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Propagation of acoustic surface waves on a phononic surface investigated by transient reflecting grating spectroscopy

I. Malfanti [a,b], A. Taschin [a,c], P. Bartolini [a], B. Bonello [d], R. Torre [a,b,*]

[a] European Laboratory for Non-Linear Spectroscopy (LENS), Univ. di Firenze, Via N. Carrara 1, I-50019 Sesto Fiorentino, Firenze, Italy
[b] Dip. di Fisica ed Astronomia, Univ. di Firenze, Via Sansone 1, I-50019 Sesto Fiorentino, Firenze, Italy
[c] Istituto Nazionale di Ottica (INO) - CNR, Largo E. Fermi 6, I-50125 Firenze, Italy
[d] Institute de NanoSciences de Paris (INSP), 140 rue de Lourmel, 75015 Paris, France

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ABSTRACT

We present a study of surface acoustic waves (SAW) propagation on a 1D phononic surface (PS) by mean of an heterodyne-detected transient reflecting grating experiment. We excited and detected coherent stationary SAWs characterized by variable wave-vectors. The measured SAW frequencies enables the characterization of the band diagram of this PS sample beyond the first Brillouin zone (BZ). Four different SAW frequencies have been revealed, whose band diagram show articulated dispersion phenomena. In order to address the nature of the investigated SAWs, the experimental results are compared with a numerical simulation of elastic modes based on a finite element model. The observed SAWs are addressed to four Bloch waves characterized by different frequencies and surface energy localization. Moreover, we measured the SAW propagation on a flat non-phononic part of the sample surface and compared it with results from the PS.

1. Introduction

The study of propagation of surface acoustic waves (SAW) has relevant interest in both fundamental research and technological applications, from geophysical studies on seismic waves to the realization of electro-acoustic devices. Starting with the pioneering works of Lord Rayleigh (1885, 1888) a large number of experimental and theoretical studies have been published on SAW science (Landau and Lifshitz, 1959; Auld, 1973; Victorov, 1981; Oliner, 1978).

During the last 20 years, there was a great deal of interest for periodic elastic structures, which are called since that time phononic crystals, by analogy with their optical counterpart the photonic crystals. The propagation of acoustic waves in phononic crystals shows many peculiar phenomena that open the possibility for the realization of acoustic metamaterials (for a review see Lu et al., 2009). A clear example is the creation of phononic band gaps (Kushwaha et al., 1994) (i.e. a frequency intervals over which the propagation of sound is forbidden), that enables a unique control on the propagation of sound (Khelif et al., 2004). Other phenomena are connected with the acoustic processes characterized by frequencies and wave-vectors at the band edge, where the folding and bending of the acoustic bands take place.

* Corresponding author at: European Laboratory for Non-Linear Spectroscopy (LENS), Univ. di Firenze, Via N. Carrara 1, I-50019 Sesto Fiorentino, Firenze, Italy. Tel.: +39 0554572495; fax: +39 0554572451.
E-mail address: torre@lens.unifi.it (R. Torre).

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Relevant examples are the negative refraction phenomena (Feng et al., 2006; Cummer and Schurig, 2007) and the focusing processes (Yang et al., 2004; Zhang et al., 2009).

The presence of artificial periodic elastic structure in a material produces relevant variations even on the nature and properties of SAWs. Just a simple periodic modulation of the surface profile is able to introduce new and interesting modifications of SAWs (Auld et al., 1976; Glass et al., 1981; Gulyaev, 1998). The phononic surface phenomena were already an issue in the technological application of SAWs in the interdigital transducers (IDT) (Oliner, 1978), but recently they met a renewed interest thanks to the boost of phononic crystal studies (Laude et al., 2006; Zhang et al., 2006; Olsson and El-Kady, 2009; Bonello et al., 2010). At present, the research on acoustic properties of phononic surfaces (PS) aimed at both the fundamental aspects and the applicative ones. The complete definition of the PS elastic properties remains to be achieved and the new properties emerging from the periodic arrangement of the surface itself could develop a new generation of SAW devices.

A simple 1D PS can be made by engraving parallel grooves on a homogeneous substrate (Auld et al., 1976; Glass et al., 1981; Glass and Maradudin, 1983). Contrary, to a flat surface, where only one non-dispersive Rayleigh mode can exist, in a corrugated surface new modes characterized by different polarization, penetration and dispersion characteristics appear. Moreover, PS phenomena manifest when the SAW wavelengths are comparable to the depth of the grooves and they approach the spatial periodicity. New effects such as opening of band gaps, folding of some branches in the Brillouin zone, dispersion of SAWs occur (Zhang et al., 2006; Laude et al., 2006; Maznev, 2008). Yet, the SAWs characterized by wave-vectors close to the band edge show non-propagative nature (Laude et al., 2006; Maznev and Wright, 2009). In fact, at the Brillouin zone (BZ) limit, the SAWs approach the zero group velocity so that their elastic energy would not propagate remaining spatially localized. In spite of the great amount of experimental and theoretical studies, a complete and detailed description of these new acoustic modes and phenomena remains an open problem.

The investigation of SAWs can be performed by different experimental techniques (Auld, 1973), recently the techniques based on laser pulses have proved to be particularly suitable to study the high frequency SAWs (Hess, 2002). Especially, the transient reflecting grating (TRG) techniques (Kasinski et al., 1988; Fishman et al., 1991; Duggal et al., 1992; Sawada and Harata, 1995) enable the excitation and probing of coherent SAWs measuring their dynamics in the direct time domain. In these experiments two temporally overlapped picosecond laser pulses are crossed at the surface, the resulting interference pattern excites two counter propagating SAWs by thermoelastic excitation. The temporal evolution of the induced surface transient grating is probed by the diffraction of a separate laser beam. The SAW wave-vector is experimentally fixed by the exciting grating period enabling the scan of the acoustic band diagram.

Recently mainly two types 1D PS samples have been investigated by pulsed laser spectroscopy. A first type is realized depositing a surface periodic structure made by parallel strips of metal and amorphous dielectric matter on a solid substrate (Antonelli et al., 2002; Profunnser et al., 2006) whereas the second is made of deep parallel grooves engraved on the homogeneous substrate covered by an uniform metal thin film (Dhar and Rogers, 2000). Both these samples have been also investigated by TRG techniques (Dhar and Rogers, 2000; Maznev, 2008; Maznev and Wright, 2009). In these experiments the presence of different SAW modes, band gaps and long living SAWs have been detected but the full characterization of the acoustic waves is missed because of some experimental limitations. So, the complete understanding of the Bloch waves on PS covering the full wave-vector range, inclusive of band edge part, remains to be achieved.

In this work we report the study of surface waves propagating in a 1D PS. The sample is made of a grating of grooves engraved on the surface of an amorphous silica substrate coated with an uniform gold thin film. We have measured and compared the SAW propagation on the unpatterned region of the sample with the region presenting the 1D PS structure. The experimental study has been performed by a heterodyne detected transient grating technique realized in reflection geometry. The improved experimental set-up and the very high signal to noise ratio obtained enables us to reveal and measure the presence of new SAW modes that were not detected in the previous TG experiment, including the elusive leaky waves. Moreover we could excite a larger wave-vector range, extending the band diagram characterization well beyond the first Brillouin zone. The effect of the phononic structure on the SAW propagation has been observed and discussed. The experimental data have been compared to those obtained by the simulation realized with the finite element analysis. The simulation enables to address the observed SAWs to four Bloch waves, characterizing their physical characteristics (e.g. surface energy localization and wave polarization).

2. Experiment and simulation

We characterized a sample made by a fused silica plate where a 1D PS structure has been realized. An image of the sample is shown in Fig. 1(a). Two distinct area are clearly distinguishable, a flat surface (FS) region and a grooved one (5×5 mm) that is the phononic surface (PS) part. During this work we have experimentally characterized both regions. The grooving displayed in Fig. 1(b) is obtained by a photo-lithographic procedure. The 1D surface pattern has been impressed on a layer of photo-resist, coated on the glass surface, using a optical mask. The reactive ion etching enables to hollow the square-wave pattern on the glass surface. The remaining photoresist is then removed with acetone. Finally, in order to excite surface acoustic waves, a thin gold film is deposited on both the FS and the PS by evaporation. In Fig. 1(c) a schematic view of the grooving is given. The parameters peculiar of the grating are: the step $d_1 = 5$ μm, with a duty cycle of $d_2/d_1 = 52\%$, and the depth of the grooves $d_3 = 0.860$ μm. The gold film thickness is $h = 0.130$ μm for both the FS and PS regions. The silica plate has a total thickness of 2 mm. The samples were investigated by means of a heterodyne detected transient reflecting grating experiment (HD-TRG). TRG is a time resolved spectroscopic technique that allows the