Multi-wavelength polar-dielectric superlens and graphene superlens

P. Li, T. Taubner

1. Insitute of physics (IA), RWTH Aachen University

A superlens is a very promising device to overcome the diffraction limit and resolve subwavelength features. However, the practical application of the superlens is limited by its narrow bandwidth. For dispersive materials, this condition limits operation to a very small wavelength range for each material system. In order to overcome this bandwidth limitation of superlenses, we propose two new designs based on layered materials: a multi-wavelength superlens using different polar dielectrics and a frequency-tunable graphene superlens.

A so-called superlens (SL) is capable of imaging the samples at subwavelength resolution by using a thin slab of a material with negative permittivity [1]. In principle, due to the small effective wavelength of surface modes at the interfaces between the negative-permittivity layer and positive-permittivity host, the SL can be seen as a practical version of perfect lens allowing for non-diffraction-limited imaging and sensing. However, a practical limitation in the SL is the narrow bandwidth. Although the surface resonance contributes a lot to the ultrahigh resolution of the SL, it also constrains that the SL can only work in the frequency range close to the resonance [2], which limits superlenses in spectroscopic applications.

In order to overcome this limitation, we present two possibilities based on layered materials. The first idea is a multi-wavelength SL [3] with layered phonon-resonant dielectrics. This proposed scheme is based on the fact that increasing the number of phonon resonant dielectrics in a multilayered system can provide additional degrees of freedom for superlensing at multiple wavelengths. In other words, a subwavelength image can be achieved at many different wavelengths by only one single lens. Considering the abundance of polar dielectrics, the wavelength range of our lens can cover from IR to THz frequencies by choosing suitable materials.

Generally, the superlensing effect requires a matching condition $\varepsilon_{lens}(\lambda)=-|\varepsilon_{host}(\lambda)|$, where ε_{host} is the permittivity of the host medium interfacing the lens [1]. For dispersive materials, this condition limits operation to a small wavelength range for each material system. For example, the condition is met at a wavelength of around 365 nm for silver–polymer combination [4], and 11 μm [2] for SiC-SiO_2 case.Our design is based on a multilayer (ML) superlensing theory. The superlensing condition $\varepsilon_{lens}(\lambda)=-|\varepsilon_{host}(\lambda)|$ can be fulfilled in two cases: (1) $\varepsilon_1>0$, $\varepsilon_2<0$ and (2) $\varepsilon_1<0$, $\varepsilon_2>0$. Polar dielectric layers, such as SiC, indium phosphide (InP), indium antimonide (InSb), can provide additional degrees of freedom for achieving superlensing at different wavelengths. As shown in Fig.1, dielectric permittivities of polar dielectrics are negative in the so-called *reststrahlen* band between the transverse and longitudinal optical-phonon frequencies. When the wavelength is out of the *reststrahlen* band, their permittivities become positive.

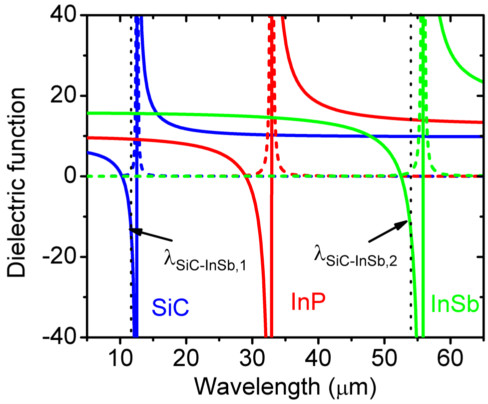

FIG. 1: Real parts (solid lines) and imaginary parts (dashed lines) of dielectric permittivities of SiC, InP and InSb. Black dotted lines indicate the matched wavelengths of SiC-InSb system

Exploiting different phonon resonances of multiple polar dielectrics can easily provide a possibility of superlensing simultaneously at multiple wavelengths. It is clearly seen in Fig.1 that the superlensing conditions for a SiC-InSb system are matched at two distinct wavelengths: $Re[\varepsilon_{InSb}]=-Re[\varepsilon_{SiC}]=15.6$ at $\lambda_1=11.7$ μm, and $Re[\varepsilon_{InSb}]=-Re[\varepsilon_{SiC}]=-9.9$ at $\lambda_2=53.7$ μm. Moreover, respective absorption of the two materials is small at these matching wavelengths, which will significantly improve the resolution of our SL. Our further numerical simulations also confirm that a subwavelength sized Au slit can be well resolved by a SiC-InSb SL at these two different wavelengths (see ref.3).

The second idea is to design a frequency-tunable "graphene superlens" (GL) [5]. This novel graphene-based device enables the enhancement of evanescent waves for near-field subwavelength imaging. Due to the non-resonant enhancement provided by the graphene sheets, this graphene lens yields new promising properties including broad intrinsic bandwidth and low sensitivity to loss, together with a still good subwavelength resolution of around $\lambda/7$ for a bilayer case and over $\lambda/10$ for the multilayered configuration. Most importantly, due to the large frequency-tunability *via* the dynamical tuning of chemical potentials μ_c, our proposed graphene lens can act as an ultrabroadband sub-diffraction-limited imaging device to in principle cover the nearly whole range from mid-IR to THz frequencies.

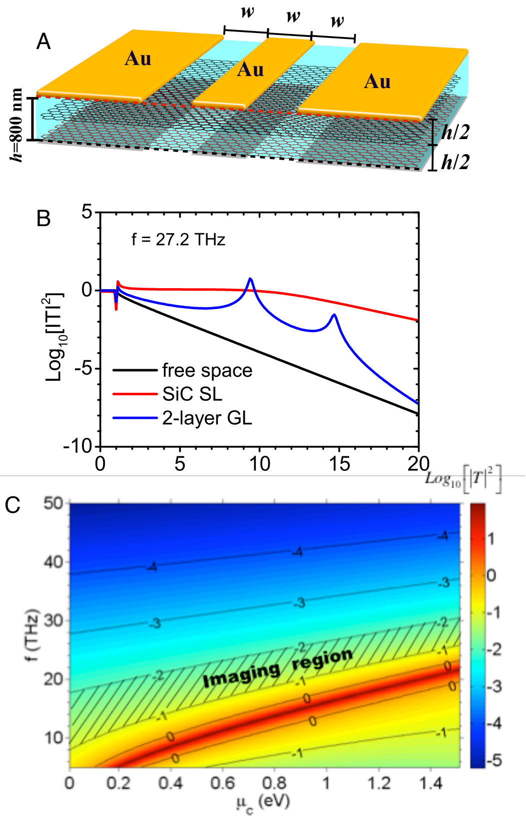

FIG. 3: A. Sketch of a 2-layered GL under the Au double slit. B. Comparison of the OTF for the SiC superlens, 2-layer GL and the case in free space. C. The broadband frequency-tunability in a GL.

In order to show this important effect, we start with a bilayer GL as illustrated in Figure 2A, where two GSs are embedded in a host dielectric medium with a permittivity of ε_h=3. The total thickness of the GL is h=800 nm. To better show this performance, we compare optical transfer functions (the transmittance of high-k_x components) of the double-layer GL, the SiC-SL and the case of free space at the same frequency f=27.2 THz (≈11 μm, the resonance of the SiC-SL) in Figure 2B. It is clearly seen that in free space the transmittance of subwavelength components decays very fast. On the other hand, in the SiC-SL the transmittance for all evanescent waves is uniformly amplified due to the resonant nature of surface modes at the matching SiC-SiO_2 interface, leading to nearly perfect imaging in the near field. Interestingly, the bilayer GL is an intermediate case between the SL and the case of free space. This near-field enhancement leads to the subwavelength imaging in our graphene lens.

The biggest advantage of using graphene for subwavelength imaging is the frequency tunability. In Figure 2C, we show the contour plot of the transmittance as a function of the chemical potential μ_c and frequency *f*. In principle, the imaging frequency range (marked with oblique lines) of the GL can be continuously tuned from mid-IR to THz frequencies when we decrease the chemical potential from 1.5 eV to 0.1 eV. For example, the frequency corresponding to |T|=0.3 (for k_x=7k_0) will shift from 27.2 THz to 13 THz when we change the μ_c from 1.5 eV to 0.2 eV. And for a reasonable doping level $\mu_c \leq$ 1.2 eV, as seen from Figure 3b, the operating frequencies of our 2-layered GL are covering the range from 28 THz (maximum covered frequency at μ_c=1.2 eV) to 8 THz (minimum covered frequency at μ_c=0.1 eV). With this large tunability of imaging frequencies, our bilayer GL can definitely act as an ultra-broadband subdiffractive imaging system at IR and THz regimes.

Besides these presented exciting results, the GL concept further offers other bright prospects: for example, a possibility is to roll the planar GL into a cylindrical shape, which may provide a tunable magnifying lens for far-field imaging at IR and THz frequencies. Moreover, since graphene is two-dimensional (2D) conducting sheet, our concept of using conducting sheets for subwavelength imaging can also be generalized to that of a “conducting sheet lens” (CSL) and easily transferred to other conventional systems like 2D electron gases (2DEG), opening up various exciting ways to achieve broadband subwavelength imaging with semiconductor heterostructures.

This work was supported by the Excellence Initiative, the Ministry of Innovation of North Rhine-Westphalia, the DFG under the SFB 917.

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