Mid-Infrared Optical Nanoantennas Using Hyperbolic Hexagonal Boron Nitride Phonon Polaritons

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***Abstract*—We demonstrate deeply subwavelength hexagonal boron nitride (h-BN) resonating nano particles and nanoantennas operating at mid infrared (mid-IR) frequencies. The resonant response is due to h-BN phonon polaritons, similarly to plasmon polaritons in graphene particles, allowing strong field enhancement in the gap of dipole h-BN nanoantennas. We image the near field of these structures using hyperspectral photo-induced force microscopy (PiFM) and scattering type near field optical microscopy (s-NSOM). The higher quality factor of these phonon polaritons with respect to graphene plasmons paves the way to new applications for mid-IR nano-optics as well as new research prospects for antenna theory.**

***Keywords*—Hexagonal boron nitride, phonon polariton, nanoantennas, mid-infrared, near field microscopy.**

I. H-BN NANORESONATORS

Graphene plasmon polaritons have attracted great interest for the realization of highly miniaturized optical antenna for terahertz and infrared light [1, 2]. However, other types of polaritons have been recently discovered in 2D materials, which can lead to similar or even better performances. Notably, phonon polaritons in h-BN have been observed as highly confined surface modes both in unpatterned and patterned h-BN flakes of few to hundreds of nanometers [3-8].

A phonon polariton consists of strong coupling between light and phonons, i.e. vibration of atoms in a solid around their equilibrium position. Unlike graphene, coupling is possible in h-BN since its unit cell is composed of two different atoms (boron and nitrogen) with slightly different charge (due to the asymmetry of the covalent bonds). An applied electric field can then pull these atoms away from each other, and excite optical phonons. This results in two restrahlen bands (RS1 and RS2) where the in-plane and out-of-plane permittivity reaches negative values up to several hundreds (Fig 1A). In the RS2 band, a fundamental guided mode exists (Fig 1B, 1C) with geometry very close to graphene plasmons.

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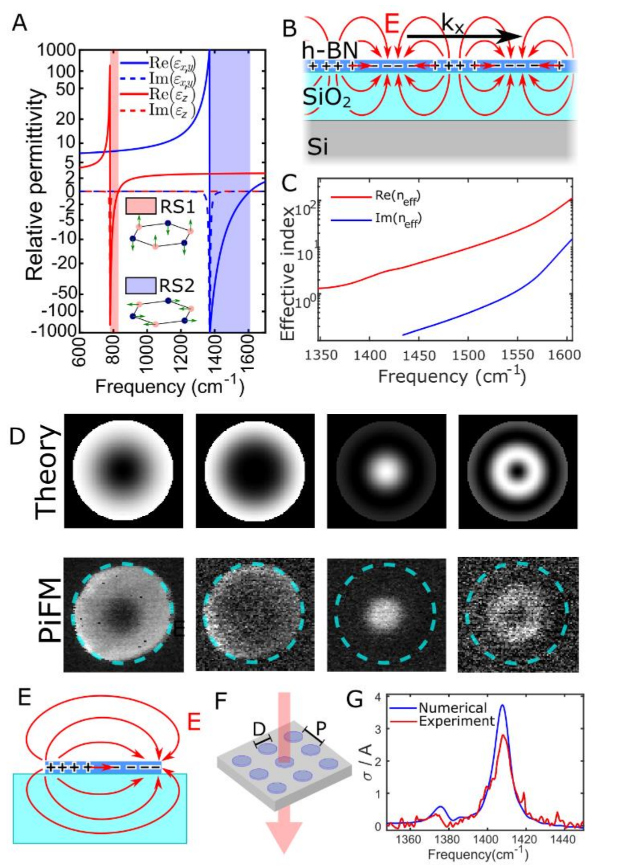

Fig. 1. A) In plane and out of plane components of the anisotropic dielectric permittivity of h-BN. B) Fundamental propagation mode in the RS2 band for a flake of h-BN and C) its effective index as a function of the frequency. D) comparison between theory and PiFM measures of the first resonant modes of an h-BN nanodisc of thickness 50 nm and diameter 730 nm. Because in PiFM both excitation and readout of the mode are performed by the AFM tip, all the imaged modes have circular symmetry. For instance, at the frequency of the fundamental mode (dipolar, figure E), both polarization are excited and the final image is isotropic. F) An array of nanodiscs (disc diameter D = 480 nm, periodicity P = 1.25μm) on silicon can interact with incident light via the bright modes. G) Extinction cross-section of a single nanodisc obtained from FTIR transmission measurements of the array in F, and compared with FDTD simulations. The cross-section has been normalized with respect to the actual area of the disc. The fundamental resonance occurs for 1410 cm^{-1}, at which the cross-section is about 3 times larger than the actual area.

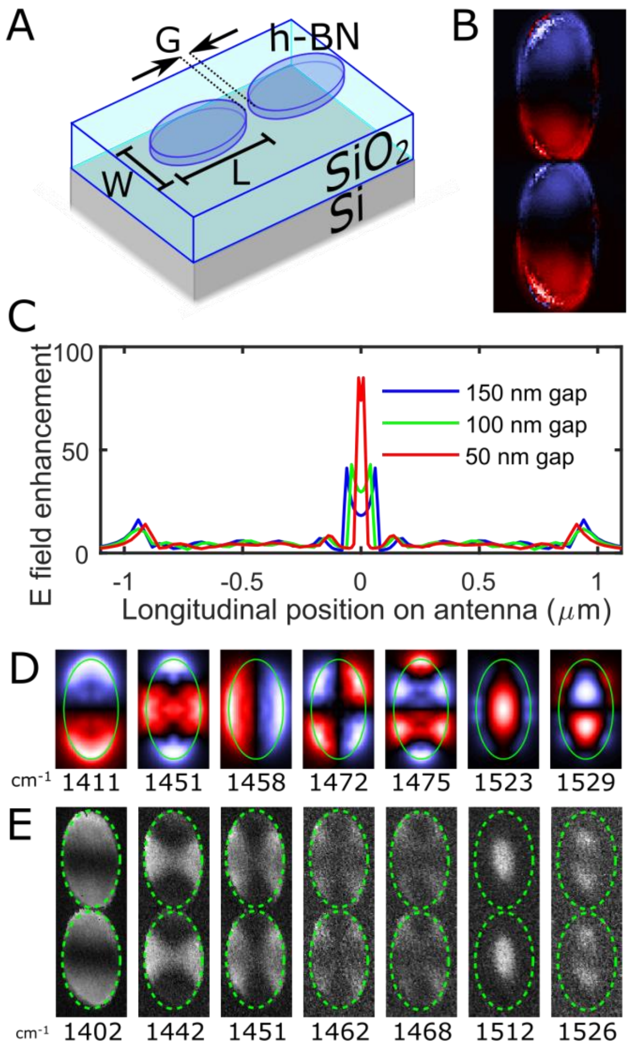

Fig. 2. A) Geometry of the proposed optical polaritonic h-BN dipole antenna (W = 440 nm, L = 850 nm, $G \cong$ 50 nm, t = 50 nm). B) Near field image of the electric field (z component) of the fundamental mode of the antenna, imaged with s-NSOM. The image shows the real part with sign, so that the opposite field values at the extremes are visible. C) Numerical simulations of the electric field (component parallel to the antenna) for different gap sizes. The increasing field for smaller gaps indicates that the device is operating as an antenna. D) numerical simulation of the first seven resonant modes for a single elliptical antenna arm. E) PiFM imaging of the first modes, which show excellent agreement with the theoretical calculations.

When h-BN is patterned in shapes having size in the order of the guided wavelength, these particles act as nano-resonators. h-BN nanodiscs, for example, exhibit a rich spectrum of resonances that can be imaged using PiFM. This technique consists in tapping the sample with an AFM tip while shining modulated light on it; the optical forces created on the tip by the optical fields can then be read from the AFM signals. The resulting imaged modes are in excellent agreement with theory (Fig 1D). The fundamental mode is bright (Fig 1E), i.e. can be excited simply by shining light on the sample (Fig 1F). Due to the strong interaction and high quality factor (Q>100) of the resonance, the extinction cross-section of a single particle is several times its actual area (Fig 1G).

II. H-BN Nanoantennas

If the nano-disc is elongated to form an ellipse, the fundamental resonance will be polarized along the major ellipse axis, with maximum field intensity at the ends of the major axis. Placing two of such ellipses close to each other, it is possible to create an h-BN dipole nanoantenna (Fig. 2A). Shining light polarized along the antenna and performing s-SNOM measurement, the resonant mode of the antenna can be imaged including phase information (Fig. 2B).

Numerical simulations show that the longitudinal field is greatly enhanced (up to almost 100 times) in the antenna gap (Fig. 2C), and it is larger for smaller gap. This is consistent with the behavior of an antenna, where the field in the gap is the input voltage divided by the gap length G, and hence is expected to be inversely proportional to G. Finally, higher order modes are visible with PiFM (Fig. 2D) and they match well with the numerical FDTD simulations (Fig. 2E).

III. Conclusions

We believe that the unique ability of phonon polaritons in h-BN nanostructures to enhance the interaction of infrared light with matter will pave the way to a new class of efficient and highly miniaturized nanophotonics devices. In fact, these phonon polaritons are certainly excellent candidates to be mid-infrared counterparts for noble metal plasmons in the visible range, with important implications for future mid-infrared optical devices and antennas.

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