Single-peak narrowband thermal emission of light based on plasmonic metasurfaces driven by quasi-BIC

Sen Yang[1], **Mingze He**[2], **Josh Nordlander**[3], **Joshua D. Caldwell**[1,2], **and Justus C. Ndukaife1**[1,4]

1. Interdisciplinary Materials Science, Vanderbilt University, TN 37235, USA
2. Department of Mechanical Engineering, Vanderbilt University, TN 37235, USA
3. Department of Materials Science and Engineering, Pennsylvania State University, University Park, PA 16801, USA
4. Department of Electrical and Computer Engineering, Vanderbilt University, Nashville, Tennessee 37235, USA
justus.ndukaife@vanderbilt.edu

The development of inexpensive and efficient infrared light sources is highly desirable for a variety of applications, including free-space communications, infrared beacons, barcodes, and monitoring environmental pollutants and toxins through molecular sensing metrologies like non-dispersive infrared (NDIR) sensing. Thermal emitters typically have a broad spectrum determined by Planck's law. Consequently, wavelength-selective thermal emitters with a narrow bandwidth and high peak emissivity are of particular interest due to the lack of cost-effective light sources in the mid- to long-wave infrared range. The principle of thermal emission control is based on Kirchhoff's law of thermal radiation, which states that the emissivity of an object equals its absorptivity for a given frequency, direction, and polarization. By creating an optical resonance and engineering the absorptivity at a specific frequency, a well-performing thermal emitter can be achieved. Metallic nanostructures have been extensively studied in this regard; however, their strong free carrier absorption results in undesired emissions over a wide wavelength range, and the emission peaks are broadened ($Q < 10$). Surface-phonon polariton resonances in polar materials are also promising candidates but have intrinsic limitations such as the inability to tune the emission wavelength over a wide range. Thermal metasurfaces offer another promising avenue, as experimentally demonstrated in [1], with the ability to emit arbitrarily polarized and unidirectional light. However, the optical properties of dielectric materials used in these metasurfaces are dependent on temperature.

Here we introduce a novel approach to create a narrowband thermal emitter with a single peak using a mirror-coupled plasmonic quasi-BIC metasurface [2]. The metasurface is composed of elliptical gold resonators arranged in a zigzag array, positioned on a DyF_3 dielectric spacer, followed by a CdO reflector and a sapphire substrate (see Fig. 1(a)). We have specifically selected these materials to ensure that the optical responses of the emitter remain stable under different temperatures. Our proposed system is designed to support a resonance at 2222 cm^{-1}, which overlaps with the absorption peak of N_2O, since one of our intended applications is NDIR sensing. Unlike all-dielectric designs, metallic nanostructures are less susceptible to temperature-dependent resonance variation as their permittivity is dominated by the imaginary part at mid-IR. We have engineered the critical coupling between the intrinsic material loss and the radiative loss of the quasi-BIC mode, resulting in an ultra-narrowband absorptance peak with a Q of approximately 65 and near-unity absorptance of 96.6%. This level of performance is not achievable in traditional metallic designs. By introducing slots (see Fig. 1(b)) [3], we have been able to achieve an even higher Q of approximately 111, with the peak absorptance remaining high at 66.4%. Compared to other strategies, such as Tamm plasmon polariton thermal emitters [4], phonon polariton resonances, and photonic crystals, our design offers a well-balanced performance and fabrication complexity. It allows for a designable single-frequency peak ranging from 3 um to 13 um (see Figure 1(e)) while having a relatively simple fabrication process. Notably, our proposed quasi-BIC-based thermal emitter is not limited to wide-angle single wavelength operation, and more complicated functions such as polarization engineering (see Figure 1(c)) and directionality are also proposed.

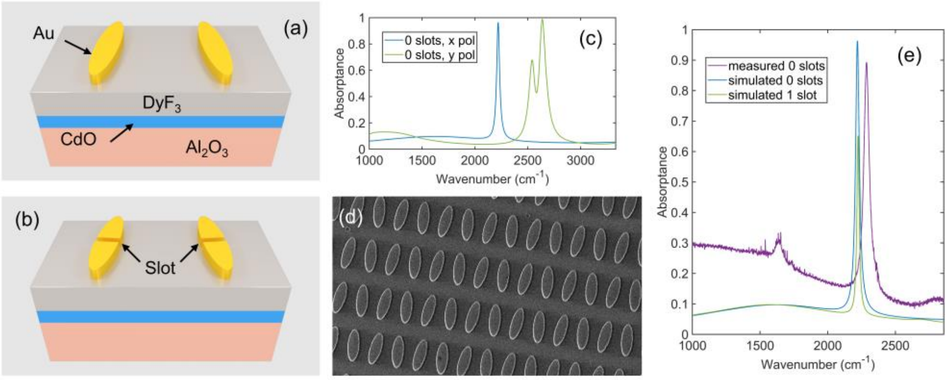

Fig. 1 (a) Schematic of the mirror-coupled plasmonic quasi-BIC metasurface. (b) Adding a slot to each of the elliptical gold antennas in one unit cell. (c) Simulated absorptance spectra for 0 slots case with *x* and *y* polarizations, respectively. (d) Representative SEM image. (e) Simulated and measured absorptance spectra for 0 and 1 slots cases with *x* polarization.

References

[1] Nolen, J.R., Overvig, A.C., Cotrufo, M. and Alù, A. (2023). arXiv preprint, arXiv:2301.12301.
[2] Wang, J., Weber, T., Aigner, A., Maier, S.A. and Tittl, A. (2022). *arXiv preprint*, arXiv:2211.03673.
[3] Yang, S., He, M., Hong, C., Caldwell, J. D., and Ndukaife, J. C. (2022). *Nano Lett.*, **22**(20), 8060-8067.
[4] He, M., Nolen, J.R., Nordlander, J., Cleri, A., McIlwaine, N.S., Tang, Y., Lu, G., Folland, et al. (2021). Nat. Mater. 20(12), 1663-1669.