

## Modeling of electromagnetic wave propagation in semimetals

G. G. Gentili<sup>1</sup>, M. Oldoni<sup>1</sup>, A. Molle<sup>2</sup>, C. Martella<sup>2</sup>, C. Masetti<sup>2</sup>

1. Politecnico di Milano, DEIB, via Ponzio 34/5, 20133 Milano (Italy)

2. IMM-CNR, 20864 Via C. Olivetti, Agrate B. (MB)

**Abstract:** We describe a Finite Element Method formulation for the analysis of arbitrary layers of semimetal deposited on a substrate. The magneto-electric coupling has been introduced by axion electromagnetics. Numerical results indicate in some cases non reciprocal propagation in the form of anisotropic plasmons.

Weyl and Dirac semimetals may be considered a new frontier of non-trivial topological materials [1]. Their unconventional electromagnetic properties may open the way to applications in mm-wave, sub-THz and optics, such as new types of isolators and circulators, but also in thermal engineering (non-reciprocal thermal emission) [1-3].

The purpose of this paper is to set up a numerical modeling of electromagnetic propagation in semimetals. In some cases, the problem has been studied quite extensively in the past (e.g. graphene, a 2D Dirac semimetal), but in other cases there is basically no data available in the literature, whose focus is on the band structure and the corresponding physical properties.

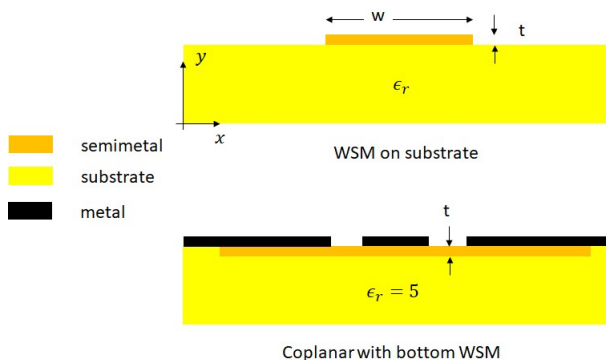
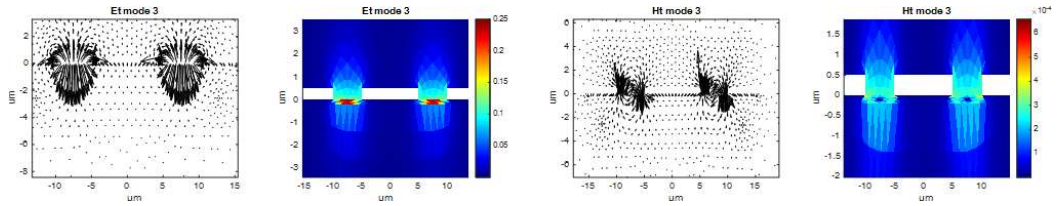


Fig.1 | The cross-sections of the structures analyzed.

However, an accurate modeling of wave propagation can be important in practical applications, especially in the sub-THz and THz frequency range. It should be noted that the specific form of magneto-electric coupling does not allow the use of commercial software and even by introducing some simplifications, the numerical performance of currently available commercial software was observed to lack of robustness.



**Fig. 2.** A mode propagating in the semimetal

For these reasons we have developed a custom numerical modeling of propagation in general semimetals based on the Finite Element Method (FEM). We discuss in this work the application to Weyl semimetals. The equation of propagation is derived in the frame of axion Maxwell's equations, obtained from a modified Lagrangian that includes the axion term [4]. The final result, after some manipulations, can be written as:

$$\begin{aligned}\nabla \times \mathbf{E} &= -j\omega\mathbf{B} \\ \nabla \times \mathbf{B} &= j\omega\mu_0\mathbf{E} - \frac{j\mu_0e^2\omega_e}{2\pi^2\omega\hbar}\nabla \times \mathbf{E} + \frac{\mu_0e^2}{2\pi^2\hbar}\boldsymbol{\kappa} \times \mathbf{E}\end{aligned}$$

The second term in the right-hand member of the second equation represents the chiral magnetic effect, whereas the last term represents the contribution of anomalous Hall current.

The discretization of the corresponding weak form is straightforward and it leads to a sparse non-symmetrical matrix equation that is solved by standard routines. The structures analyzed are shown in Fig. 1. An example of anisotropic plasmons is shown in Fig. 2. A more detailed discussion on the various modes is presented at the meeting.

## Contacts:

Gian Guido Gentili (gianguido.gentili@polimi.it)  
Alessandro Molle (alessandro.molle@cnr.it)

## References

[1] Rizza, C., Molle, A. Closing the THz gap with Dirac semimetals. *Light Sci Appl* **11**, 124 (2022). <https://doi.org/10.1038/s41377-022-00812-w>.

[2] Guo, C., Asadchy, V.S., Zhao, B. *et al.* Light control with Weyl semimetals. *eLight* **3**, 2 (2023). <https://doi.org/10.1186/s43593-022-00036-w>.

[3] Mustafa Sarisaman *et al* 2024 *J. Phys.: Condens. Matter* **36** 405603.

[4] Gratus, Jonathan and McCall, Martin W. and Kinsler, Paul, "Electromagnetism, axions, and topology: A first-order operator approach to constitutive responses provides greater freedom", *Phys. Rev. A* 101, 043804 – Published 7 April, 2020.