Graphene-based Mid-infrared Plasmonic Conveyor Belt Network for Versatile Manipulations of Nanoscale Objects

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Abstract: We show that a graphene-based mid-infrared plasmonic conveyor belt network can induce tunable bipolar optical gradient forces on nano-objects made of dispersive materials, which can be exploited for trapping, transportation, sorting and fractionation of nano-objects. © 2021 The Author(s)

Optical tweezers based on tightly focused laser beams are powerful tools for manipulating microscopic objects and therefore have found a wide range of applications. However, due to the fundamental diffraction limit of light, the trapping efficiency of conventional optical tweezers becomes insufficient for nanoscale objects with sizes much smaller than the wavelength of light. Plasmonic structures based on noble metals can confine light in deep-subwavelength scales, and hence have been exploited for trapping nanoscale objects with sizes down to a few nm [1]. However, the lack of real-time tunability of metal-based plasmonic structures makes transportation and other manipulations of trapped nanoscale objects rather challenging. In this regard, tunable plasmonic structures based on materials with real-time tunable optical properties, such as graphene, provide a promising solution to overcoming this challenge [2-4]. Here, we show that graphene nanoribbons (GNR) with tunable mid-infrared (MIR) plasmonic resonances can be utilized to form an electrically controlled plasmonic conveyor belt network to simultaneously and independently trap and transport multiple nano-objects. Furthermore, such a GNR plasmonic conveyor belt network can induce tunable bipolar (i.e., trapping or repulsive) optical gradient forces on nano-objects made of materials with strong permittivity dispersions in the MIR region. The tunable bipolar optical forces can be exploited to achieve selective filtering, sorting and fractionation of nano-objects in a mixture based on their material compositions.

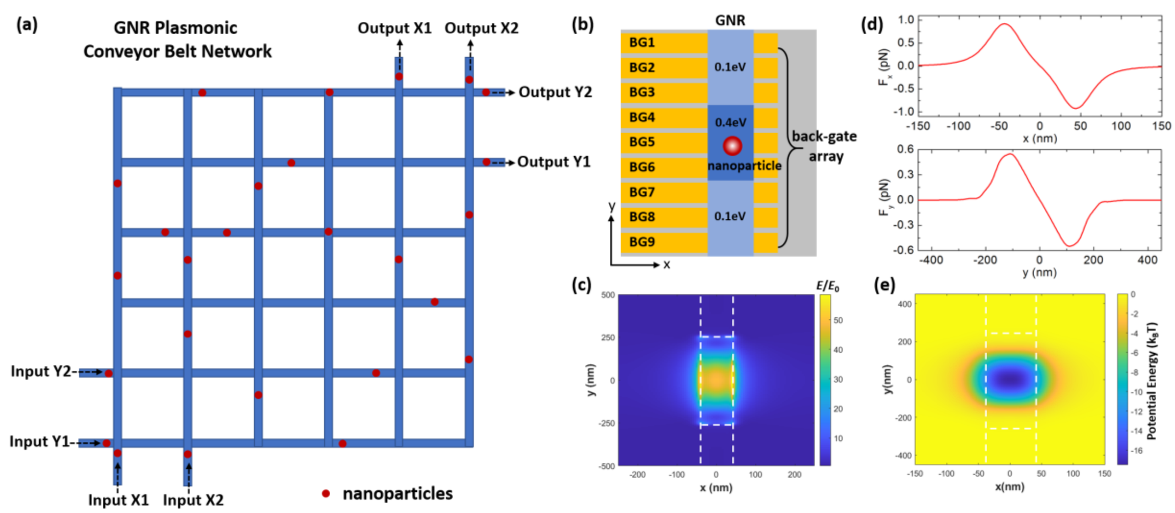

Figure 1 (a) Conceptual schematic of the proposed GNR plasmonic conveyor belt network. (b) Schematic of a local section of a GNR plasmonic conveyor belt integrated with a back-gate array to control the GNR Fermi energy distribution. (c) Electric field enhancement profile of the plasmonic resonance mode for the GNR configuration shown in (b). (d) Calculated position-dependent x-component and y-component of the optical force on a dielectric nanosphere at 10nm above the GNR plasmonic conveyor belt section shown in (b). (e) Calculated potential energy profile corresponding to the force calculation in (d). The white dashed lines in (d)&(e) mark the borders of the different GNR sections.

The conceptual schematic of the proposed GNR plasmonic conveyor belt network is shown in Fig. 1a, which consists of two sets of GNRs perpendicular to and intersecting each other [4]. The network can contain multiple input/output ports for nano-objects. An array of back-gates is implemented below each GNR (see Fig. 1b) to control the local carrier density (Fermi energy) distribution, which in turn determines the local plasmonic resonance mode. For example, if the graphene Fermi energy distribution is configured as shown in Fig. 1b, the middle section can support a localized plasmonic resonance mode with exceedingly high field confinement and enhancement at the desired MIR operating wavelength, as shown in Fig. 1c. Therefore, when a nano-object with a positive polarizability enters the vicinity of this resonant GNR section (e.g., as a result of its random Brownian motion in a liquid medium), it can experience a large gradient force that pulls it to the center of the resonant GNR section, as shown by the calculated optical force components in Fig. 1d (assuming a nanosphere with 50nm diameter and a refractive index of 2.5). The corresponding potential energy profile is shown in Fig. 1e, which has a depth significantly exceeding $10k_BT$ (T=300K) at a moderate optical excitation intensity of $1mW/\mu m^2$. Multiple localized resonant sections can be established in the GNR network to trap multiple nano-objects simultaneously. Furthermore, by reconfiguring the Fermi energy distribution in the GNRs using the back-gates, the individual resonant sections can be shifted along the GNRs, which in turn shift the individual potential wells and hence transport the trapped nano-objects independently [4]. Therefore, the operation of such versatile nano-object transportation within the plasmonic conveyor belt network is fully controlled electrically, without the need for any change to the excitation light source.

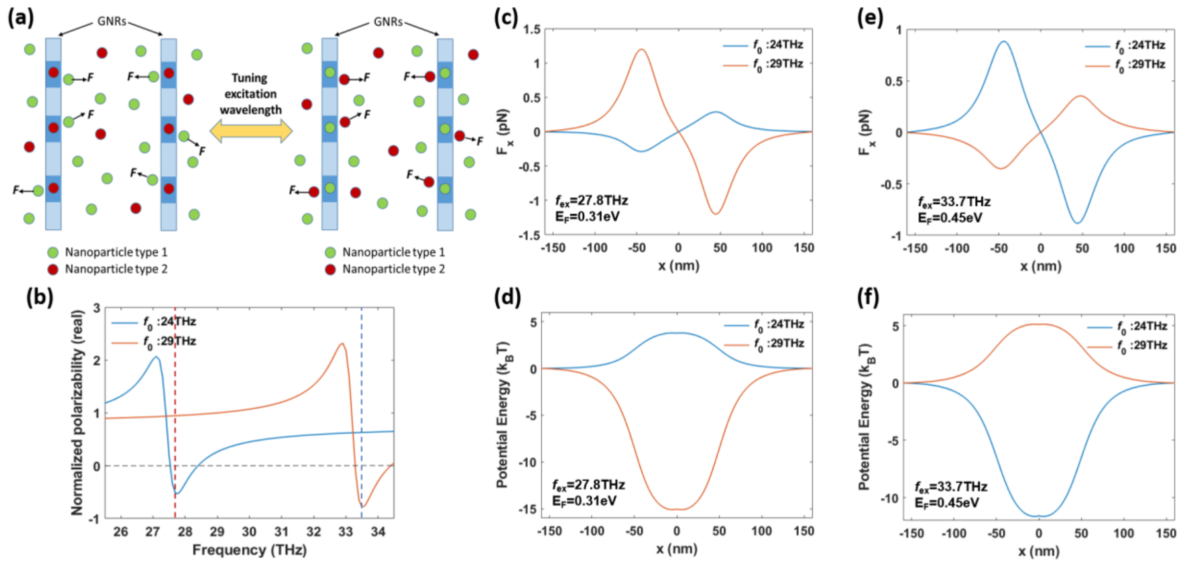

Figure 2 (a) Schematic illustrating the functionality of selective sorting and fractionation of different types of nano-objects in a mixture. (b) Normalized polarizability of two types of nano-objects made of two different dispersive materials with the specified Lorentz resonance frequencies (f_0). (c-d) Calculated x-component of the optical forces and the potential energy profiles for the two types of nano-objects in (b) when the GNR Fermi energy is set to 0.31eV and the optical excitation frequency is tuned to 27.8THz. In this case, the nano-objects with f_0=29THz are trapped and the nano-objects with f_0=24THz are rejected by the GNR. (e-f) Calculated x-component of the optical forces and the potential energy profiles for the two types of nano-objects in (b) when the GNR Fermi energy is set to 0.45eV and the optical excitation frequency is tuned to 33.7THz. In this case, the nano-objects with f_0=24THz are trapped and the nano-objects with f_0=29THz are rejected by the GNR.

Another key capability/functionality of this MIR GNR plasmonic conveyor belt network is that it can induce tunable bipolar optical gradient forces on nano-objects made of dispersive materials, which can be exploited for selective filtering, sorting and fractionation of nano-objects in a mixture, as illustrated by the conceptual example in Fig. 2a. Many materials have strong Lorentzian permittivity dispersions in the MIR region due to their optical phonons or molecular vibrational modes, which in turn lead to large polarizability dispersions of nano-objects made of such materials. In fact, the polarizability of such a nano-object can vary drastically within a narrow spectral range and change its sign, as shown in the examples in Fig. 2b. A nano-object with a negative polarizability will experience a repulsive optical gradient force. Therefore, if two (or more) types of nano-objects with different polarizability dispersions (e.g., those in Fig. 2b) are mixed together, by tuning the localized GNR plasmonic resonance and the optical excitation frequencies accordingly, the GNRs can selectively trap and transport one type of nano-objects only while repelling the other, as evidenced by the calculated optical forces and the corresponding potential energy profiles in Fig. 2c-f. This capability is difficult to realize in conventional optical tweezers and plasmonic tweezers, and further enhances the versatility of the GNR plasmonic conveyor belt network for different applications.

This work is in part supported by the National Science Foundation (NSF) (Award No. ECCS-1847203).

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