The nanostructured acoustic Fresnel lens for focusing THz phonons in gold

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Abstract

Tremendous progress in nano-photonics using hybrid metal-ferromagnet nanostructures [1,2] was recenty extended to acoustics with THz frequency waves [3]. The ability to focus THz frequency phonons with acoustic wavelength of a few nanometers would extend the horizons of nano-photonics with plenty of exciting applications in life sciences and data recording technologies.

Photoacoustic imaging and spectroscopy represent a bunch of widely used techniques exploiting generation and detection of high frequency ultrasound for imaging and nondestructive characterization of biological objects [4]. In some cases, in order to generate acoustic images with ~100 MHz frequency acoustics waves the researchers are using an acoustic Fresnel zone plate [5]. By analogy with optics it consists of a set of rings with different radius to provide constructive interference in a focal point.

Here we consider the possibility to focus sound waves in the terahertz (THz) frequency range (acoustic wavelength of the order of a few tens of nanometers) by a miniature Fresnel lens presented on Fig. 1a. The proposed Fresnel lens consists of a thin cobalt layer (40 nm) sandwiched between a dielectric substrate and a crystalline (111) layer of gold (500 nm, equal to the focal length). A sequence of five rings (with the outer radius of 400 nm) can be etched in cobalt by electron lithography before sputtering the gold layer on top. The cobalt thickness of 40 nm is chosen such that acoustic wave at 0.1 THz frequency propagating through gold and cobalt accumulate a phase difference of □. A good acoustic impedance matching between gold, cobalt and sapphire [3] suggests that acoustic reflections at these interfaces can be neglected and the acoustic Fresnel lens generates spatial phase modulation. The geometrical path difference of acoustic waves coming to the focal spot from the two adjacent zones in a Fresnel lens is also equal to □, leading to the constructive interference of sound waves in the focal point.

In the isotropic approximation such Fresnel zone plate would generate a spatially isotropic acoustic strain distribution in a focal spot with a diameter of 60 nm (FWHM), as shown in Fig. 1b. However, due to the high acoustic anisotropy in gold crystal the intensity distribution in the focal plane is strongly distorted resembling the lattice symmetry (i.e. the 3-rd order symmetry (111) axes in cubic gold) along the propagation direction, see Fig. 1c.

This structure makes it possible to focus longitudinal phonons with frequency of 0.1THz (acoustic wavelength in gold (111) direction equals to 34 nm) down to the spot size below 60 nm (FWHM). Therefore our Fresnel lens can be used in sub-100 nm ultra-high resolution microscopy. A more complicated version of the Fresnel lens with asymmetric zones can be developed to compensate for focal distortions and create a perfect focus like in Fig. 1b.

By analogy with optical tweezers that use field-gradient force of a highly focused laser beam to trap and move microscopic dielectric objects, our acoustic Fresnel lens can be also used for acoustic trapping of tiny living objects (viruses, cells of cancer etc.) with particle size larger than acoustic wavelength (in the so-called Mie regime).

References

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Figures

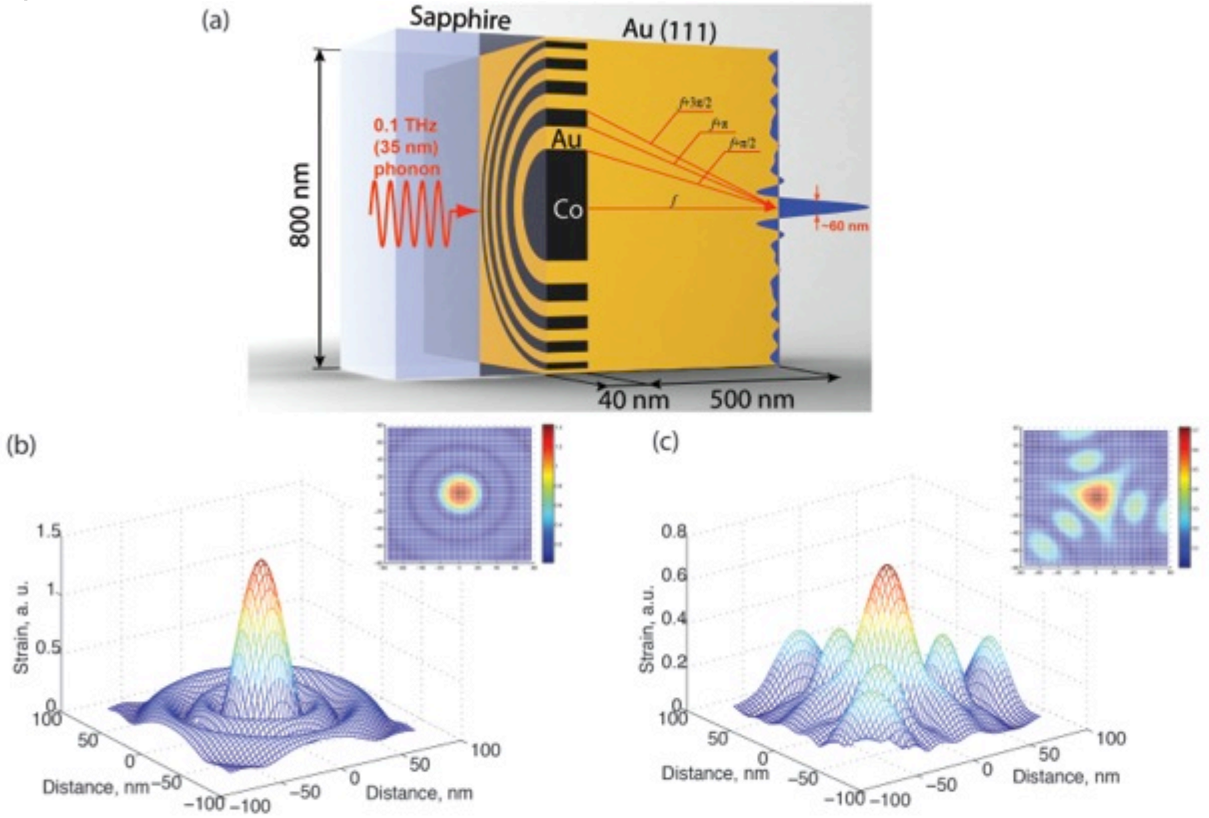

Fig. 1: (a) Model of the nanostructured acoustic Fresnel lens showing the focusing of a monochromatic sound wave at frequency of 0.1 THz into the small acoustic focal spot of 60 nm. (b) An ideal distribution of strain in focal plane for an isotropic case. (c) Strain distribution taking into account the acoustic anisotropy in gold. For this case the maximum intensity in the central spot is observed 200 nm beyond the expected focal distance, i.e. in a 700 nm thick gold layer.