Fundamental theoretical limits of graphene tunable and non-reciprocal devices

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In recent years, there has been a surge of interest in graphene-based devices for various terahertz and photonic applications [1-8]. Among other, terahertz tunable metamaterials [1-3], amplitude modulators [4, 5], and isolators have been demonstrated. There is a growing effort to optimize these devices for real applications. However, the absence of guidelines concerning the best possible performances yields to designs having sub-optimal performance or unnecessarily complex structures.

We developed a rigorous and general theoretical framework to determine absolute upper bounds on the performances of graphene passive reconfigurable and non-reciprocal devices [8]. Remarkably these limits are related only to graphene conductivity and are independent of the particular geometrical structure of the device. Based on the theory developed, we demonstrate how designs closely approaching these fundamental bounds can be achieved. Our analysis not only provides information on the best possible performances of graphene reconfigurable devices as a function of graphene parameters, but indicates how such optimal performance can be approached by the simplest design.

The results are a direct derivation from Maxwell's equations, and apply to any graphene reconfigurable or non-reciprocal device. Since the bound apply to any device describable with a scattering matrix, both planar devices and guided ones are subject to it. Additionally, the bound can be easily adapted to other 2D materials.

Two examples of bounds that we will present are briefly described here. The first one concerns two states passive reconfigurable devices with a tunable transmission coefficient. These can be either two ports guided device working with confined waves or (meta)surfaces working with free space waves. Let us assume that the tunability is achieved using graphene biased by an electrostatic field. The two states 'A' and 'B' are characterized by two different gate voltages V_A and V_B which cause the graphene conductivity to take two distinct values σ_A and σ_B thanks to the electric field effect. This leads in turn to the two values T_A and T_B of the tunable transmission coefficient. We will show that there is a precise mathematical bound involving $|T_A|$ and $|T_B|$ and depending uniquely on σ_A and σ_B. Importantly, the bound applies to on-off modulators and switches, tunable passive devices where the design is optimized to maximize one among $|T_A|$ and $|T_B|$ and to minimize the other one.

The second example concerns graphene non-reciprocal isolators. These devices are based on the tensorial conductivity of graphene under magnetostatic field bias. Non reciprocal two-ports devices are characterized by two different scattering parameters for the signal propagating from port 1 to port 2 and for the one propagating from port 2 to port 1 (namely $S_{12} \neq S_{21}$). Isolators are devices where one among $|S_{12}|$ and $|S_{21}|$ is minimized and the other is maximized. We will show that there is a mathematical bound involving $|S_{12}|$ and $|S_{21}|$. Again this bound can be formulated in terms of graphene conductivity only.

The complete demonstration of the bounds is inspired by a previous formulation for 3D materials used in circuit theory [9]. In addition, we provide extensive validation of the bound simulating a large number of graphene modulators and isolators having different geometries but identical graphene parameters (and hence the same bound holds for all the devices). No simulated device ever overcame the theoretical limit. Some devices are extremely close to the upper bound and thus they can be considered as optimal.

We believe that these bounds represent a very important knowledge advancement on the potential performances of graphene devices and that they provide useful guidelines for maximizing the efficiency of graphene modulators and isolators.

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