Nonreciprocal Graphene-based Leaky-Wave Antennas: Theory and Applications

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Leaky-wave antennas (LWAs) have received considerable attention in recent decades thanks to their exciting radiation and beam-scanning properties [1]. These structures are based on the energy that is gradually radiated to free-space by an electromagnetic wave that propagates trough a waveguide with a phase velocity larger than the speed of light. Even though the fundamentals of leaky-waves were unveiled by electrical engineers during the second half of last century [1], their application to other fields such as optics and physics has allowed to understand and correctly interpret many intriguing phenomena across the electromagnetic spectrum, including extraordinary transmission, electromagnetic induced transparency, Wood's anomaly, or Cherenkov radiation. In addition, leaky-wave antennas with exciting properties, including the ability to independently control their complex propagation constant, reconfigurability, or even non-reciprocity, have recently been put forward at microwaves, millimeter-waves, and optics. At terahertz, a frequency region that lies in the technological gap between the well-developed areas of photonics and electronics, the potential of leaky-waves has not yet been fully exploited due to immature state of technology and relatively large amount of losses that materials exhibit in this band. In a related context, graphene has recently led to a revolution in material science thanks to its outstanding thermal, electrical, and mechanical properties. In particular, this two-dimensional material supports the propagation of surface plasmon polaritons (SPPs) at terahertz and infrared frequencies that exhibit moderate loss, strong wave localization, and the exceptional property of being tunable by applying a modest DC bias. Such properties have recently been applied to realize a wide variety of plasmonic antennas, including resonant dipoles and reflectarrays, at terahertz. In addition to inherent reconfigurability, graphene antennas show high radiation efficiency thanks to their large intrinsic wave impedance that permits to easily match photomixers –one of the most common terahertz sources– with high input impedances ($\approx$10kΩ). On the contrary, common metallic antennas at terahertz, despite exhibiting lower loss, have a small input impedance (in the range of 100s Ω) that prevents the efficient coupling of terahertz waves and their subsequent radiation.

In our previous works [2-4], we have introduced several configurations to realize graphene-based leaky-wave antennas at terahertz by spatially modulating graphene's conductivity, thus achieving efficiency radiation with beam scanning functionalities at a single operation frequency. In this contribution, we explore magnetic-free non-reciprocal leaky-wave radiation [5] enabled by the spatiotemporal modulation of graphene's conductivity. In order to analyze and design such antennas, we introduce a theoretical framework based on rigorously computing the eigenstates of the structure by expanding the electromagnetic fields in an infinite set of space-time harmonics. The resulting asymmetric dispersion relation permits to unveil the physical mechanisms that enables nonreciprocity in this type antennas: (i) the radiation pattern is different in reception and in transmission, with a change in gain, beamwidth, and pointing angle that depends on the modulation frequency; and (ii) the inherent frequency conversion of the system implies that the waves at the port oscillate at different frequency when operating in reception or in transmission. We have applied this formalism to investigate the response of nonreciprocal leaky-wave antennas versus graphene's biasing scheme, loss, and Fermi potential as well as to analyze and design antennas using realistic material properties. Results, validated through rigorous harmonic-balanced full-wave simulations in COMSOL Multiphysics, confirm the potential of this technology to achieve efficient nonreciprocal terahertz radiation. We envision that nonreciprocal leaky-wave antennas at terahertz will have ample applications in non-invading sensing, communication systems, and defense systems, among others.

[1] D. R. Jackson and A. A. Oliner, "Leaky-wave antennas," Mod. Antenna Handbook, pp. 325–367, 2008.
[2] D. Correas-Serrano and J. S. Gomez-Diaz, "Graphene-based Antennas for Terahertz Systems: A Review", *Fermat*, 2017.
[3] J. S. Gomez-Diaz, M. Esquius-Morote, and J. Perruisseau-Carrier, "Plane wave excitation-detection of non-resonant plasmons along finite-width graphene strips," Opt. Express, vol. 21, no. 21, p. 24856, 2013.
[4] M. Esquius-Morote, J. S. Gomez-Diaz, et al, "Sinusoidally modulated graphene leaky-wave antenna for electronic beamscanning at THz," IEEE Trans. Terahertz Sci. Technol., vol. 4, no. 1, pp. 116–122, May 2014.
[5] D. Correas-Serrano, J. S. Gomez-Diaz, et al, "Nonreciprocal Graphene Devices and Antennas Based on Spatiotemporal Modulation," IEEE Antennas Wirel. Propag. Lett., vol. 15, no. c, pp.1529–1533, 2016.