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Coherent acoustic phonon transport in optophononic waveguides

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ABSTRACT

To achieve full control over acoustic phonons at ultrahigh frequencies, it is essential to characterize the phonon transport properties. Recent works have shown that surface acoustic waves at gigahertz frequencies can propagate over micrometer distances in different nanostructures such as nanowires, nanogratings, and nanoantennas. Here, we aim at investigating acoustic phonon transport by designing a GaAs/AlAs optophononic waveguide. Along the vertical direction of the waveguide, a Fabry-Perot cavity ensures an efficient confinement of acoustic phonons that has been demonstrated in planar and micropillar structures. In the lateral direction, the interface of air and semiconductor serves as an acoustic mirror to reflect phonons in the waveguide. We perform pump-probe experiments to generate coherent acoustic phonons at one position and detect them remotely on the waveguide. We analyze the signals originated by phonons generated in the pump position reaching the remote probe location, revealing a clear indication of phonon transport at room temperature. Our findings have potential applications in quantum technologies and data processing.

Keywords: Nanophononics, Optomechanics, acoustic phonons, coherent phonon generation, phononic waveguides

1. INTRODUCTION

Acoustic phonons with ultrahigh frequencies will play a critical role as information carriers in signal processing and as mediators for qubits in quantum computing due to their long lifetimes, short wavelengths, and slow velocities.¹⁻⁵ At the same time, acoustic phonons exhibit the striking ability of coupling with other excitations, such as photons, plasmons, excitons, and polaritons.⁶⁻⁹ In this context, it is important to characterize and manipulate acoustic phonon dynamics. Surface and subsurface acoustic waves have been reported to propagate over micrometer distances in the range of a few gigahertz frequencies (below 10 GHz) in various structures such as nanowires, nanogratings, and nanoantennas.^{7,10-13} One of the main challenges is to reach a higher frequency regime, which is crucial in the field of quantum technologies.^{4,14,15} In this work, we introduce optophononic waveguides based on GaAs and AlAs multilayer structures. The vertical structure functions as an optophononic resonator with high Q-factors, similar to previously reported structures.^{6,16-19} The interface of air and semiconductor serves as an acoustic mirror to reflect phonons laterally, guiding phonons propagating in the waveguide. By means of coherent generation and detection of acoustic phonons in a pump-probe setup, we analyze the phonon signals generated remotely. We observed a signal at ~ 20 GHz, indicating phonon transport over $8 \mu\text{m}$ at room temperature. This result constitutes a first step towards complex phononic networks and data processing applications.

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2. OPTOPHONONIC WAVEGUIDES

The multilayer structure is grown on a 001-orientation GaAs substrate using molecular beam epitaxy. Vertically, it consists of two distributed Bragg reflectors (DBRs): 14 and 18 periods of GaAs/AlAs on the top and bottom, enclosing a ~ 127 nm thick GaAs spacer. This design enables the simultaneous confinement of infrared light at ~ 900 nm and acoustic phonons at ~ 20 GHz, achieving a quality factor of ~ 1300 .^{6,14,20,21} The planar cavity is etched into a triangular shape with dimensions of $20 \mu\text{m}$ in width and $250 \mu\text{m}$ in length as depicted in Fig. 1, using electron-beam lithography and inductively coupled plasma etching. In the lateral direction, due to the contrast of the indices of refraction between the air and semiconductors, the interface induces a total acoustic reflection. The experiments are conducted on the broad side of the structure and far from the edge, assuming negligible back reflection from the base edge.

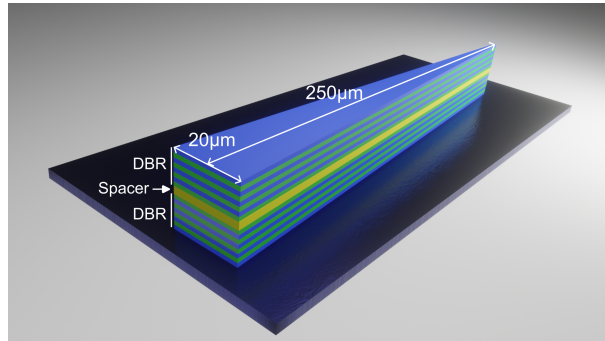


Figure 1. Schematic of an optophononic waveguide. The vertical structure is formed by two distributed Bragg reflectors (DBRs) enclosing a $\lambda/2$ GaAs spacer. The width and the length of the triangular cross-section are $20 \mu\text{m}$ and $250 \mu\text{m}$, respectively.

3. PUMP PROBE EXPERIMENT

A Ti-sapphire laser with an 80-MHz repetition rate is split into two cross-polarized beams: the pump and the probe. The pump beam generates phonons in the sample via the deformation potential mechanism. The presence of phonons perturbs the refractive index of the material and thus changes the optical reflectivity detected by the probe beam. By manipulating the time delay between the two beams, we reconstruct the transient reflectivity in the time domain.^{16,22,23} The beams focus onto the sample with a spot size of approximately $2.5 \mu\text{m}$. The powers of the pump and probe beams are set to 1 mW and 3 mW, respectively. The pump is modulated at 800 kHz to implement a synchronous detection scheme. In order to evaluate the propagation of coherent acoustic phonons, we performed two types of measurements: 1) a local measurement, where the pump and probe beams are focused at the same position; and 2) a remote measurement, where the probe beam is separated from the pump beam by a spatial distance of $8 \mu\text{m}$ on the waveguide.

4. RESULTS

Figure 2(a-c) presents the experimental results for the local case, where pump and probe overlap. The time trace (Fig. 2(a)) at $t=0$ shows a significant change in reflectivity due to the electronic excitation on the sample. A following slow decay is associated to thermal relaxation. After subtracting the low-frequency components, the Fourier transform (FT) of the signal features the confined phonon mode at 20 GHz (Fig. 2(c)). In order to track the signal in the frequency and time domain, we perform a short-time Fourier transform (STFT) (Fig. 2(b)). An exponential decay of the phonon amplitude is evident, which results from phonon scattering and leakage towards the substrate and the waveguide. An echo signal at ~ 1 ns manifests in the STFT and is related to the strain traveling vertically towards the air-sample interface and its reflection back to the spacer of the vertical structure. Figure 2(d-f) shows the same analysis for the case of a remote measurement conducted at a separation distance of $8 \mu\text{m}$. The time trace is comparatively weaker. The pronounced peak at 20 GHz in the spectrum indicates that the phonons generated at the pump position are detected at the probe position, directly indicating phonon

transport. The STFT highlights the time evolution of a phonon signal which reaches the maximum amplitude at ~ 8 ns. The remaining signal before 3 ns is considered to be the residual signal generated by the build-up of previous pump pulses.

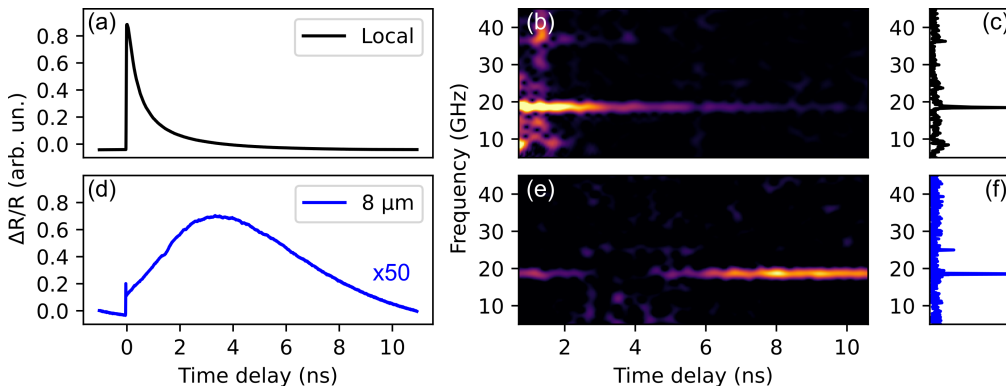


Figure 2. Experimental results of local(a-c) and remote(d-f) measurements. (a) and (c) are the differential reflectivities in the time domain. (c) and (f) are Fourier transform (FT) of the time traces with low-frequency component removal. (b) and (e) are the results of short-time Fourier transform (STFT).

5. CONCLUSION AND DISCUSSION

In this study, we have shown the coherent propagation of acoustic phonons at 20 GHz in an optophononic waveguide over $8 \mu\text{m}$ at room temperature. On this triangular structure, the effect of width between the lateral boundaries could be exploited by conducting the experiments close to the tip side. Moreover, improved and functional geometries can be studied to tailor light-matter interactions and the phonon transport properties. A higher frequency regime could be reached by engineering the vertical multilayer, though the phonon mean free path would impact the efficiency of the device. The roles of the substrate, laser power, spot size, and repetition rate of the excitation laser, remain critical elements to be investigated. Our work enables a new acoustic device that has the potential to serve as a key element in the development of a universal mediator in data processing and phononic networks.

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