ESSERC 2024

W2: Wideband Optical Antennae for Use in Energy Harvesting Applications

Effects of External Magnetic Field on Carrier Dynamics of Graphene

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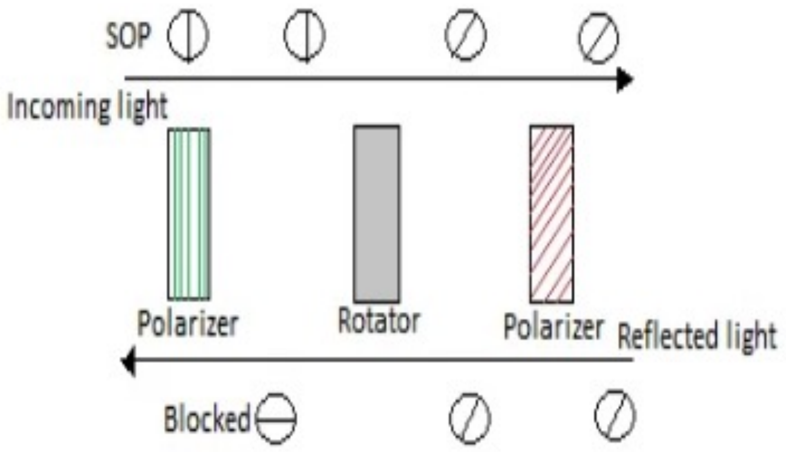
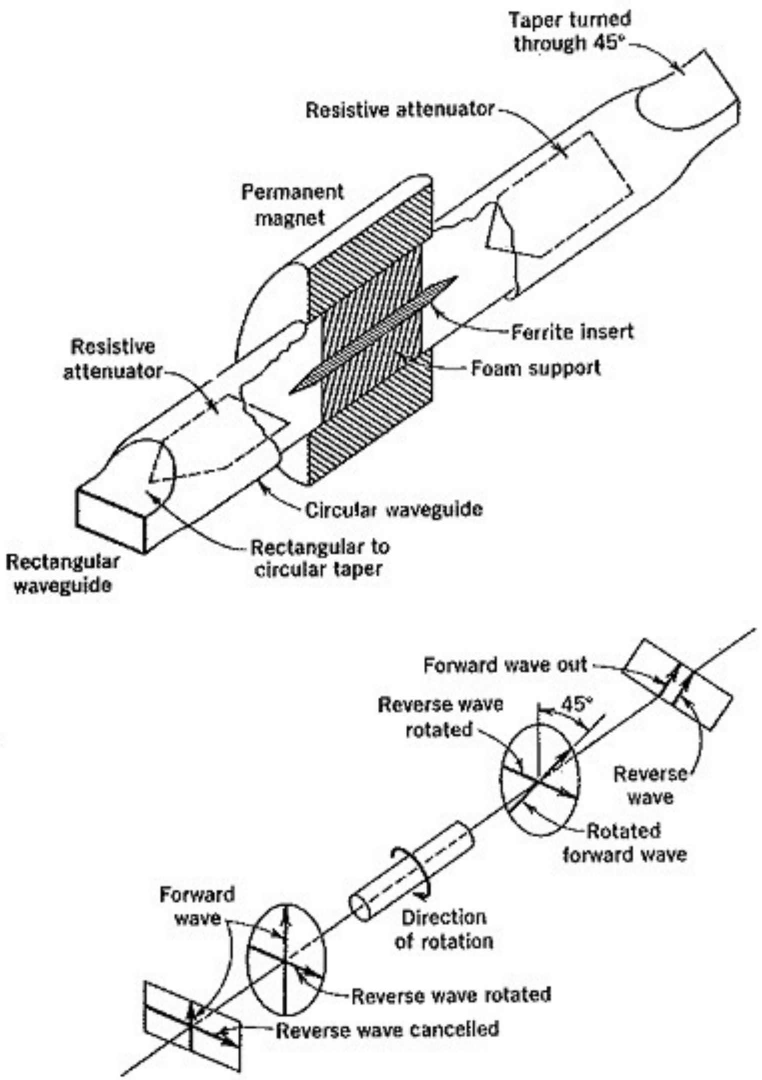
Non-reciprocal effects due to magnetic fields have been known for a long time in applied electromagnetism. A typical example is the optical isolator widely used in telecommunication systems, e.g. to stabilize optical amplifiers or to isolate semiconductor lasers (the simplest, polarization-dependent version is shown):



The key for the isolator effect is the nonreciprocal rotation of the forward and backward propagating light – a very uncommon effect in normal optical components!



Another example, even "older", is the use of ferrites in microwave waveguides, to obtain non-reciprocal functionalities (isolators, circulators).

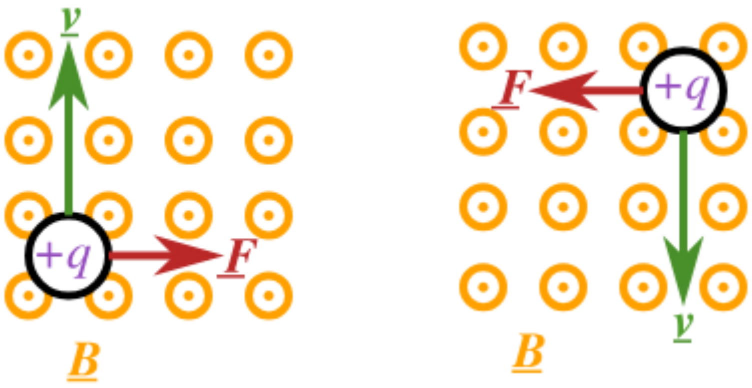
In the figure on the left, an isolator for microwave application is shown.

Both in optical and RF application, a key "ingredient" is the presence of a magnetic field

Could magnetic fields play a beneficial role in graphene rectenna developments?

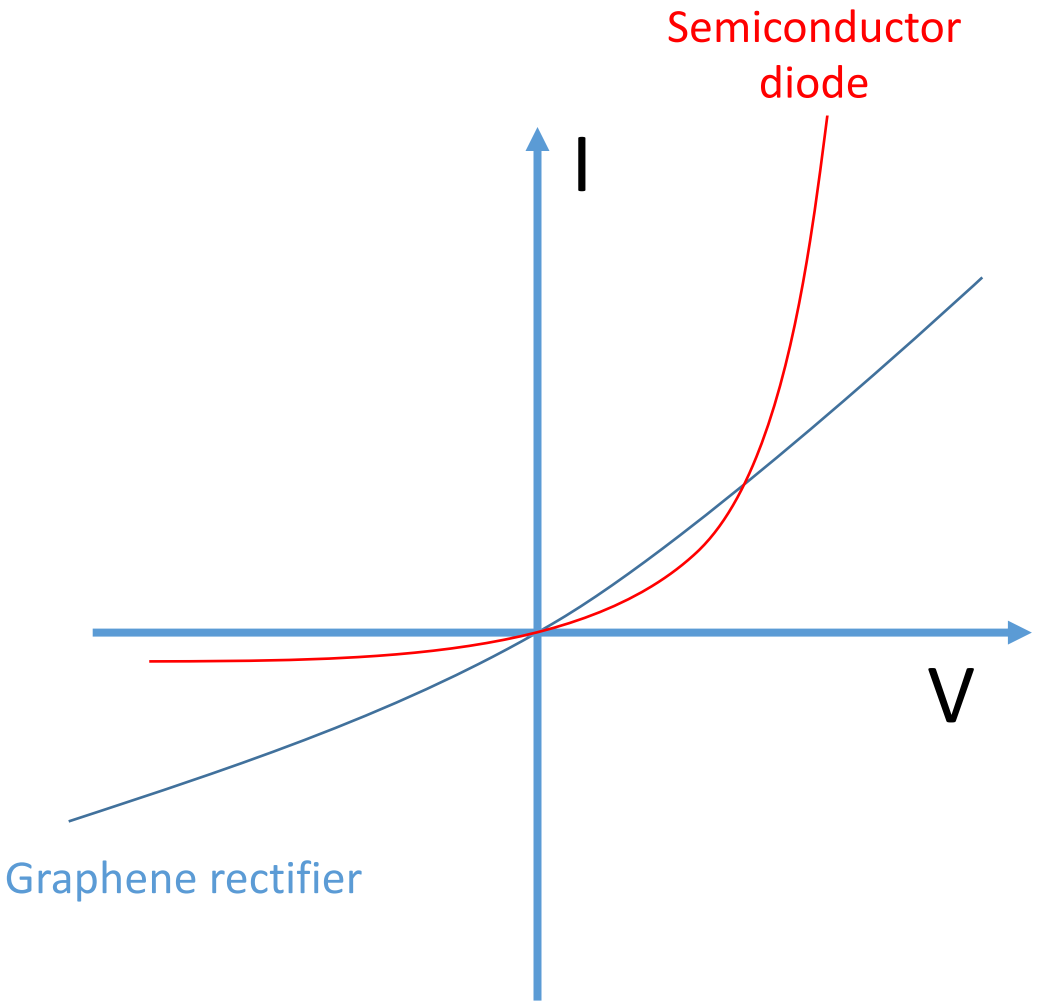
By analogy, we could be led to think that a magnetic field perpendicular to the graphene layer could modify significantly the trajectories of the graphene charge carriers.

If confirmed and put to work, devices mirroring the nonreciprocal operation of the optical/RF components mentioned in the previous slides could be envisaged.



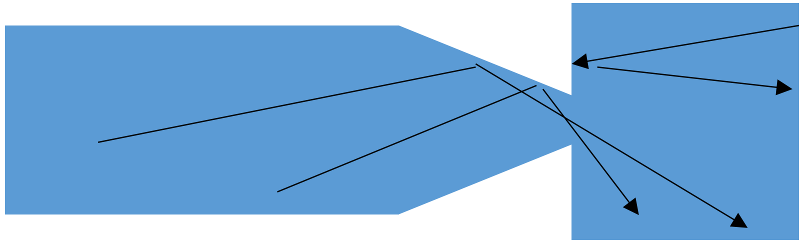
The basic idea relies on the well-known formula of the Lorentz force:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$



The problem:

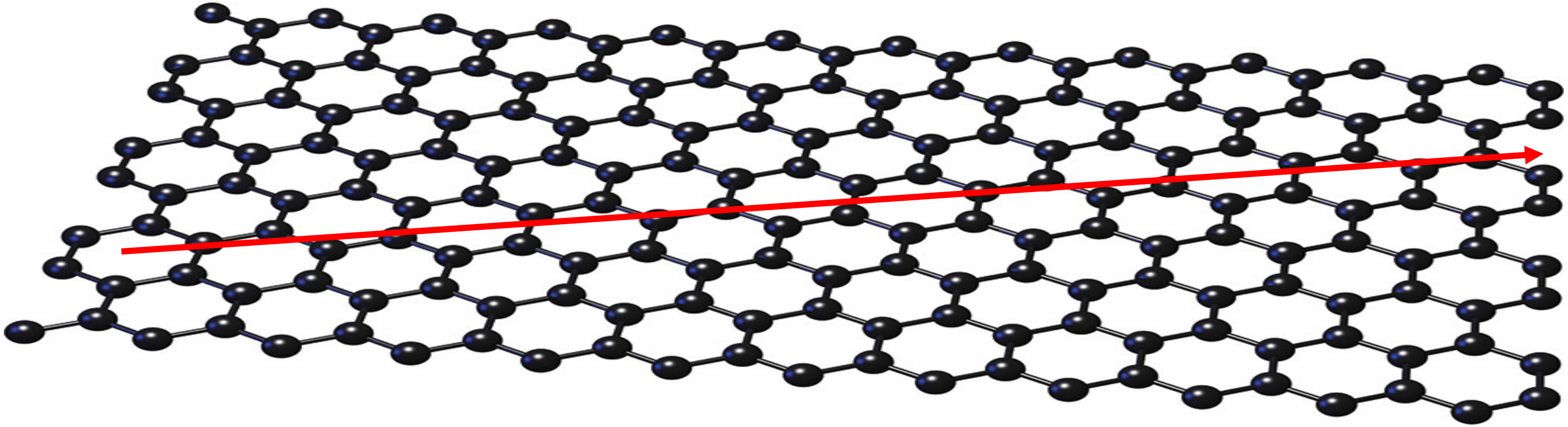
GREENERGY research has proven the viability of several structures leading to a rectification effect. The non-reciprocity of the resulting devices is nevertheless not optimal yet.



In spite of the apparent analogy with liquid flow, which intuitively justify the rectification effect, the physics of the graphene rectifier (here of the “geometric diode” type) is definitively more complex.

Graphene: a 2-D material with very long mean free paths

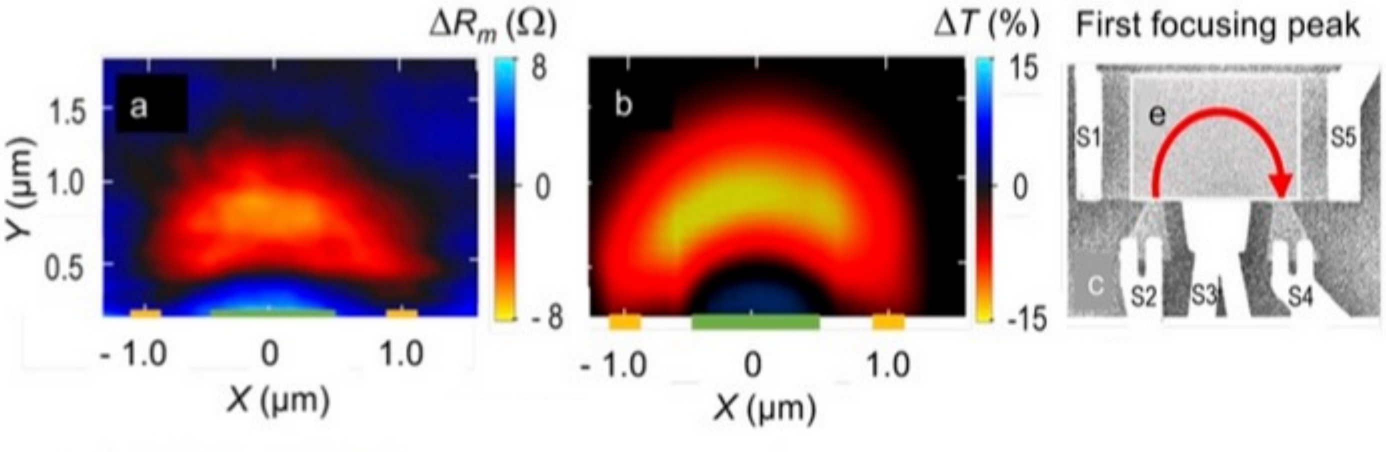
In graphene, charge carriers encounter minimal scattering due to the lack of a bandgap and high symmetry of the lattice. Graphene's high mobility (up to 200,000 cm2^22/V·s at room temperature) is due to minimal electron-phonon interactions and weak scattering from impurities when high-quality samples are used



For high-quality graphene samples, particularly those encapsulated in hexagonal boron nitride (h-BN), the mean free path at room temperature can range between **0.5 to 1 micrometer (μm)**

Possible role of magnetic fields in enhancing rectennas' non-reciprocity

The cyclotronic bending of the graphene charge carriers trajectory has been observed experimentally, confirming that on micron-size devices the effect in ballistic regime is similar to that observed on free particles

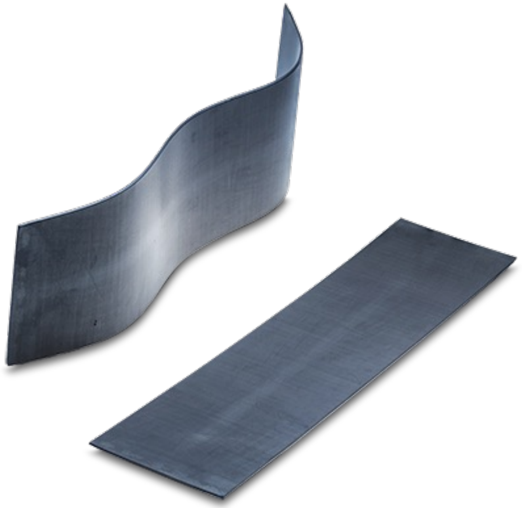


From: "Imaging Cyclotron Orbits of Electrons in Graphene",Sagar Bhandari, Gil-Ho Lee, Anna Klales, Kenji Watanabe, Takashi Taniguchi, Eric Heller, Philip Kim, and Robert M. Westervelt; DOI: 10.1021/acs.nanolett.5b04609
Nano Lett. 2016, 16, 1690–1694

Would be such an approach feasible?

In the quoted article (Westerwald et.al.) the magnetic fields ranged from 0.09 T to 0.14T The addition of a “magnetic floor” under the graphene device seems reasonable, as the magnetic fields at the surface of the most common magnetic materials fall in a similar ballpark:

Magnetic Rubber: 20 – 200 mT (200 – 2000 G)
Ferrite Magnets: 150 – 300 mT (1500 – 3000 G)
Neodymium Magnets: 1 – 1.4 T (10,000 – 14,000 G)



Conclusions:

The non-reciprocal action of magnetic fields on graphene charge carriers introduces direction-dependent variations in charge transport, enhancing the I-V asymmetry in rectifiers. This could lead to more efficient, tunable, and high-performance graphene-based electronic devices, opening up new possibilities in nanoelectronics and signal processing technologies.

Further investigation and consistent quality of graphene samples are needed to explore the idea in greater detail.

Thanks for your kind attention !