Electrically Controlled Graphene Nano-Ribbon Plasmonic Conveyor Belt Network

Peter Q. Liu*, Puspita Paul
Department of Electrical Engineering, University at Buffalo, The State University of New York, Buffalo, NY 14260, United States
**Email: pqliu@buffalo.edu*

Abstract: We present a graphene nano-ribbon based plasmonic conveyor belt network for simultaneous and independent trapping and transportation of multiple nano-objects, which are entirely achieved by electrostatically varying the carrier density distribution in the graphene structures.

1. Introduction

Optical tweezers are powerful tools for manipulating micro- and nano-scale objects. The performance of conventional optical tweezers based on focused laser beams is ultimately constrained by the diffraction limit. Nanophotonic structures such as plasmonic antennas are capable of confining light beyond the diffraction limit to deep subwavelength scale, and hence can more effectively achieve trapping of nano-objects with characteristic dimensions down to the 10nm range. However, as the optical responses of metal-based plasmonic structures lack real-time tunability, nano-objects are mostly trapped at the discrete locations around the plasmonic structures, and it is challenging to transport the trapped objects using such plasmonic tweezers. Previously demonstrated schemes for achieving a conveyor belt type functionality for particle transportation based on metallic plasmonic structures involve sophisticated tuning of the properties of the excitation light source, such as its wavelength and polarization [1,2]. Even though multiple objects can be trapped simultaneously by multiple plasmonic structures, these schemes based on tuning the excitation light source cannot manipulate individual objects independently, if they are not far away from each other (i.e., if the distances between different trapped objects are comparable to or smaller than the excitation light wavelength). Here, taking advantage of the large tunability of graphene plasmonic structures, we propose and analyze the performance of a graphene nano-ribbon (GNR) based plasmonic conveyor belt network, which can simultaneously and independently trap and transport multiple nano-objects within the network [3]. The transportation of the trapped objects is achieved solely by varying the carrier density distribution in the GNRs using an array of back-gates, without any need for changing the excitation light source. The proposed graphene-based plasmonic conveyor belt network operates with a mid-infrared excitation source, which is also complementary to the near-infrared and visible light sources used in conventional optical tweezers and plasmonic tweezers, and may lead to a variety of new applications.

2. Structure Design

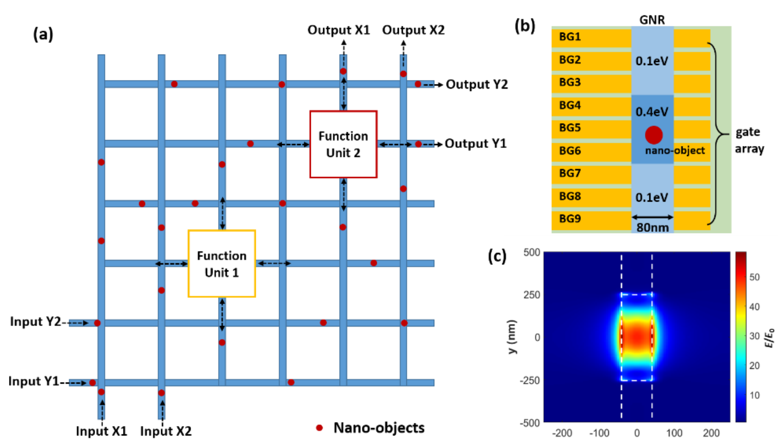

Fig. 1. (a) A conceptual schematic of the proposed GNR-based plasmonic conveyor belt network.
(b) Schematic of a GNR section with its Fermi energy distribution controlled by a back-gate array.
(c) Near-field enhancement profile of the plasmonic resonance mode of the non-uniform GNR in (b).

A conceptual schematic of the proposed GNR plasmonic conveyor belt network is illustrated in Fig. 1(a). The network can contain multiple input/output ports and embedded function units. Multiple nano-objects can be simultaneously and independently transported between different ports and embedded function units within the network. As shown in the schematic of a local section of the GNR network in Fig. 1(b), an array of back-gates are implemented below the GNRs to electrostatically reconfigure the carrier density (Fermi energy E_F) distribution in the GNRs, which can support a strong plasmonic resonance at the target operation wavelength. In this study, we choose 9.3μm as the operation wavelength, which can be provided by a CO_2 laser or a quantum cascade laser. When E_F is tuned to 0.4eV, the designed 80nm-wide GNR supports a plasmonic resonance at the excitation wavelength, whereas when E_F is tuned away from this value, the GNR plasmonic resonance also shifts to a different wavelength and cannot be excited by the light source. Therefore, when the E_F distribution is configured non-uniformly along the GNR as in Fig. 1(b), the plasmonic resonance mode excited by the light source is localized in the middle section, as shown in the near-field profile in Fig. 1(c). Due to the large near-field gradient surrounding this resonant GNR section, a nano-object located in the vicinity will be trapped to this resonant section. As we can reconfigure the E_F distribution using the back-gate array, the resonant section can be shifted along the GNR, which in turn transports the trapped nano-object accordingly.

3. Performance Analysis Results

We conducted theoretical analysis of the performance of the proposed GNR plasmonic conveyor belt network [3]. Some of the key results are presented in Fig. 2. Figure 2(a) shows the calculated trapping forces on a dielectric nano-sphere (50nm diameter) at 15nm above the GNR, as well as the corresponding potential energy profiles, for two different values of E_F in the non-resonant GNR sections. The calculations were done as the location of the nanosphere was varied along the GNR, and a moderate excitation intensity of 1mW/μm^2 was assumed. Indeed, the nanosphere experiences significant optical trapping force when it is near the resonant GNR section. The trapping potential energy significantly exceeds $10k_BT$ at room temperature, which guarantees stable trapping during particle transportation.

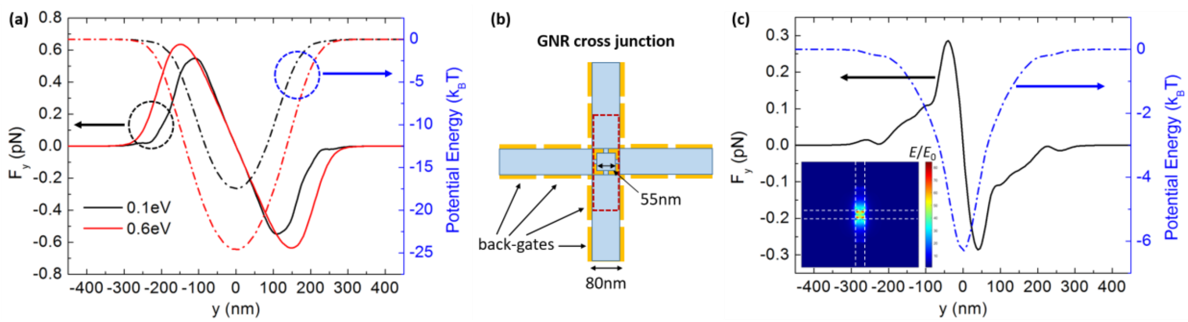

Fig. 2.(a) Calculated optical trapping forces and corresponding potential energy profiles for a dielectric nanosphere above the GNR shown in Fig. 1(b), assuming the two specified E_F values in the non-resonant GNR sections. **(b)** Schematic of an optimized cross junction design. **(c)** Calculated optical trapping force and corresponding potential energy profile for trapping the nanosphere at the designed cross junction.

The GNR network also contains cross junctions. The ability to achieve all-directional routing at such cross junctions is crucial for a fully functioning network. Employing the cross junction design in Fig. 2(b), when the GNR region in the red box is biased at E_F=0.4eV, a nano-object can be reliably transported to the junction center [3], as shown by the trapping force and corresponding potential energy profile in Fig. 2(c), as well as the field distribution of the localized plasmonic resonant mode in the inset of Fig. 2(c). By reconfiguring the carrier density distribution, the trapped object can then be shifted from the cross junction center into any GNR branch, hence achieving all-directional routing.

4. Conclusion

We propose and analyze the performance of a GNR plasmonic conveyor belt network, which can simultaneously and independently trap and transport multiple nano-objects within the network. A large trapping potential in excess of $10k_BT$ at room temperature can be realized at a moderate excitation light intensity (~1mW/μm^2) in the mid-infrared. Transportation of trapped nano-objects are achieved solely by electrically reconfiguring the carrier density distribution in GNRs, without any need for tuning the excitation source. This new platform for optical trapping and manipulation has high design flexibility and system scalability, and may find a wide range of applications in different areas, such as lab-on-a-chip for biochemical assays, assembling nanoparticles to form more complex structures and devices, as well as manipulating nanoparticles for studying many-body physics and advancing quantum information technologies.

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

[1] Y. Zheng et al., "Nano-optical conveyor belt, part II: demonstration of handoff between near-field optical traps," Nano Lett. **14**, 2971 (2014).
[2] Z. Kang et al., "Plasmonic graded nano-disks as nano-optical conveyor belt," Opt. Express **22**, 19567-19572 (2014).
[3] P.Q. Liu, P. Paul, "Graphene Nanoribbon Plasmonic Conveyor Belt Network for Optical Trapping and Transportation of Nanoparticles," ACS Photonics **7**, 3456-3466 (2020).