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Numerical analysis of waveguide-integrated graphene thermal emitter

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Abstract

We developed a numerical simulation method to evaluate coupling efficiency of waveguide-integrated graphene thermal emitter, which enables numerical analysis of the coupling behavior for thermal emission. The numerical simulation presents the feasibility of efficient coupling of thermal emission from graphene into a Si waveguide.

1. Introduction

On-chip light source for integrated photonic circuit is one of the most crucial components for monolithic on-chip photonic systems. Waveguide-integrated hybrid lasers with compound semiconductor quantum well or quantum dot are widely investigated but costly fabrication and process compatibility still are issues to be solved [1]. Aside from lasing source, recent progress in graphene thermal emitter is exhibiting the potential of alternative solution to on-chip light source for photonic circuit [2-5]. The concept of graphene thermal emitter is elevating electron temperature in graphene by Joule heating under high bias for thermal radiation. Thanks to small heat capacity and high temperature stability of graphene, suspended graphene thermal emitter can achieve bright visible emission under 2800K in vacuum [2]. Encapsulation with boron nitride or alumina will bring long operation time in air and fast on-off modulation speed in these devices [3, 4]. Recent work on integration of photonic crystal cavity and graphene thermal emitter proposed an enhanced narrow band thermal emission from graphene [5].

In order to integrate graphene thermal emitter with photonic circuit, radiation from graphene should be coupled into waveguide as shown in Fig.1. Although concept of coupling between carbon nanotube and waveguide has been proposed [6], there is no clear study on coupling between graphene thermal emitter and waveguide to date. In this paper, we numerically studied a graphene thermal emitter coupled with a Si waveguide by developing a numerical simulation method to analyze coupling efficiency in arbitrary structure. We conducted simulations with different graphene-waveguide setups for coupling effect and polarization analysis. The developed simualtion model enables numerical analysis of coupling effect in graphene thermal emitters and the simulation result suggests the feasibility of a waveguide-coupled graphene thermal emitter.

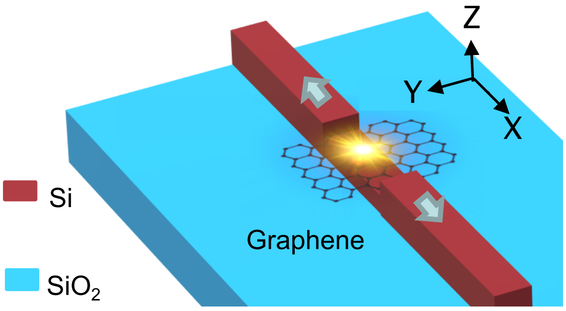

Fig. 1 Schematic of waveguide-coupled graphene thermal emitter.

2. Simulation method

To consider thermal radiation interacting with waveguide in nanometer scale, we employ a theory of near-field thermal radiation which describes the coupling behavior of thermal emitter and waveguide by Eq. (1):

$$P(\omega, T, r) = \frac{\hbar\omega}{1 - \exp\left(\frac{\hbar\omega}{k_B T}\right)} \rho_{LDOS}(\omega, r), \qquad (1)$$

where ω is photon frequency, T is temperature and r is position. The local density of state (LDOS) ρ_{LDOS} is available optical mode for thermal radiation in local position, which is the key to study coupling effect in this device. Although it's not feasible to calculate LDOS analytically for arbitrary structure, alternatively we can calculate the ratio of LDOS normalized to free space DOS by dipole excitation [7], which is similar to the definition of Purcell factor in cavity quantum dynamics.

We developed a simulation model using a commercial FDTD software which enables dipole excitation. To evaluate LDOS in a graphene thermal emitter, we set multiple dipole sources inside region of graphene. Considering the random thermal excitation, dipoles at different position have random orientations to eliminate the directionality. Also, to achieve incoherence between dipoles, we conduct

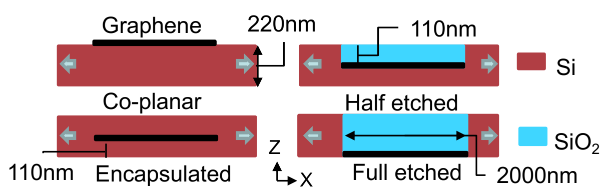

Fig. 2 Cross sections of different waveguide coupling setups.

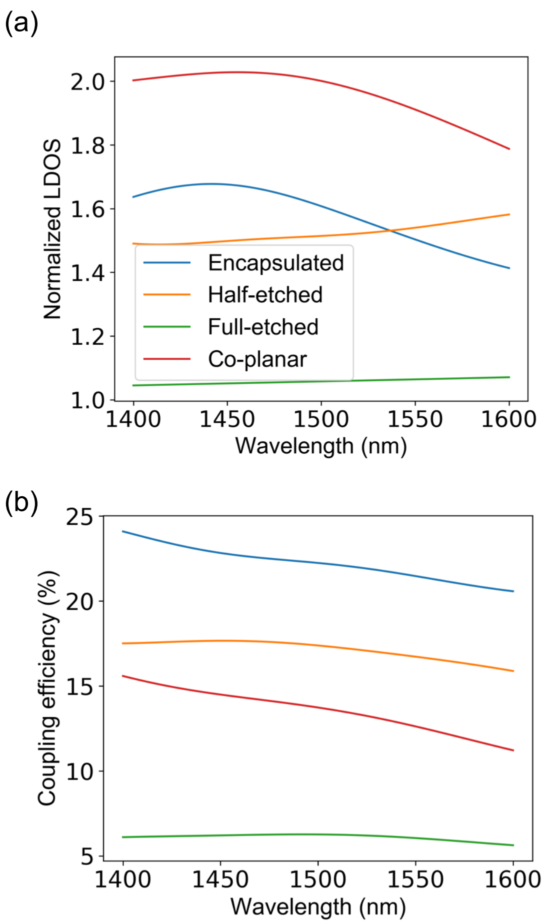

Fig. 3 (a) Averaged LDOS normalized to free space DOS and (b) averaged coupling efficiency.

multiple simulations with only one dipole exciting at once. With this incoherent dipole array, we conducted simulations in four different coupling setups with cross sections shown in Fig. 2. We considered the Si strip waveguide for communication band (width: 550nm) and ignored temperature change for simplicity. We set transmission box enclosing dipole source to extract real dipole radiation power for calculating normalized LDOS. Optical power coupled into waveguide is received to evaluate coupling efficiency.

3. Results and discussions

We present the areal average of normalized LDOS and coupling efficiency in Fig. 3. Here coupling efficiency is defined as ratio of optical power coupled in waveguide to total radiation power from dipole source. It is noticed that although simple co-planar setup shows highest LDOS, but with a small portion coupled in to waveguide. On the other hand, encapsulated graphene inside waveguide will provide highest coupling efficiency. For a more explicit comparison of performance in different setups, we multiplied LDOS and coupling efficiency to get normalized coupling power, which is the ratio of optical power coupled into waveguide to the radiation power in free space device, with result shown in Fig. 4. We see the encapsulated graphene in waveguide shows the highest performance with over 30 percent of coupled power compared to free space device, which comes from sufficient overlap between graphene and waveguide mode.

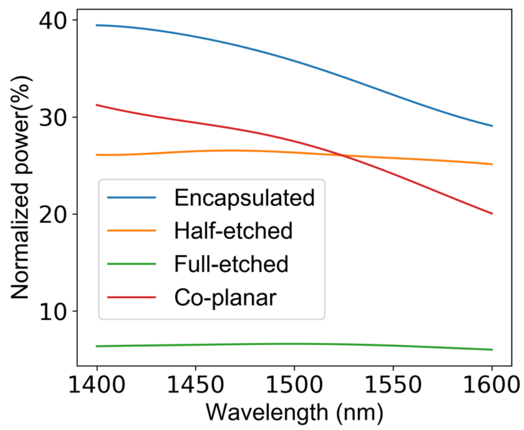

Fig. 4 Coupled power normalized to free space graphene thermal emitter.

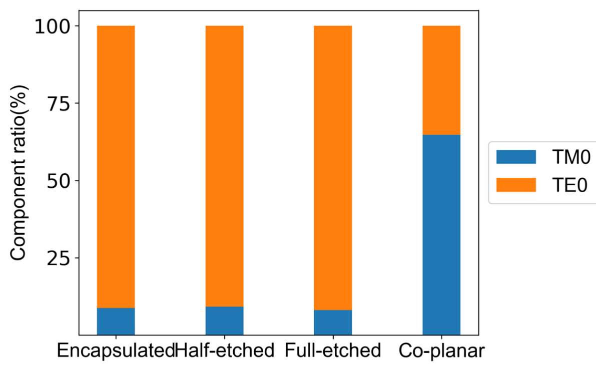

Fig. 5 Mode component ratio at 1550 nm for different setups.

We also conducted mode analysis at a 1550 nm wavelength with result shown in Fig. 5. This result reflects a strong structure-dependent polarization. It comes from overlap with different waveguide mode in different graphene-waveguide setups. This unique property can be utilized to match the polarization requirement posed by specific applications.

4. Conclusions

We numerically analyzed graphene thermal emitters by developing the dipole excitation method with FDTD simulation. The numerical analysis predicted that an encapsulated graphene thermal emitter exhibited efficient coupling of thermal emission into waveguide modes.

Acknowledgements

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