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► To cite this version:

Chushuang Xiang, Anne Rodriguez, Edson Cardozo de Oliveira, Luc Le Gratiet, Isabelle Sagnes, et al.. Enhanced efficiency of coherent acoustic phonon generation and detection using elliptical micropillars. SPIE Photonics Europe 2024, SPIE, Apr 2024, Strasbourg, France. hal-04532319

HAL Id: hal-04532319

<https://cnrs.hal.science/hal-04532319>

Submitted on 4 Apr 2024

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Enhanced efficiency of coherent acoustic phonon generation and detection using elliptical micropillars

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ABSTRACT

Optophononic resonators based on GaAs/AlAs multilayer structures can confine near-infrared photons and sub-terahertz phonons. Previous works have studied the generation and detection of coherent acoustic phonons in planar and circular micropillar cavities. However, these structures exhibit only one optical cavity mode, which makes it challenging to reach the efficient generation and sensitive detection simultaneously in a standard pump-probe experiment. Here, we propose the use of elliptical micropillars to reach an improved condition of these two processes. The elliptical cross-section of the microcavity lifts the degeneracy of the fundamental optical modes, related to each of its major and minor axes. By tuning the pump pulses in resonance with one optical mode, the generation efficiency is enhanced by maximizing the electromagnetic field inside the cavity. Meanwhile, the probe pulses at the same wavelength and with orthogonal polarization detects phonons at the slope of the other mode, where it is sensitive to reflectivity changes. We experimentally demonstrated that the phonon amplitude is enhanced by introducing the ellipticity compared to the circular micropillar. This improvement is promising for future developments in constructing efficient phonon transducers.

Keywords: Nanophononics, acoustic phonons, time-resolved Brillouin spectroscopy, elliptical micropillars

1. INTRODUCTION

Optophononic resonators based on GaAs/AlAs multilayer structures can confine near-infrared photons and sub-terahertz phonons.¹⁻⁵ Different strategies have been proposed to enhance the efficiencies of generation and detection of acoustic phonons in the planar and micropillar structures, e.g. integrating samples to single mode fibers to achieve long term stable and reproducible signals, varying the incidence angle of the laser to reach the double optical enhancement configuration.^{1,4,6-10} Excitation and detection at different wavelengths is another method to improve the phonon signal that has been applied in plasmonic resonators and quantum dot layer systems.¹¹⁻¹³ However, most of these approaches are based on altering experimental conditions. In this work, we use micropillars with elliptical cross-sections to enhance the phonon amplitude based on a standard pump-probe scheme with one single wavelength and normal incidence on the sample. Introducing an ellipticity to the micropillars splits the degenerate optical cavity modes.^{10,14} Due to this property, elliptical micropillars have been used to improve the emission of single photon sources based on quantum dots embedded in the spacer and polarization filtering in Brillouin scattering.^{10,15-18} We take advantages of the two optical cavity modes which are linearly polarized and aligned with the major and minor axes of the elliptical cross-section. The pump pulse, polarized parallel to the major axis, excites the sample in resonance with the corresponding optical mode. At the same time, the probe pulse with orthogonal polarization is located at the slope of the other mode, enabling sensitive detection. We theoretically proposed and experimentally compared the wavelength-dependent phonon amplitude in circular and elliptical micropillars. Our study contributes to advancing the development of an efficient platform for exciting and detecting acoustic phonons.¹⁹

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2. ELLIPTICAL MICROPILLARS

We studied two micropillars with different cross-sections (elliptical and circular) obtained by electron beam lithography and inductively coupled plasma etching of a planar cavity. The microcavity is formed by two distributed Bragg reflectors (DBRs) enclosing a half-wavelength spacer. The top and bottom DBRs consist of 25 and 29 periods of $\text{Ga}_{0.9}\text{Al}_{0.1}\text{As}/\text{Ga}_{0.05}\text{Al}_{0.95}\text{As}$ multilayers. It is designed to simultaneously confine infrared light at ~ 900 nm and phonons at ~ 20 GHz.^{2,3,6,10} The optical properties of the two micropillars are characterized by using broadband light, collecting the reflected light to a double spectrometer, and analyzing in a charge-coupled device. Figure 1 shows the Lorentzian fits of the measured reflectivity spectra. The reflectivity of the circular micropillar with a diameter of $4 \mu\text{m}$ (Fig. 1(a)) exhibits only one optical mode centered at 902.17 nm. In contrast, two non-degenerate optical modes are present in the reflectivity of the elliptical micropillar (Fig. 1(b)) with a major (minor) axis length of $4 \mu\text{m}$ ($2.4 \mu\text{m}$). The red (blue) curve shows the cavity mode at 901.33 nm (901.25 nm) in the polarization of vertical (V) (horizontal (H)) direction, resulting in a splitting of 0.08 nm.

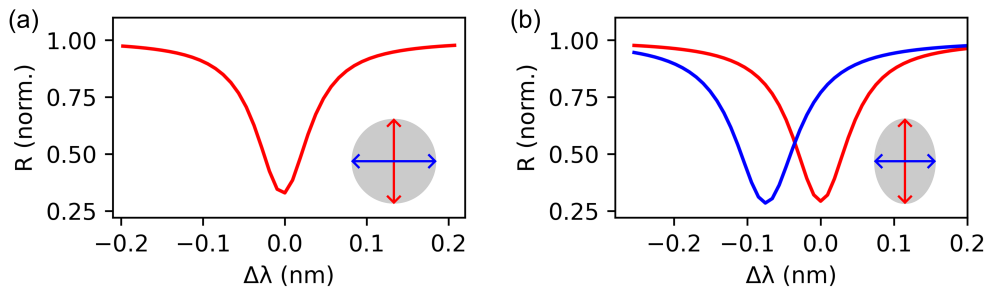


Figure 1. Fitted reflectivity spectra of a (a) circular micropillar with a diameter of $4 \mu\text{m}$ and (b) an elliptical micropillar with a major (minor) axis length of $4 \mu\text{m}$ ($2.4 \mu\text{m}$).

3. METHODS

3.1 Optical measurements for generation and detection of acoustic phonons

We employ the time-domain Brillouin scattering technique to study phonon generation and detection.²⁰ A Ti-sapphire laser delivers picosecond pulses of 5 ps full width at half maximum. The pulses pass through a polarization beam splitter (PBS) and are divided into pump and probe beams. The pump generates phonons dominantly through the deformation potential mechanism. The probe detects phonons through the transient change in the reflectivity with a time delay.^{2,21,22} The two beams are focused on the sample with a spot size of approximately $2.2 \mu\text{m}$. The polarizations of the two beams initialized by the PBS are orthogonal and linear. We use a combination of quarter and half waveplates to align the polarization of the pump with the major axis such that it is coupled to the V mode. At the same time, the probe is automatically polarized along the minor axis and coupled to the H mode. The powers of the pump and probe are set to $40 \mu\text{W}$ and $100 \mu\text{W}$, respectively.

3.2 Transfer matrix simulations

We theoretically study the amplitude of phonon generation and detection using transfer matrix method. In this simulation, we focus on the amplitude at the frequency of the confined acoustic mode ω_0 as a function of the laser wavelength λ . The generation amplitude is determined by the overlap integral of the electric field square modulus $|E(\lambda, z)|^2$, strain distribution $\eta(\omega, z)$, and material-dependent photoelastic constant $p(z)$, where z is the position along the growth axis.^{23,24} At the acoustic cavity mode ω_0 , the product of the strain distribution $\eta(\omega_0, z)$ and photoelastic constant can be described as a constant. In that case, the generation efficiency is proportional to $|E(\lambda, z)|^2$. The detection spectrum, independent of the generation process, is equivalent to the reflectivity R variation spectrum. We simulate the presence of phonons by introducing a perturbation for the refractive index n along the structure which is proportional to $\eta(\omega_0, z)$ and $p(z)$.²⁴ As described in the experiment, the pulses with a Gaussian profile have a width that is twice the optical cavity linewidth. To account for that, the simulated phonon amplitude is an integral result of laser spectrum, generation, and detection efficiencies.

4. RESULTS

We measured laser wavelength-dependent amplitude of acoustic phonons in the two micropillars as shown in Fig. 2(a). For the circular micropillar, the signal is maximum when the laser is slightly shifted relative to the optical mode. At this wavelength, the laser is positioned at the slope of the optical cavity mode, where the detection is sensitive. By introducing the elliptical cross-section, the maximum amplitude is significantly higher than in the circular micropillar. The amplitude reaches the maximum close to the V mode, where the efficiencies of generation and detection are enhanced simultaneously. This enhancement of the phonon amplitude is consistent with the simulation results in Fig. 2(b).

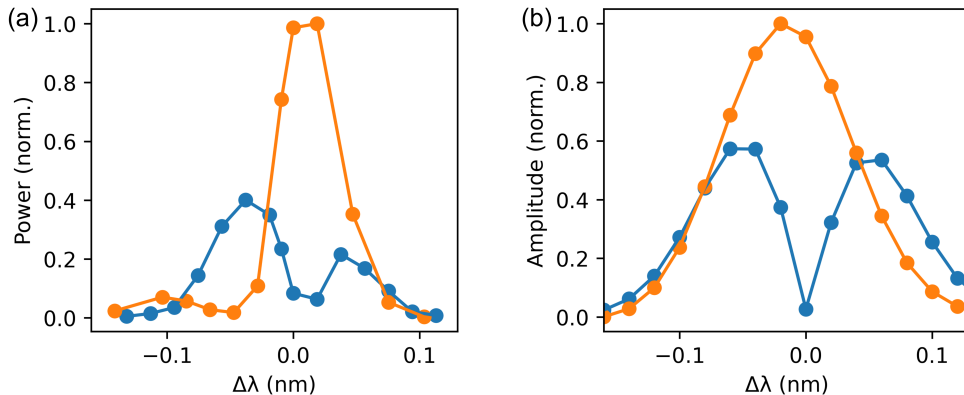


Figure 2. Comparison of phonon amplitude in the circular (blue) and elliptical (orange) micropillars. (a) Measured power of phonons as a function of laser wavelength shifting relative to the V mode. (b) Simulated phonon amplitude using transfer matrix method.

5. CONCLUSIONS

In this work, we have studied the generation and detection efficiencies in two micropillars with different cross-sections. With the comparison of wavelength dependent studies, we demonstrated that the maximum measured amplitude in the elliptical micropillar is significantly higher than in the circular micropillar. The optimal condition in which these two processes are maximized can be explored in micropillars with various ellipticities. Our study constitutes the first step to the efficient acoustic transducer and has potential applications in data processing.

ACKNOWLEDGEMENTS

The authors thank P. Priya for fruitful discussions. The authors acknowledge funding from European Research Council Consolidator Grant No.101045089 (T-Recs). This work was supported by the French RENATECH network, and through a public grant overseen by the ANR as part of the “Investissements d’Avenir” Program (Labex NanoSaclay Grant No. ANR-10-LABX-0035).

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