Coherent generation of acoustic phonons in an optical microcavity

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Abstract. Coherent acoustic phonons confined in a nanocavity are generated in an optical microcavity. The confinement of the femtosecond light pulse in the optical resonator amplifies both processes, generation and detection of the acoustic phonons. In addition, due to the standing wave character of the photon field, phonons of wavevector q = 0 and q = 2k (k is the light wavenumber) contribute to both the generation and detection in time resolved reflectivity measurements, further optimizing the pump and probe experiments. Time resolved differential reflectivity experiments are reported as a function of laser energy. The optical cavity resonance is apparent in the amplitude and spectral features of the Fourier transformed signals.

1. Introduction

Semiconductor optical microcavities are planar Fabry-Perot resonators, where the mirrors are distributed Bragg reflectors (DBR), i.e., alternating λ/4 layers of materials of high and low index of refraction. Optical microcavities confine photons both spatially and spectrally, and have been the focus of many studies during recent years. [1] They have been used in different experiments, ranging from the modification of photon lifetimes [1] to Raman signal amplification, [2] to name a few. Acoustic nanocavities are the phononic equivalent of planar optical microcavities. [3, 4, 5] They are constituted by two acoustic distributed Bragg mirrors (BR) enclosing an acoustic spacer. These devices confine sound both spectrally and spatially. Setting the characteristic thickness of the layers to the order of a few nm, the confined sound is in the technologically relevant GHz-THz range. The required control in the layers’ thickness, and sharp interfaces between the different materials, is nowadays achievable by epitaxial techniques as, e.g. Molecular Beam Epitaxy (MBE). Acoustic nanocavities could provide, in addition, the required feedback system of a phonon laser. In the present work we present the results on the coherent generation of acoustic phonons in an optical microcavity, where the photon confinement is used to enhance the generation and detection processes.
2. Design of the cavity for sound and light

A scheme of the studied sample is shown in fig. 1. The acoustic nanocavity is formed by two GaAs/AlAs 12 periods BR, and a $\lambda_s/2$ GaAs spacer, where $\lambda_s$ represents the wavelength of the acoustic vibration. The BRs are GaAs/AlAs $3\lambda_s/4$, $\lambda_s/4$ superlattices of 6.1 nm, and 2.4 nm respectively. The acoustic confined mode is centered at $\sim$0.59 THz. The acoustic nanocavity is grown on a 30 periods AlAs/AlGaAs (62.3 nm, 53.3 nm) optical DBR. The interface air-sample is a low reflectivity mirror ($R \sim$30%). The acoustic nanocavity structure plays the role of a $\lambda_l$ spacer of an asymmetric optical microcavity ($\lambda_l$ is a light wavelength). The spacer is limited by air on top, and by the DBR at the bottom. The asymmetric low-Q microcavity presents a confined optical mode at $\sim$737 nm. A similar sample was studied by Raman scattering in Ref. [6]. This double resonator for phonons and photons, [3] under optical resonance, presents a maximum of the electromagnetic field that coincides with the maximum of the atomic displacement in the acoustic spacer. The sample was grown on a GaAs (001) substrate by MBE.

![Figure 1. Scheme of the sample. The acoustic nanocavity is formed by two GaAs/AlAs BR separated by an acoustic spacer. The acoustic nanocavity constitutes a $\lambda$ spacer of the asymmetric optical microcavity.](image1)

![Figure 2. Typical time trace of a pump-probe differential reflectivity experiment. The signal was filtered to remove the slowly decaying background corresponding to the electronic response of the system. The inset shows a zoom of the same signal to highlight the coherent character of the oscillations.](image2)

3. Coherent acoustic generation by picosecond ultrasonics

We performed coherent phonon generation experiments on the sample. We used a tunable Ti:Saphire laser between 770 and 780 nm, to study the time dependent optical reflectivity of the microcavity. The typical spot size both for the pump and the probe beams was $\sim$ 50$\mu$m, the pulse duration $\sim$ 100 fs, and the energy 0.36 and 0.11 nJ per pulse for the pump and probe respectively. The sample was cooled down to $\sim$ 80 K.

The output of the time resolved pump and probe reflectivity experiment that we report in this paper is shown in Fig. 2. The time trace filtered to subtract the slowly decaying but intense electronic response of the system can be observed. The inset is a zoom of the same signal to highlight that what is observed is not noise but clearly defined sub-THz oscillations. The later, which are standard in the coherent phonon generation literature, are due to the coherent oscillation of the lattice following the incident laser impulsion. [7, 8, 9]
The presence of the optical mirror (and therefore, of the optical cavity mode) modifies the coherent phonon generation and detection processes through two main factors: on one hand, the intensity of the electromagnetic field is amplified within the microcavity, showing its maximum in resonance condition at the center of the GaAs acoustic spacer. On the other hand, the optical cavity mode is a stationary wave, so phonons of wavevector \( q = 0 \) and \( q = 2k \) (\( k \) is the light wavenumber) contribute to both the generation and detection in time resolved reflectivity measurements further optimizing the pump-probe signal, i.e., the generated spectrum exactly coincides with the detection sensitivity function of the structure. Without optical confinement the generation \( (q \sim 0) \) and detection \( (q \sim 2k) \) functions have common energy bands only due to light absorption and finite size effects. [10, 11]

In an experiment with optical microcavities, the laser wavelength and the incidence angle determine the optical resonance condition. In fig. 3 we show the Fourier Transform of the time dependent optical reflectivity as a function of the laser wavelength, for an experiment performed at normal incidence. The considered range corresponds to a band from a minimum of reflectivity (780 nm) up to 770 nm, where the electromagnetic field starts to be amplified by the cavity, and no electronic resonance is present. The most intense peak corresponds to the nanocavity mode. A secondary weaker peak can be observed at 0.55 THz; this signal is associated to vibrations localized in the superlattices (phonon mirrors).

Changing the incidence angle of both the pump and probe beams it is possible to modify the position of the optical bandgap without changing neither the acoustic nor the electronic characteristics of the system. We have verified that with an incidence angle of \( \sim 65^\circ \) the studied band presents a minimum of reflectivity in the 770-780 nm band, and practically no optical confinement effects are observed. An amplification factor of \( \sim 30 \) was observed comparing the cases with and without optical confinement. As already stated, under optical confinement the generated and detected spectra coincide, and intense peaks are enhanced with respect to the weaker ones. This effect is the cause of the quasi-monochromatic peak observed in fig. 3. In the experiment performed with no optical confinement (not shown here), two peaks of similar intensities are identified, one associated to the superlattice vibrations, and the second one to the cavity mode.

In order to study the phonon dynamics in the double-resonator we have performed a Windowed Fourier Transform (WFT) of the time trace. Fig. 4 shows a WFT using a rectangular 150 ps window. It can be observed an intense signal around 0.59 THz corresponding to the confined acoustic nanocavity mode; this mode contributes to the signal much longer than the rest of the modes. From this analysis a lifetime of \( \sim 215 \) ps can be derived, in agreement with previous results obtained in a planar nanocavity without optical confinement. [12] Several short-lived and weaker modes appear at lower and higher energies, mainly related to vibrations localized in the acoustic mirrors. These modes rapidly escape into the substrate, without any further contribution to the modulation of the optical reflectivity.

4. Conclusions
In this work we have presented the results of pump-probe experiments performed on an acoustic nanocavity embedded in an optical microcavity. We have studied the phonon dynamics in an acoustic nanocavity, where the cavity phonons keep modulating the optical reflectivity of the structure much longer than the rest of the vibrations. Lifetimes of \( \sim 215 \) ps have been observed, verifying the confinement characteristics of the acoustic resonators. In addition, a study of the pump-probe signal as a function of the laser wavelength demonstrated the enhancement of the generation and detection processes due to the standing character of the amplified pump and probe electromagnetic fields. The studied system opens new possibilities towards the development of monochromatic acoustic sources and the study of systems where the intensity of the acoustic signal is a main issue.
Figure 3. Fourier Transform of the time dependent optical reflectivity as a function of the laser wavelength. The most intense peak corresponds to the nanocavity mode. The amplification of the signal is due mainly to optical confinement effects.

Figure 4. Windowed Fourier transform of the time dependent optical reflectivity. Note the long-lived signal at 0.59 THz corresponding to the confined acoustic mode in the nanocavity.

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References
[1] Skolnick M S, Fisher T A and Whittaker D M 1998 Semicond. Sci. Technol. 13 645669
[2] Fainstein A and Jusserand B 2006 Light Scattering in Solids IX ed M Cardona and G Guntherodt (Springer-Verlag, Heidelberg)
[3] Trigo M, Bruchhausen A, Fainstein A, Jusserand B and Thierry-Mieg V 2002 Phys. Rev. Lett. 89 227402
[4] Shin-ichiro Tamura, Haruka Watanabe and Takashi Kawasaki 2005 Phys. Rev. B 72 165306
[5] Huynh A, Lanzillotti-Kimura N D, Jusserand B, Perrin B, Fainstein A, Pascual-Winter M F, Peronne E and Lemaître A 2006 Phys. Rev. Lett. 97 115502
[6] Fainstein A, Jusserand B and Thierry-Mieg V 1996 Phys. Rev. B 53 R13287
[7] Kini R N, Kent A J, Stanton N M and Henini M 2006 Appl. Phys. Lett. 88 134112
[8] Kung-Hsuan Lin, Chieh-Feng Chang, Chang-Chi Pan, Jen-Inn Chyi, Stacia Keller, Umesh Mishra, Steven P DenBaars and Chi-Kuang Sun 2006 Appl. Phys. Lett. 89 143103
[9] Albrecht Bartels, Thomas Dekorsy, Heinrich Kurz and Klaus Kohler 1999 Phys. Rev. Lett. 82 1044
[10] Mizoguchi K, Hase M, Nakashima S and Nakayama M 1999 Phys. Rev. B 60 8262
[11] Lanzillotti-Kimura N D, Fainstein A and Jusserand B 2005 Phys. Rev. B 71 041305(R)
[12] Pascual Winter M F, Rozas G, Fainstein A, Jusserand B, Perrin B, Huynh A, Vaccaro P O and Saravanan S 2007 Phys. Rev. Lett. 98 265501