Radiation of Single Emitters Near Topological Insulators

24th AIP Congress

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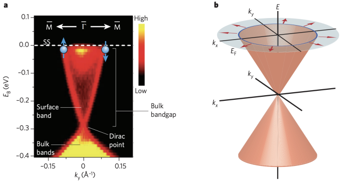
Motivation

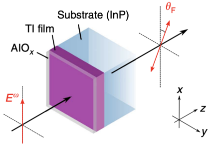
- Topological Insulators: Materials that present an insulating bulk while still having conductive edge states on their surface.
- Efforts to optically characterize TI seek to measure very small effects with specific and difficult-to-reproduce experimental conditions (i.e. Faraday Rotation).
- Objective: find new, fast, and spatially resolved techniques to characterize TIs optically.

Dirac Cone for Bi_2Se_3: ARPES vs Theoretical



Joel Moore. "The birth of topological insulators". In: *Nature* 464 (Mar. 2010), pp. 194–8

Faraday Rotation on TI Setup Sketch



Ken N Okada et al. "Terahertz spectroscopy on Faraday and Kerr rotations in a quantum anomalous Hall state". In: *Nature communications* 7 (2016)

Outline

Lagrangian Characterization of Topological Insulators

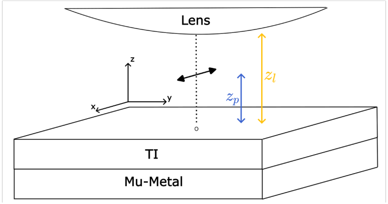
Maxwell Equations for Topological Insulators

- The Lagrangian of TI is $\mathcal{L}_0 + \mathcal{L}_{axion}$, where $\mathcal{L}_0$ is the usual electromagnetic Lagrangian and,

$$\mathcal{L}_{axion} = \frac{\alpha}{4\pi^2}\frac{\Theta(\mathbf{r},w)}{\mu_0 c}\mathbf{E}(\mathbf{r},\omega)\cdot\mathbf{B}(\mathbf{r},\omega).$$

- This extra term changes the Maxwell equations introducing an electromagnetic coupling.
- The Helmholtz equation is, then,

Sketch of Our Lens/Dipole/Material System



$$\nabla\times\frac{1}{\mu(\mathbf{r},\omega)}\nabla\times\mathbf{E}(\mathbf{r},\mathbf{w}) - \frac{\omega^2}{c^2}\epsilon(\mathbf{r},w)\mathbf{E}(\mathbf{r},w) - \underline{i\frac{\omega\alpha}{c\pi}\left[\nabla\Theta(\mathbf{r},\omega)\times\mathbf{E}(\mathbf{r},\omega)\right]} = 0.$$

Boundary Conditions for TIs and Point Charge Example

- The boundary conditions for a planar surface change.

$$[\hat{\mathbf{n}} \cdot \mathbf{B}]_{\Sigma} = 0,$$

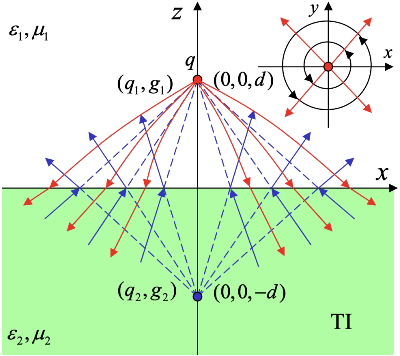
$$[\hat{\mathbf{n}} \times (\mathbf{B}/\mu)]_{\Sigma} = -\left(\frac{\alpha\Delta\Theta}{4\pi^2}\right) \hat{\mathbf{n}} \times \mathbf{E}|_{\Sigma},$$

$$[\hat{\mathbf{n}} \cdot \mathbf{E}]_{\Sigma} = 0,$$

$$[\hat{\mathbf{n}} \times (\epsilon\mathbf{E})]_{\Sigma} = -\left(\frac{\alpha\Delta\Theta}{4\pi^2}\right) \hat{\mathbf{n}} \cdot \mathbf{B}|_{\Sigma}.$$

- Point charge near TI's surface is a good example.

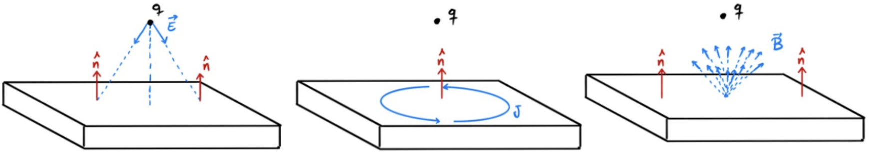
Image Method Solution for Point Charge Near a TI



Xiao-Liang Qi et al. "Inducing a Magnetic Monopole with Topological Surface States". In: *Science* 323.5918 (2009), pp. 1184–1187

Example: Point Charge near a Topological Insulator Surface

Schematization of Topological Effects of a Point Charge Near a TI



$$\sigma_{xy} = \frac{\Theta}{2\pi}\frac{e^2}{h} \qquad \mathbf{j} = \sigma_{xy}(\hat{n}\times\mathbf{E}) \qquad \hat{n}\times(\mathbf{B}/\mu) = \frac{\alpha}{\pi}\left(\frac{\Theta}{\sigma_{xy}}\right)\mathbf{j}$$

Characterizing the Reflected Emissions

Reflected and Transmitted Fields

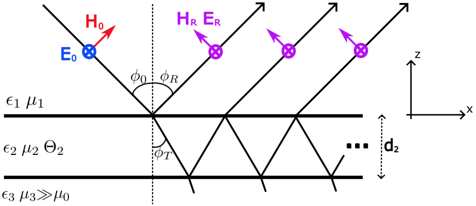
- Planar wave ansatz + new boundary conditions = Fresnel coefficients.
- New off-diagonal mixed coefficients appear:

$$\mathbf{R} = \begin{pmatrix} R_{TE,TE} & R_{TE,TM} \\ R_{TM,TE} & R_{TM,TM} \end{pmatrix}$$

- These new coefficients are small ($\times 10^{-5}$) compared to the usual ones.

J. A. Crosse, Sebastian Fuchs, and Stefan Yoshi Buhmann. "Electromagnetic Green's function for layered topological insulators". In: *Phys. Rev. A* 92 (6 Dec. 2015), p. 063831

TE polarized ray impacting the three-layered Air-TI-Mu-Metal system



Adding a Third Mu-Metal Sublayer

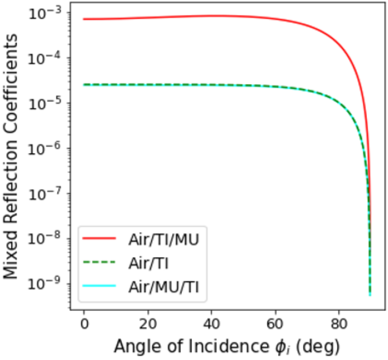


Figure: Mixed reflective coefficients as a function of the incidence angle for the three possible configurations.

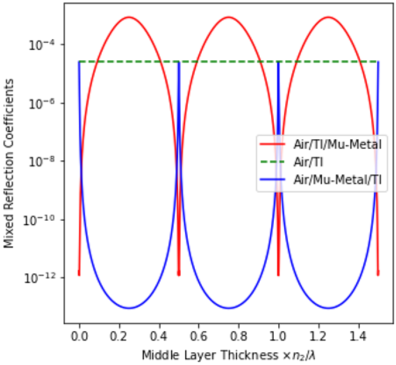
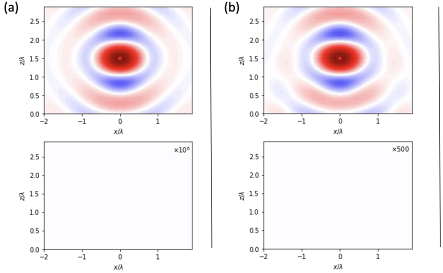


Figure: Mixed reflective coefficients as a function of the normalized middle layer's thickness.

Electric Field Components



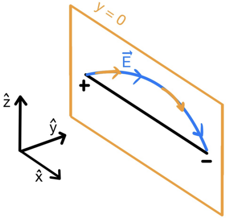
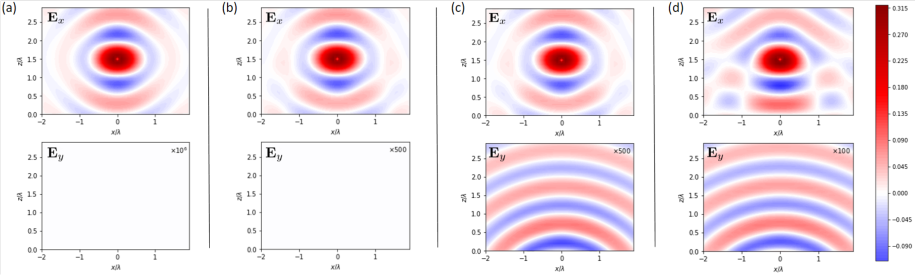


Figure: Electric field components $\mathbf{E}_i \times \lambda$ of an $\hat{x}$ oriented dipole, plotted in the $y = 0$ plane, as a function of z/λ and x/λ for (a) free-space, (b) an Air/Magnetodielectric configuration, (c) an Air/TI configuration, and an Air/TI/Mu-Metal configuration.

Electric Field Components



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Poynting Vector Deviation

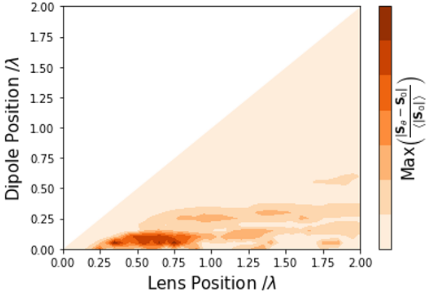


Figure: Maximum deviation in the $\hat{y}$ axis of the Poynting vector for a set of collection lens-dipole-TI configurations.

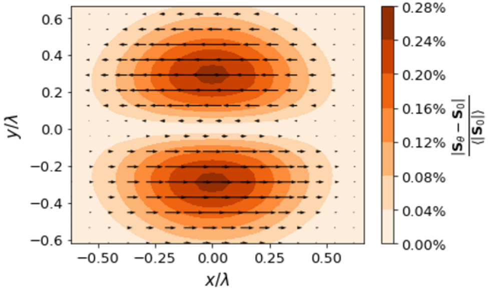
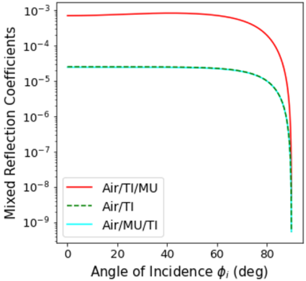
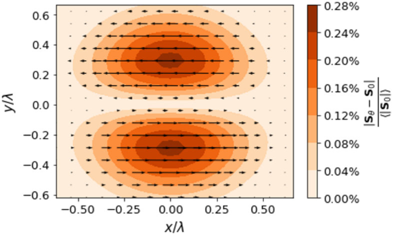


Figure: Difference between the Poynting vector generated by an $\hat{x}$ oriented dipole over a TI's surface $\mathbf{S}_\theta$, and over the equivalent magnetodielectric surface $\mathbf{S_0}$.

Summary

- By adding a third Mu-Metal sub-layer, we predict an increase of $\sim \times 10^2$ for a TI with impedance $Z = \sqrt{2}$.
- We were able to pinpoint the optimal TI middle layer's thickness, given its optical characteristics.
- We theorized a far-field Poynting vector deviation of 0.28% with an optimal system configuration, for a room temperature TI.
- Future prospects: Quantum analysis and NV-center characterization.





Acknowledgments

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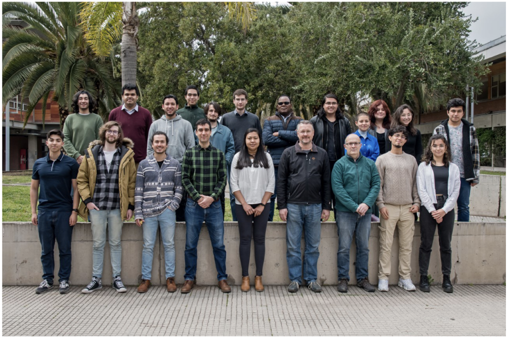

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