Probing Dirac plasmon polaritons in bismuth selenide coupled nano-antennas by terahertz near-field microscopy

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Abstract. The study of Dirac plasmon polaritons (DPPs) in two-dimensional materials has raised considerable interest in the last years for the development of tunable optical devices, plasmonic sensors, ultrafast absorbers, modulators, and switches. In particular, topological insulators (TIs) represent an ideal material platform by virtue of the plasmon polaritons sustained by the Dirac carriers in their surface states. However, tracking DPP propagation at terahertz (THz) frequencies, with wavelength much smaller than that of the free-space photons, represents a challenging task. Herein, we trace the propagation of DPPs in TI-based coupled antennas. We show how Bi_2Se_3 rectangular nano-antennas effectively confine DPPs propagation to one dimension, enhancing their visibility despite intrinsic attenuation. Furthermore, plasmon dispersion and loss properties of coupled antenna resonators, patterned at varying lengths and distances are experimentally determined using holographic near-field nano-imaging at different THz frequencies. Our study evidences modifications on the DPP wavelength along the single nano-antenna ascribable to the cross-talk between neighbouring elements. The results provide insights into DPPs characteristics, paving the way for the design of novel topological devices and metasurfaces by leveraging their directional propagation capabilities.

Introduction

Topological insulators (TIs) are quantum materials characterized by an insulating bulk and conducting surface states, conventionally known as topological surface states (TSSs), which reside within the topological bandgap [1]. Due to the unique topology of their band structure, charge carriers within TSSs are shielded from backscattering caused by defects and disorder [2]. These carriers can engage in collective excitations at the TI surface, specifically the Dirac plasmon polaritons (DPPs) [3]. This distinctive property holds promise for applications in quantum information [4], spintronics [5], terahertz (THz) photonics [6], and laser physics [7].

Experimental characterization of DPPs in TIs is crucial, yet challenging due to the fact that their wavelength is about one order of magnitude shorter than the free-space photon wavelength [3]. Recently, THz scattering-type scanning near-field optical microscopy (s-SNOM) has been successfully employed to probe DPPs in TIs [8,9]. While s-SNOM confirms the deeply subwavelength nature of DPPs, it also reveals challenges such as strong attenuation [8]. To address this issue, Bi_2Se_3 rectangular antennas have been recently adopted to efficiently confine the propagation of DPPs to a single dimension and, as a result, enhance their visibility despite the inherently strong intrinsic attenuation [10].

Here, we present a systematic investigation of DPPs properties in systems of coupled TI nano-antenna resonators and study the influence of the resonator coupling on the DDP dispersion. To capture the DDPs, we perform THz s-SNOM on a set of single Bi_2Se_3 antennas of various lengths, and on a set of double and triple antennas, sharing different lengths and coupling distance, at multiple THz frequencies. The experimental approach is based on a detector-less configuration that exploits the self-mixing (SM) phenomenon occurring in quantum cascade lasers (QCLs) [11,12]. The spatial mapping of the DPP phase, and thus the retrieval of the complex DPP wavevector $\mathbf{k}_p$ is obtained through near-field holographic mapping. The experimental results show that the s-SNOM signal within the single TI antenna resonator is dominated by the DPPs launched by the s-SNOM tip, whose dispersion can be modulated by coupling with an adjacent resonating element at an appropriate distance. The possibility to control the DPP dispersion, open promising perspectives for the development of nanophotonic devices with a response tunable-by-design.

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Results and Discussion

The Bi_2Se_3 film is grown via molecular beam epitaxy (MBE) at 80 nm thickness and patterned via electron-beam lithography in rectangular shape in single, doublet and triplet configuration (Fig. 1a), in the latter cases with a spacing of 1 and 2 µm between each nano-antenna, along the *y* direction. The DPP wavevector dispersion $\mathbf{k}_p(\omega)$ is probed at different frequencies by means of single-mode THz QCLs. The THz near-field SM signal is retrieved by lock-in detection of the voltage variation, induced by the cavity-reinjected photons across the QCL terminals, which is demodulated at the third harmonic order of the tapping frequency, so as to get rid of undesired background [11]. Holography is implemented by sampling the SM patterns in the time domain by means of an optical delay line while spatially scanning the antennas along its main axis direction.

The resulting phase profiles along the antenna axis *x* (Fig 1b) can be schematized as two counterpropagating DPPs [10]:

$$\tilde{E}_{DPP}(x) = \boldsymbol{A}\left(e^{2i\boldsymbol{k}_p\left(x+\frac{L}{2}\right)} + e^{-2i\boldsymbol{k}_p\left(x-\frac{L}{2}\right)}\right), \qquad (1)$$

where **A** is the complex amplitude, $\mathbf{k}_p = 2\pi/\lambda_p + i/L_p$ is the complex wavevector, L is the antenna length, $x = 0$ is set at the antenna center. Equation (1) well reproduces the oscillating and symmetric features at the antenna ends and their gradual damping towards the center.

Fig. 1c reports the DPP dispersion extrapolated for a single antenna (16×4 µm^2) compared to the case of the doublets and triplets at different spacings. The presence of a coupled resonator alters the DDP dispersion, causing a larger (by ~33%) propagating wavevector when the antennas become closely coupled. This occurs also in the case of triple resonators, once probing the DDP across the central element.

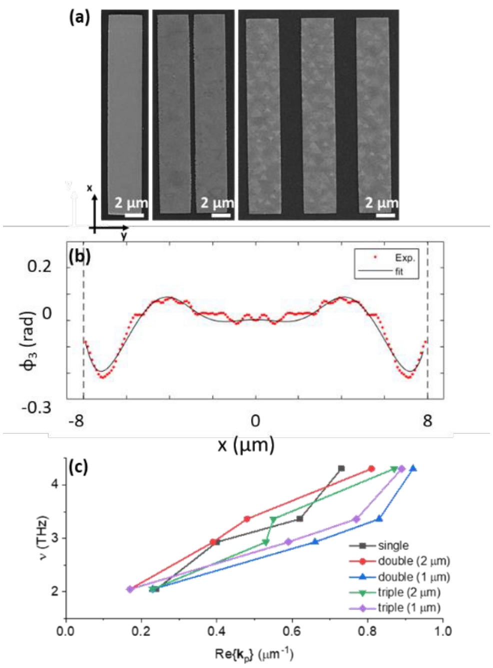

Fig. 1. (a) Representative SEM micrographs of a Bi_2Se_3 antenna and of the prototypical double- and triple-antenna systems. (b) DPP spatial phase profile measured on a single 16×4 µm^2 antenna, as retrieved by near-field holography at 3 THz, while driving the QCL source in continuous wave at a current of 370 mA, at temperature 15 K. (c) Comparison of the DPP dispersion of the single antenna and the correspondent doublet and triplet at different spacing.

Conclusions

In summary, we report on the investigation Dirac plasmon polaritons utilizing rectangular nano-antennas fabricated from MBE-grown Bi_2Se_3 via detector-less THz s-SNOM. The employed geometry serves as an effective platform for controlling and tuning the DPP dispersion of TIs at THz frequencies. A visible modulation of the near-field response is demonstrated by tailoring the coupling of the single nano-antenna with a neighbouring element that visibly alter the propagating mode dispersion. The ability to purely capture DPPs, launched by the s-SNOM tip in precisely defined structures, presents exciting prospects in THz nanoplasmonics and topological nanophotonics. Future perspectives include the development of integrated devices capable of confining THz radiation within deeply subwavelength volumes and THz metasurfaces featuring subwavelength meta-atoms.

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References

1. C. L. Kane and E. J. Mele, Phys. Rev. Lett. **95**, 146802 (2005).
2. J. E. Moore and L. Balents, Phys. Rev. B **75**, 121306 (2007).
3. P. Di Pietro, M. Ortolani, O. Limaj, A. Di Gaspare, V. Giliberti, F. Giorgianni, M. Brahlek, N. Bansal, N. Koirala, S. Oh, P. Calvani, and S. Lupi, Nat. Nanotechnol. **8**, 556 (2013).
4. M. He, H. Sun, and Q. L. He, Front. Phys. **14**, 1 (2019).
5. Q. L. He, T. L. Hughes, N. P. Armitage, Y. Tokura, and K. L. Wang, Nat. Mater. **21**, 15 (2021).
6. F. Giorgianni, E. Chiadroni, A. Rovere, M. Cestelli-Guidi, A. Perucchi, M. Bellaveglia, M. Castellano, D. Di Giovenale, G. Di Pirro, M. Ferrario, R. Pompili, C. Vaccarezza, F. Villa, A. Cianchi, A. Mostacci, M. Petrarca, M. Brahlek, N. Koirala, S. Oh, and S. Lupi, Nat. Commun. **7**, 1 (2016).
7. P. Yan, R. Lin, S. Ruan, A. Liu, H. Chen, Y. Zheng, S. Chen, C. Guo, and J. Hu, Sci. Rep. **5**, 1 (2015).
8. E. A. A. Pogna, L. Viti, A. Politano, M. Brambilla, G. Scamarcio, and M. S. Vitiello, Nat. Commun. **12**, 1 (2021).
9. S. Chen, A. Bylinkin, Z. Wang, M. Schnell, G. Chandan, P. Li, A. Y. Nikitin, S. Law, and R. Hillenbrand, Nat. Commun. **13**, 1 (2022).
10. V. Pistore, L. Viti, C. Schiattarella, Z. Wang, S. Law, O. Mitrofanov, and M. S. Vitiello, Small 2308116 (2023).
11. E. A. A. Pogna, C. Silvestri, L. L. Columbo, M. Brambilla, G. Scamarcio, and M. S. Vitiello, APL Photonics **6**, 061302 (2021).
12. K. S. Reichel, E. A. A. Pogna, S. Biasco, L. Viti, A. Di Gaspare, H. E. Beere, D. A. Ritchie, and M. S. Vitiello, Nanophotonics **10**, 1495 (2021).