Coherent Generation of Acoustic Phonons in Optical Microcavities

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Ultrafast coherent generation of acoustic phonons is studied in a semiconductor microcavity. In this work, we experimentally study the effects of the confinement of a light pulse in the cavity spacer. By changing the laser wavelength and thus the detuning with the microcavity mode, we show how the generation and detection of acoustic phonons is enhanced. The reported results open new perspectives for enhancing the generation and detection efficiency in picosecond acoustics as well as for the development of amplified THz monochromatic hypersound sources.

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I. INTRODUCTION

Acoustic phonons play an essential role in the electronic and optoelectronic properties of solids, and in particular, of semiconductors. By means of its coherent control, acoustic phonons could be used in nanoscopies based on hypersound, to process information, and to control light and charge in the nanoscale and with ultrahigh frequencies. The engineering of new devices to manipulate and control acoustic vibrations in solids is a research topic that will be crucial for the development of new applications in nanophononics. This kind of application also requires engineering of the interactions among hypersound, light, and charge.

An optical microcavity confines the electromagnetic field both spectrally and spatially, inducing strong changes in the light-matter interaction and giving rise to novel physical phenomena and devices [1, 2]. In the case of planar semiconductor optical microcavities, two distributed Bragg reflectors (DBRs) enclose an optical spacer. The light amplification and confinement characteristics are determined by the selection of materials, thickness, and number of periods that constitute each DBR and the optical spacer [2]. Optical microcavities have been the subject of very active research during the last ten years, and have been used to study the modification of the photonic lifetimes [3], parametric oscillations [1], cavity polariton Bose-Einstein condensates [4, 5], the polariton laser [6, 7], and amplification of Raman scattering signals [2], among others.

Optical microcavities also amplify the interactions between light and acoustic phonons [2]. Particularly, the photonic confinement and amplification have been used in these high-Q resonators to amplify the optical generation of phonons using Raman processes, and to evidence new effects in the phonon physics and dynamics in semiconductor nanostructures [2, 8–10]. The optical resonances can be complemented with electronic resonances giving rise to amplified Raman cross-sections up to 10^7. This scheme has been used to study confined phonons in acoustic nanocavities [11]. The use of optical confinement for the ultrafast optical coherent and enhanced generation of acoustic phonons (in contrast with incoherent generation by spontaneous Raman scattering), for the realization of a monochromatic ultrahigh frequency phonon source is a concept that has been little treated up to now [12–16]. In a previous work, we demonstrated that planar optical microcavities can be used in coherent generation experiments, showing indications of signal enhancements under optical resonance and the modification of the selection rules in the phonon generation-detection process [12, 13, 16]. Afterwards, a similar scheme was used by H. Maris and coworkers using external microcavities to study systems with small photoelastic constants [14, 15], presenting an alternative tool to the interferometric detection schemes introduced by Perrin et al [17]. The modulation of the cavity mode has been studied by the injection of hypersound pulses in both the polaritonic and optic regime [18–20]. Similarly, surface acoustic waves have been used to modulate optical microcavities and to control cavity-polaritons [21–23]. In this work, we present the experimental results of coherent phonon generation experiments in an optical microcavity under optical resonance and analyze the dependence of generation-detection efficiency on the laser wavelength.

II. EXPERIMENTAL DETAILS

We performed standard pump-probe coherent phonon generation experiments in an optical microcavity. The studied sample is an optical microcavity with an embedded acoustic nanocavity, similar to the sample studied in ref. [24]. The sample was grown on a 001 oriented GaAs substrate by molecular beam epitaxy. The optical microcavity is formed by two distributed Bragg reflectors (DBRs) enclosing the acoustic nanocavity structure (see Fig. 1). The top (bottom) mirror has three (10) periodos of AlAs/AlGaAs $\lambda_L/4-$ $\lambda_L/4$ bilayers, where λ_L is the optical wavelength ($\sim$ 785 nm for the studied point in the sample). The asymmetry in the number of periods compensates the difference between the indices of refraction of the air and the substrate, leading to a symmetric cavity mode. The Q factor of the optical microcavity is around 30, allowing the fs light pulse to enter in the cavity mode. The total thickness of the acoustic nanocavity is $2\lambda_L$. The acoustic nanocavity is formed by two Bragg reflectors formed by 13 bilayers of GaAs/AlAs $(3\lambda/4, \lambda/4)$ enclosing an acoustic spacer of GaAs ($3\lambda/2 \sim 12.3$ nm), where λ is the acoustic wavelength corresponding to 580 GHz. Due to confinement effects, the electronic transition corresponding to the mirrors will be located at higher energies than the one corresponding to the acoustic spacer.

A femtosecond laser light pulse (pump) was used to generate coherent sub-THz phonons in the structure, while a second, delayed, and less intense light pulse (probe) detected the changes in the reflectivity of the whole microcavity. To perform the experiments we used a Ti-Sapph laser, delivering 80 fs NIR light pulses, at 80 MHz. The pump beam was modulated at 1 MHz in order to allow the detection with a lock-in amplifier.

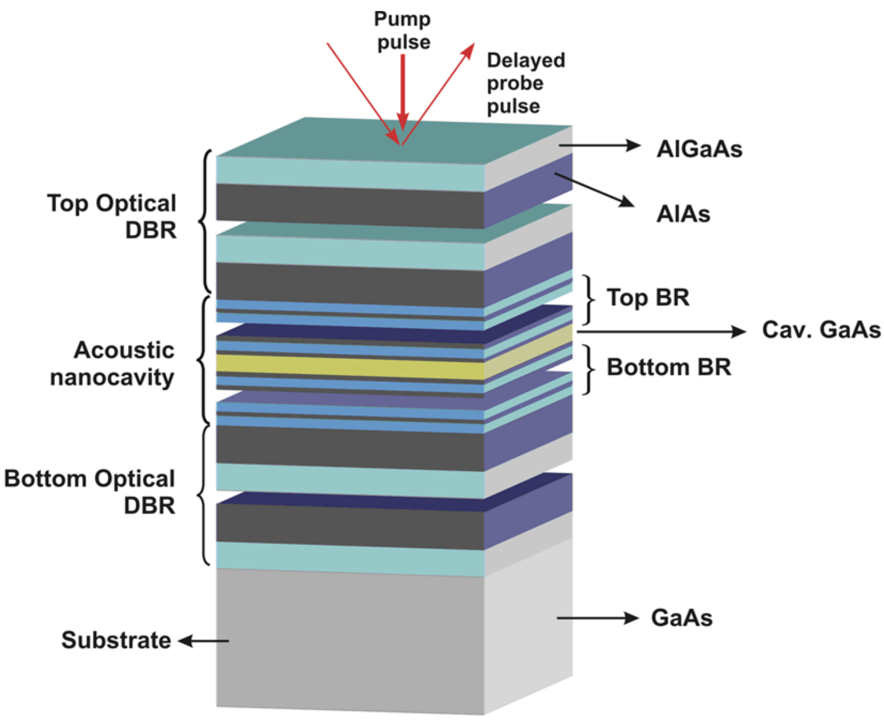

FIG. 1: Schematics of the sample and the experimental geometric configuration. Two optical DBRs are separated by an optical spacer constituted by an acoustic nanocavity. The pump and probe pulses impinge from the top side of the sample.

Typical powers of 60 mW (20 mW) for the pump (probe) beam were used. Both beams were focused onto an approximately 60 mm diameter spot. By Fourier transforming the time-dependent optical reflectivity, it is possible to recover the spectrum of acoustic excitations generated in the sample. The collected time traces were 700 ps long. The experiments were performed at 15 K, allowing us to work in the selective excitation regime, i.e., when the laser energy is in between the electronic transition energies of the quantum wells forming the acoustic Bragg mirrors and the GaAs acoustic spacer.

III. RESULTS

A typical measured time resolved reflectivity curve is shown in Fig. 2 panel a. At 50 ps, the coincidence in time between the pump and probe pulses can be identified by a strong change in the reflectivity. The coherent character of the reflectivity variations can be noted in the inset, where we present the details of the signal derivative between 100 and 200 ps, after the application of a bandpass filter between 200 and 900 GHz. With the laser energy located between the electronic transitions corresponding to the mirrors and the nanocavity spacer, the measured spectrum (see Fig. 2, panel b) is characterized by two peaks related

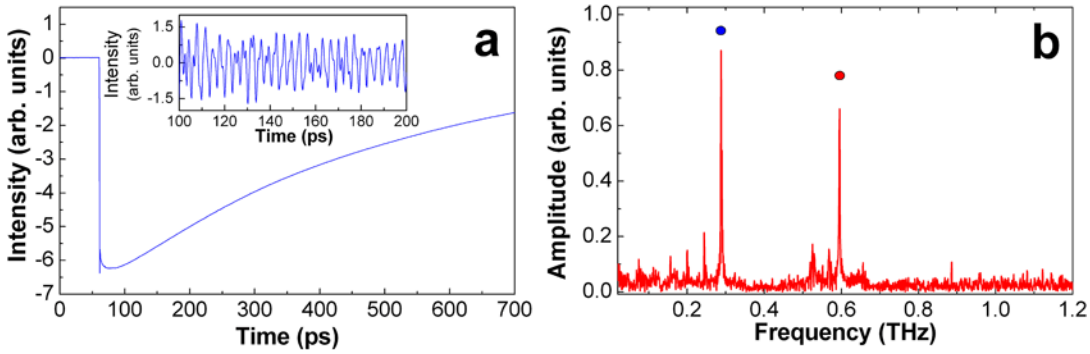

FIG. 2: Coherent phonon generation experiments. Panel a: time resolved reflectivity measured in an optical microcavity with the laser tuned with the optical mode. Inset: detail of the derivative of the signal between 100 and 200 ps after the application of a bandpass filter (200–900 GHz). Panel b: Fourier transformation of the time trace shown in panel a. Peaks indicated with circles correspond to confined acoustic cavity modes (see text for details).

to acoustic confined cavity modes in the first acoustic Brillouin zone edge (blue dot) and zone center (red dot) minigaps determined by the acoustic mirrors [24].

In order to identify the relative position of the laser and the optical cavity mode, we measured the reflectivity of the laser beam as a function of wavelength. In the top panel of Fig. 3, we present the measured optical reflectivity (black squares) between 765 and 807 nm. The green line is a gaussian fit of the measurement. In this way, the optical microcavity mode can be localized at ~ 785 nm, with FWHM of 16 nm. Note that this reflectivity was measured with the pulsed laser, leading to a small broadening of the intrinsic optical mode width. In the same plot, we also show the numerical derivative of the latter fit (gray line).

As indicated in a previous work [16], the generation efficiency using an optical microcavity will be maximum when the excitation laser is tuned to the cavity mode, i.e., when the electromagnetic field presents its maximum amplification. The generated excitations within the optical microcavity modulate the index of refraction (or equivalently, the thickness) of the optical spacer, changing the cavity mode position. Thus, the detection sensitivity should present two maxima that coincide with the extremes of the derivative of the confined mode dip in the optical reflectivity. In the same way, when the laser is perfectly tuned with the cavity mode dip, the detection sensitivity should be exactly zero. In a standard pump-probe scheme with similar incidence angles for the two beams, and identical wavelengths, both enhancement conditions cannot be met at the same time. In addition, the modulation of the imaginary part of the index of refraction will modify this general detection enhancement rules. In what follows, we analyze the experimental results of coherent phonon generation in an optical microcavity.

In the bottom panel of Fig. 3, we present the cavity mode intensity as a function of the laser wavelength. The red rhombus (blue circles) correspond to the zone center (edge) acoustic cavity mode. In both cases, it can be noted that the weight of the signal is concentrated in the region of the optical microcavity mode. In the case of the Brillouin zone

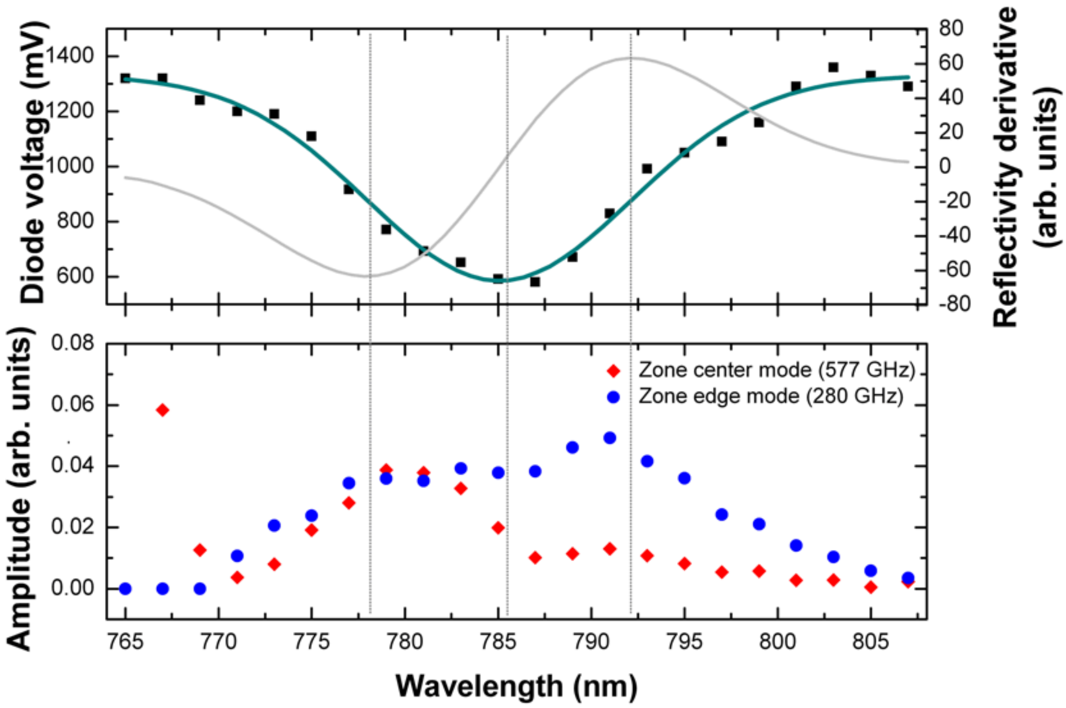

FIG. 3: Coherent phonon generation in an optical microcavity. Top panel: Optical reflectivity measured as a function of the laser wavelength (squares). The green line is a gaussian fit. In gray, the derivative of the fitting curve. Bottom panel: intensity of the cavity modes as a function of the laser wavelength. Blue (red) dots correspond to the zone edge (center) cavity mode. Vertical lines indicate the cavity mode wavelength (central line) and maximum and minimum derivative.

edge mode (with an acoustic frequency of 280 GHz), two local maxima can be identified near 778 and 792 nm, which coincide with the greatest changes of the optical reflectivity as a function of wavelength. In addition, the signal drops to zero for wavelengths shorter than 770 nm. As the laser increases its wavelength, from 792 nm, the signal starts to decrease. The intensity of the Brillouin zone center cavity mode (frequency around 580 GHz) also presents two maxima located approximately in the same positions. The maximum at 778 nm is more intense than the second one. Note that the opposite behavior is observed in the case of the Brillouin zone edge mode. For wavelengths shorter than 770 nm, the zone center cavity mode starts to increase its intensity. This can be related to the excitonic resonance with the GaAs layers forming the Bragg reflectors.

IV. DISCUSSION AND CONCLUSIONS

In this work, we have performed coherent acoustic phonon generation experiments in an optical microcavity as a function of the laser wavelength. We showed that the intensity of the characteristic confined modes of the studied sample presents two maxima that are located in the spectral region where the reflectivity presents its maximum absolute derivative. The experimental results are in good agreement with the theoretical predictions. The two maxima can be related to an enhancement of the detection sensitivity of the whole structure. The theoretical model predicts the apparition of a zero at the optical cavity mode center. However, this model assumes that the photoelastic constants are pure real numbers, which is not our case because of the proximity of the electronic transitions. Under standard geometrical conditions, where pump and probe incide with approximately the same angle, the generation and detection efficiency maxima are located in different spectral positions. The studied system opens new possibilities toward the development of coherent phonon sources, ultrafast optical modulation systems, and the enhancement of the generation and detection efficiencies in picosecond acoustics experiments.

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