# Near-field spectroscopy of a phonon polariton infrared metasurface

**Andrea Mancini[1, *], Christopher R. Gubbin[2], Rodrigo Berte[1], Alberto Politi[2], Yi Li[3], Simone De Liberato[2], and Stefan A. Maier[1]**

[1]Chair in Hybrid Nanosystems, Nanoinstitute Munich, Faculty of Physics, Ludwig-Maxilimians-Universität München, 80539 München, Germany
[2]School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom
[3]School of Microelectronics, MOE Engineering Research Center of Integrated Circuits for Next Generation Communications, Southern University of Science and Technology, Shenzhen 518055, China
*corresponding author, E-mail: `A.Mancini@lmu.de`

## Abstract

Surface Phonon Polaritons (SPhPs) can be excited in the Reststrahlen band of polar dielectrics where the dielectric function is negative. Antennas supporting surface phonon polaritons are an alternative to plasmonic resonators in the infrared, due to their reduced losses and higher field confinement. We investigate the near-field response of arrays of Silicon Carbide antennas by means of scattering scanning near field microscopy. Knowledge of the near-field response is needed for many applications requiring coupling of the antennas to other elements.

## 1. Introduction

The lifetime of plasmonic excitations depends on the material properties of the metal employed, and is related to the typical electron-electron scattering rate. As a consequence, plasmon dephasing happens in the range of tens of femtoseconds, and the quality factor of plasmonic resonances for isolated antennas is rather low. The loss in metallic antennas at optical frequencies has limited their employment in a variety of applications where high quality factors and low losses are required [1]. In the mid-IR polar dielectrics can also behave, from an electromagnetic point of view, as metals due to the presence of a region called the Reststrahlen (RS) band where the real part of the dielectric function $\varepsilon_1$ is negative. The RS band is enabled by the strong dispersive lineshape of $\varepsilon_1$ around a TO phonon. Antennas made of polar dielectrics allow subwavelength confinement and the lifetime of their localized SPhPs resonances are higher than in metals (on the order of picoseconds, two orders of magnitude higher than for plasmons) due to the smaller phonon-phonon scattering rate which determines SPhPs decay. Consequently, SPhPs antennas provide much stronger field confinement and lower losses if compared to analogous plasmonic structures in the IR. Many possible photonic applications require knowledge of the near-field spectral behavior of the system under investigation, which cannot be obtained or easily inferred from far-field measurements. Scattering scanning near field optical microscopy (sSNOM) has been demonstrated as a powerful tool to investigate the near-field properties of optical resonators [3]. Here, we report on the near-field study a metasurface composed of Silicon Carbide (SiC) cylindrical antennas [4].

## 2. Results and Discussion

One limitation of SPhPs is the narrow frequency band in which they can be excited. SiC is particularly interesting as its RS band is one of the largest of known polar dielectrics, spanning from $\omega_{\mathrm{TO}}$=796 cm$^{-1}$ to $\omega_{\mathrm{LO}}$=973 cm$^{-1}$. Moreover, SiC is already employed in power electronics and its processing is CMOS-compatible. Among different geometries, arrays of SiC pillars have attracted considerable attention thanks to their rich electromagnetic response, including broadly tunable modes [5] and nonlinear response [6]. In Fig. 1(a) a SEM image of a portion of one of the arrays is reported, along the experimental FTIR (b) and simulated (c) reflectance spectra for different metasurfaces with varying spacing *P*.

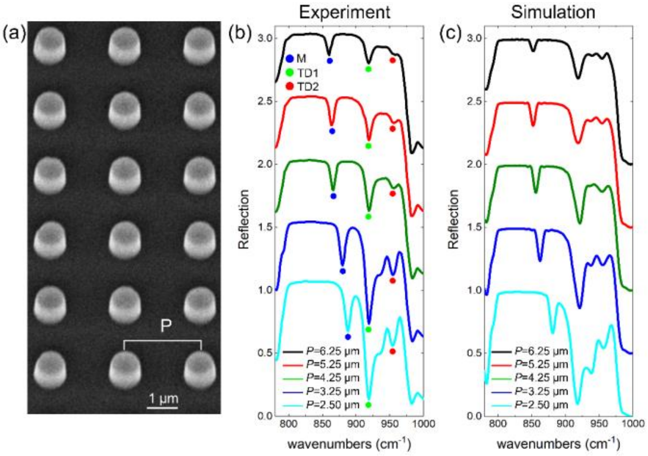

Figure 1: (a) SEM of a portion of a SiC pillars array. Experimental (b) and simulated (c) reflectance spectra for different array spacing *P*. The different modes are highlighted by dots.

The modes of the structure can be described from the coupling of simple longitudinal and transverse resonances of a single pillar to the bare SiC surface supporting SPhPs at $\omega$=951 cm$^{-1}$ [6]. Three main resonances can be identified from the spectra, a monopolar mode (M) redshifting with increasing $P$ and two transverse dipolar resonances (TD1 and TD2) at $\omega_{TD1}$=921 cm$^{-1}$ and $\omega_{TD2}$=955 cm$^{-1}$ independent of $P$. For $P$=2.5 $\mu$m the field enhancement simulations for the three resonances are reported in Fig. 2.

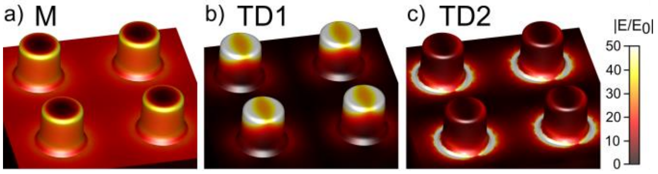

Figure 2: Simulated field profiles for the M mode (a) the TD1 mode (b) and the TD2 mode (c).

We study the near-field response of the arrays by positioning the sSNOM tip either on top of one of the pillars, or on the substrate between them, as shown in Fig. 3.

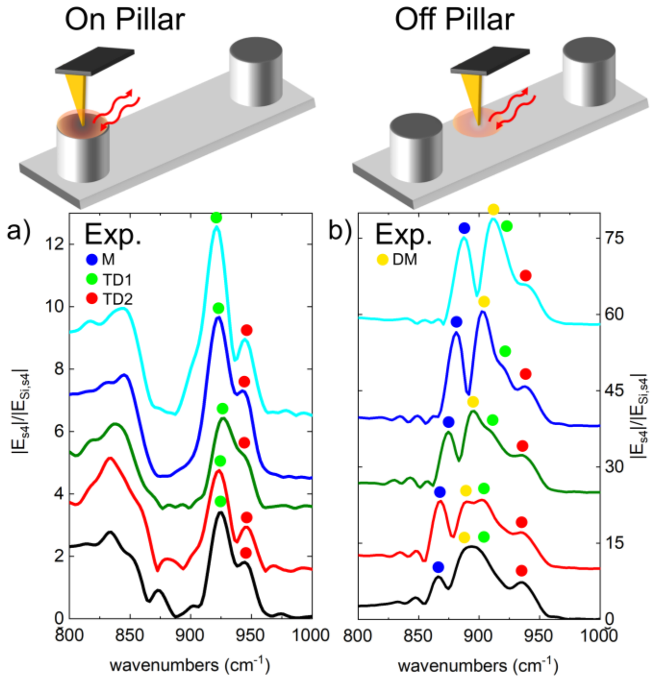

Figure 3: Near-field measurements of the different arrays when placing the AFM tip on top of a pillar (a) or on the substrate between pillars (b).

The response on the pillars is independent of $P$, as two peaks, marked with green and red dots, at $\omega_{TD1}$=920 cm$^{-1}$ and $\omega_{TD2}$=945 cm$^{-1}$ can be individuated for all $P$ with frequencies matching the far-field measurements. When measuring off pillars the monopolar mode can be identified as the lower energy peak, closely matching the frequency reported in the FTIR far-field data. An additional peak appears in the spectra (yellow dot in Fig. 3(b)), redshifting with the monopolar mode, which has no counterpart in the far-field. This mode arises from the near-field illumination of the tip, which allows excitations of modes that are otherwise "dark" due to having net zero dipole moment. We confirm this with simulations where we take into account the presence of the AFM tip in the form of a metallic sphere located on top of a pillar. To isolate the contribution of the tip we first solve for the pillar in the absence of the sphere with plane wave excitation, and then we use this field as a background that we subtract from the full simulation including the sphere. An additional peak analogous to what observed in the experiments is found in the tip-induced scattering cross section [4].

## 3. Conclusions

In conclusion, we reported on the near-field study of the spectral response of arrays of SPhPs SiC pillar resonators in the mid-IR by means of sSNOM. The understanding of the near-field spectral response of SPhPs resonators is of critical importance for their employment in any application requiring near-field interaction. We further employ 3D electromagnetic simulations to understand the effect of the sSNOM tip in modifying the response of the SPhPs antennas.

## References

[1] J. B. Khurgin, "How to deal with the loss in plasmonics and metamaterials," *Nat. Nanotechnol.*, vol. 10, no. 1, pp. 2–6, 2015.

[2] J. D. Caldwell *et al.*, "Review article Low-loss , infrared and terahertz nanophotonics using surface phonon polaritons," pp. 44–68, 2015.

[3] R. Hillenbrand, T. Taubner, and F. Keilmann, "Phonon-enhanced light-matter interaction at the nanometre scale," *Nature*, vol. 418, no. 6894, pp. 159–162, 2002.

[4] Mancini, Andrea, et al. "Near-field spectroscopy of cylindrical phonon-polariton antennas." ACS nano 14.7, 8508-8517, (2020).

[5] Y. Chen *et al.*, "Spectral Tuning of Localized Surface Phonon Polariton Resonators for Low-Loss Mid-IR Applications," *ACS Photonics*, vol. 1, no. 8, pp. 718–724, 2014.

[6] I. Razdolski *et al.*, "Resonant Enhancement of Second-Harmonic Generation in the Mid- Infrared Using Localized Surface Phonon Polaritons in Subdi ff ractional Nanostructures," 2016

[7] C. R. Gubbin, S. A. Maier, and S. De Liberato, "Theoretical investigation of phonon polaritons in SiC micropillar resonators," vol. 035313, pp. 1–9, 2017.