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Original research article

Investigation of the tunable plasmonic whispering gallery mode properties for graphene monolayer nanodisk cavities

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ABSTRACT

Tunable graphene plasmonic whispering gallery mode nanodisks formed by nanoscale chemical potential variation on an infinite freestanding graphene monolayer at near-infrared wavelength range are proposed and numerically investigated in this paper. The Q-factor of a high-order whispering gallery mode of 136 and an extremely small mode volume of 4.8×10^{-7} $(\lambda_0/n)^3$ with a large Purcell factor of 1.7×10^8 is achieved in a cavity radius of 10 nm. This graphene based nanodisk cavity structure with an ultrasmall mode volume and large Purcell factor is a promising candidate for high efficiency plasmonic emitting sources, filters, or a key component in the fields of transformation plasmonics and plasmonic integrated circuits technique in the future.

1. Introduction

In recent years, an enormous interest has been surrounding the field of optical whispering gallery (WG) dielectric cavities with high quality factors as well as small mode volume [1] because of their applications such as low-threshold lasers, cavity quantum electrodynamics, sensing, nonlinear enhancement, switching, etc. However, conventional dielectric cavity is in micrometer scale and further size reduction is challenging due to the optical diffraction limit. This becomes the significant obstacle to miniaturize photonic devices based on WG dielectric cavities. Surface plasmons (SPs) enable the confinement of electromagnetic (EM) field to scales far below the conventional optical diffractive limit [2]. Combining distinct whispering gallery mode (WGM) and surface plasmon polartions (SPP) features, the plasmonic whispering gallery resonant cavities with deep subwavelength mode volume and high Q factor can be a new building block for the high-density integration of photonic devices. Noble metals have been widely regarded as the best available plasmonic materials for nanophotonic application, including single-photon sources, transistors and ultra-compact circuitry at the nanoscale [3]. Nevertheless, the noble metal supported plasmon is hardly tunable in devices and generally has large Ohmic losses, which limits the development of novel functional photonic devices with high performance.

To date, researches have shown that graphene offers an extremely high quantum efficiency for light-matter interaction and strong plamons due to its unique honeycomb lattice structure and the corresponding Dirac-type energy band [4]. Graphene has been recognized as a new platform for plasmon waveguiding at infrared frequency [5] and can be considered

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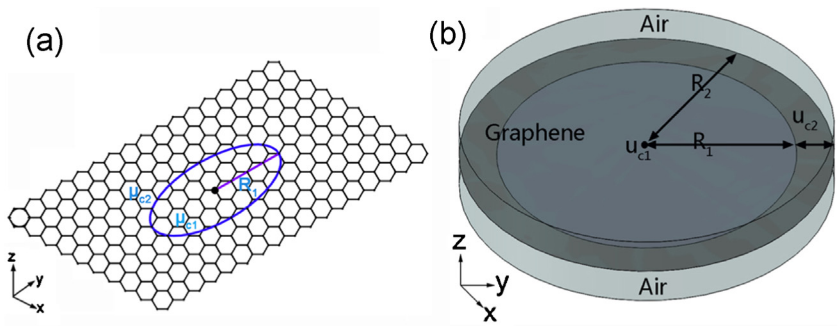

Fig. 1. 3D (a) and computational (b) views of schematic diagram of nanodisk resonator in a single freestanding graphene monolayer, which has two different conductivity regions. μ_{c1} and μ_{c2} represent difference chemical potential. R_1 corresponds to the cavity radius, and R_2 is the radius of the computational window, respectively.

as terahertz metamaterials [6]. So far, graphene supported SPPs have demonstrated extremely high confinement, tunability via electrical gating or chemical doping [7–9], and relatively low loss resulting from long lifetime. These advantages make graphene to be an ideal platform of plasmonic integrated circuits technique and transformation plasmonics. Furthermore, it is an attractive alternative to traditional metal plasmonics in optical photonic and optoelectronic application, including nonlinear optics [10–12], optical nano-imaging [7,8], photodetector [13], broadband optical modulator [14] and nano-ribbon waveguides [15].

Albeit the isolated graphene nanostructures have been proposed and numerical studied in terms of quantum mechanics [16–18], the dependence of the characteristic parameters such as quality (Q) factor, effective mode volume, and Purcell factor upon the geometry and material parameters is still unclear. The mechanisms behind these principles are not revealed yet. Furthermore, in the fields of plasmonic integrated circuits or transformation plasmonics, the plasmonic nanostructures are always designed on a certain plasmonic platform, thus the properties of the large area plasmonic platform should influence the performances of the nanostructures inevitably, which are yet unrevealed in the reported literatures. In this work, we use graphene monolayer with a certain chemical potential μ_{c2} as the plasmonic platform, and propose the tunable WGM nanocavity resonators, which are formed by chemical potential variation in deep nanoscale on the graphene monolayer sheet. The characteristic parameters of the nanoresonators such as Q factors, mode volumes, are studied as function of geometry parameters and material parameters systematically. Also, the mechanisms behind these disciplines are investigated. We believe this proposed structure could be a fundamental component of the high-density plasmonic integrated circuits and on-chip plasmonic interconnect technique in the future.

2. Numerical simulation

It should be mentioned that a single freestanding graphene monolayer sheet can be treated as an infinitesimally thin sheet so that it can be characterized by the surface conductivity [9,19,20]. Along the graphene sheet, the surface current density is defined by $J=\sigma_g E$, where E and σ_g are the electric component of the electromagnetic field and the surface conductivity of graphene, respectively. The surface conductivity of graphene can be derived from Kubo formula [17] which is composed of the contributions from both the interband electron–electron transition and the intraband electron–photon scattering. Both of the contributions depend on the chemical potential of graphene μ_c, the frequency of incident light ω, the momentum relaxation time τ and the absolute temperature. We work on the FEM simulation of the electromagnetic fields by using the eigen frequency solver of the commercial software COMSOL. For simplicity, we only consider the nanodisk with a round shape in this work. The schematic figure of the nanodisk and the computational window is shown in Fig. 1. Here, μ_{c1} indicates the chemical potential of the nanodisk, which is surrounded by the same sheet of graphene with a different chemical potential μ_{c2}. The simulation parameters are set at $\mu_{c1}=0.9$ eV and $\mu_{c2}=0.6$ eV. It has demonstrated that the chemical potential of graphene can be tuned to as high as 2 eV chemical doping or electrical gating [21,22]. Also, we set the relaxation time $\tau=0.5$ ps. Pioneering experimental works demonstrated a relaxation time higher than 3 ps [23]. We believe such a rather conservative choice of τ here is enough to ignore the practical loss of graphene. Additionally, the temperature is chosen below 250 K to ensure the high chemical potential to be possible.

3. Results and discussions

3.1. The field distribution of WG mode

The WG modes are found at the resonance wavelengths of 1.27 μm and 1.25 μm. One is the fundamental mode circulating along the circumference of the nanodisk cavity shown in Fig. 2(a), with an azimuthal mode number of 6. The other is a high-order mode with the radial mode number of 2, azimuthal mode number of 2, as shown in Fig. 2(b). The Q-factors of the two