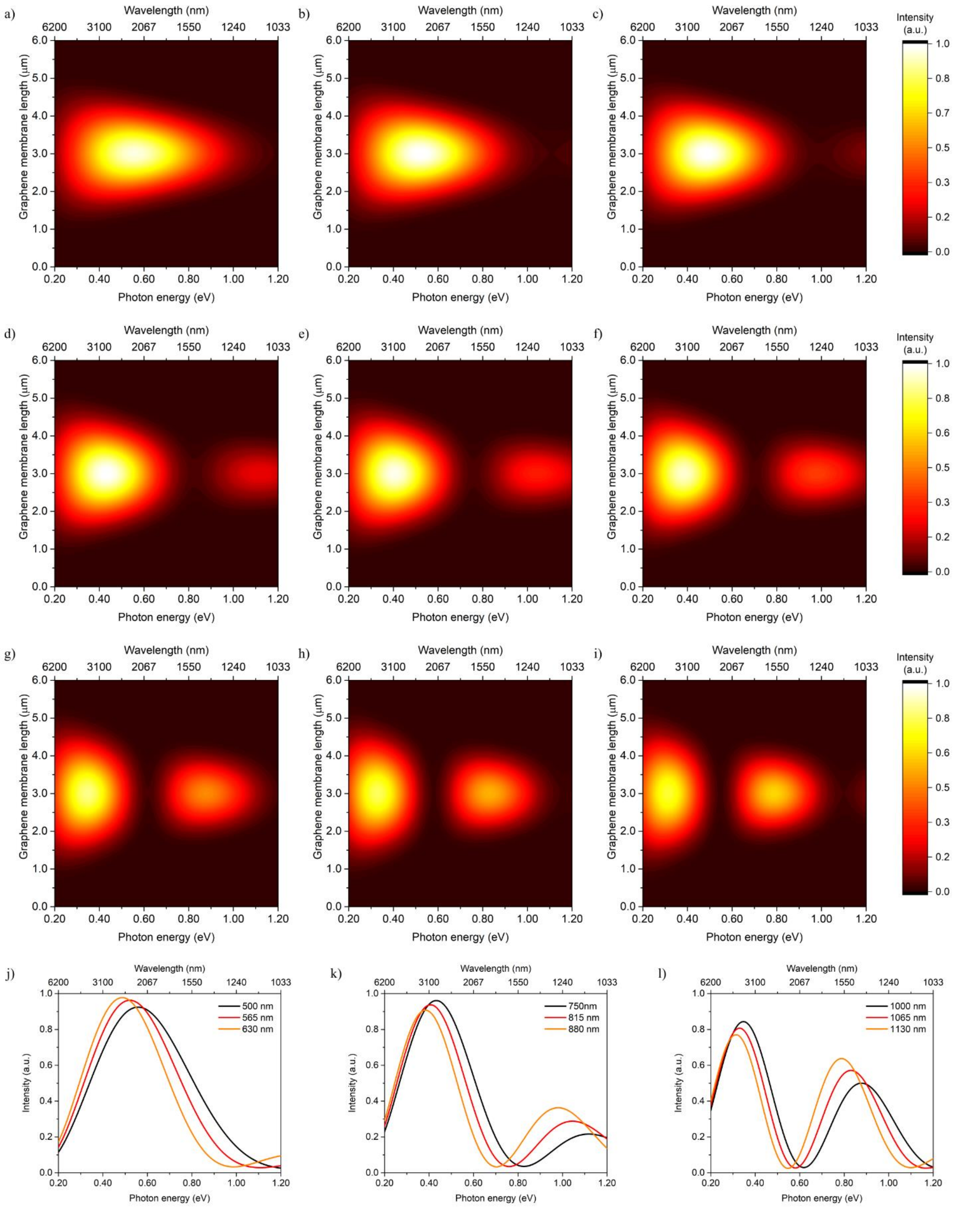


Fig. 2. Predicted spectral output along the length of graphene membrane for the distance $b$ = 500 nm (a) electrostatically deflected to $b$ = 565 nm (b) and $b$ = 630 nm (c), distance $b$ = 750 nm (d), deflected to $b$ = 815 nm (e) and $b$ = 880 nm (f), distance $b$ = 1000 nm (g), deflected to $b$ = 1065 nm (h) and $b$= 1130 nm (i); intensity modulation at the central part of the graphene membrane for three distance ranges (j-l).

$$\kappa(T) = \kappa_0 \left({T_0}/{T}\right)^{\gamma}, \tag{2}$$

where $\kappa_0$ is the thermal conductivity at $T_0$ = 300 K, $\gamma$ is a fitting parameter assumed as $\gamma \approx 1.9$ and $\gamma \approx 1.7$ for exfoliated and CVD-grown graphene, respectively [11].

As for the suspended membrane, the thermal conductivity of graphene drops drastically with temperature, from $\kappa \approx 2500$ Wm$^{-1}$K$^{-1}$ at room temperature to $\kappa \approx 323$ Wm$^{-1}$K$^{-1}$ at 1000 K (for CVD graphene), a high-intensity thermal spot in the middle of the trically biased stripe can be observed. For a graphene membrane of length $L$, the width $W$, and the thickness $d$, the temperature distribution along the transport direction can be written in the form [11]:

$$T(x) = \left(\left(T_0^{(1-\gamma)} + \frac{PL(1-\gamma)}{8\kappa_0 T_0 W d}\left(1 - \left(\frac{2x}{L}\right)^2\right)\right)\right)^{1/{1-\gamma}}, \tag{3}$$

where $x = \pm\ L/2$ and $P$ is the power dissipation at the graphene membrane.

For electrically biased suspended graphene, the nonequilibrium state between electrons (or optical phonons OPs) and acoustic phonons APs can be assumed. A nonequilibrium coefficient $\alpha$ was introduced [2]:

$$T_{op} = T_{ap} + \alpha\left(T_{ap} - T_0\right), \tag{4}$$

where $\alpha$ = 0.39 is a fitting parameter found experimentally for monolayer graphene [2]. Top is the optical phonon temperature, which equals the electron temperature, and $T_{ap}$ is the acoustical phonon temperature.

In the case of a membrane suspended over a mirror membrane at a distance $b$, the interference effect of radiation emitted from the graphene and reflected from the mirror membrane is taken into account. For relatively small deflections of the mirror membrane (i.e., membrane curvature radius $R >> L$), the two-beam interference formula can be used [12]:

$$I(\omega, b) = I_0(\omega)\left(\frac{1+|r(\omega)|^2}{2} + [r(\omega)cos(2\omega b/c)]\right), \tag{5}$$

where $r(\omega)$ is the reflection coefficient of electrostatically actuated membrane and $c$ is the speed of light.

Formulas (1)-(5) were used to calculate the spectral output of graphene membrane integrated with electrostatically actuated mirror. Phase change of $\pi$ radians at reflection from membrane was taken into account. Following graphene membrane dimensions were assumed: length $L$ = 6 µm, width $W$ = 1.2 µm and thickness $d$ = 0.335 nm. Dissipated power $P$ = 0.35 mW was taken into account. Calculations were carried out for $\varepsilon$ = 0.02, $\alpha$ = 0.39 and $\gamma$ = 1.92 [2]. Three distance ranges $b$ (between graphene and silicon membrane) were assumed in calculations $b$ = 500 – 630 nm, $b$ = 750 – 880 nm and $b$ = 1000 – 1130 nm, taking into consideration the deflection of silicon membrane from the nominal, undeflected position. Small dimensions of the silicon membrane impose restrictions to realizable deflection and achievable wavelength tuning range. For membrane width in the 10 µm range, the realizable deflection of 130 nm can be assumed. Calculations were carried out for a silicon membrane of thickness $t_{Si}$ = 350 nm coated with $t_{Au}$ = 100 nm of gold. The value of memebrane reflectivity $r$ in the considered wavelenth range varies between 0.94 (for 0.2 eV (6.2 µm)) and 0.98 (for 1.2 eV (1 µm)) [13].

Figure 2 presents the predicted spectral output along the length of the graphene layer for different distances d between the graphene and mirror membranes, varying from 500 nm (a) to 1130 nm (i). With increased distance $d$ more pronounced interference effects can be observed resulting in multiple peaks in the considered spectral range. Figure 2 (j-l) show the resulting intensity modulation at the central part of the graphene membrane, where the predicted wavelength tuning can be observed.

In summary, we presented the concept of the novel tuneable light source based on a suspended graphene membrane and a miniaturized electrostatic actuation principle. The spectral characteristics in IR were simulated for chosen geometries of the source. The calculations allowed to assess e.g., the maximum source tuneability, which is 360 nm for the peak 2.88 µm and the nominal distance between the mirror and the graphene membrane $b$ = 750 nm (mirror deflection of 130 nm). The predicted tunability is interesting for many applications of the integrated graphene light sources, including low-cost, miniaturized, and efficient spectrometry systems. The results pave the way to the demonstration of the new technology of integrated 2D material devices.

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