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Extraordinary transmission of gigahertz surface acoustic waves

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1. Introduction

When acoustic waves propagate through an aperture, extraordinary transmission occurs when the amplitude transmission is superior to the amount predicted by a consideration of the aperture size alone. Introduced in optics by Ebbesen *et al.* [1], this concept has led to several studies in acoustics. Theoretical calculations for bulk waves [2-5] as well as experiments in various configurations have been reported [6-11]. However, this phenomenon has not yet been demonstrated for the case of surface acoustic waves.

Here, we investigate the case of extraordinary transmission of surface acoustic waves in solids and demonstrate, by means of numerical simulations, that this phenomenon also exists for such waves. To this end, we simulate a resonator structure in silicon and demonstrate a transmission efficiency of up to ~4 using GHz surface acoustic waves as an example. Such a frequency range corresponds to that used in surface acoustic waves filters and is therefore of interest for device applications.

2. Numerical simulations

The simulations are conducted with a commercial time-domain finite-element method (FEM) package PZFlex (Weidlinger Associates Inc.). The three-dimensional (3D) model consists of a crystalline Si (100) substrate divided into three regions: two slabs and a cavity resonator mounted in a bridge-like structure (see Fig. 1). The choice of silicon is motivated by its convenient possibilities for fabrication. The left (right) slab is of dimension 120×120 μm^2 (80×120 μm^2) with a depth of 90 μm. The sub-wavelength-bridge connecting the two slabs is of length L and lateral thickness R=0.25 μm, the latter being chosen to be much smaller than the acoustic wavelength (λ~5 μm at 1 GHz). The connecting bridge can contain a protrusion on both sides of cross section $d \times r$ (see Fig. 1). The bridge and the cavity section also have a depth of 90 μm.

In the simulation, the 3D elements, each consisting of eight nodes arranged on an orthogonal grid, measure 0.221×0.221×0.221 μm^3, leading to a total number of elements ~2×10^8. The top-surface is assumed to be free and absorbing boundaries are applied on the slab boundaries to simulate an infinite medium.

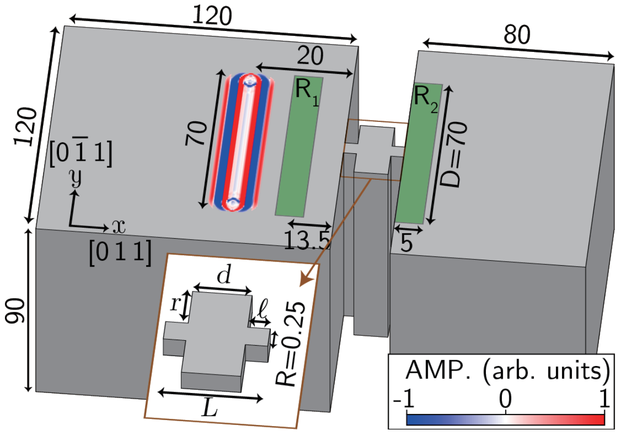

Fig. 1: Schematic representation of the simulated sample, consisting of a straight waveguide containing a cavity resonator. Zones R_1 and R_2 are used to determine the transmission enhancement factor. Distances are in microns.

The thermoelastic laser excitation is represented by a simplified elastic-dipole model [13] with a spatial distribution of horizontal surface forces along the x axis proportional to $x\exp(-x^2/x_0^2)$, with x_0=1 μm, applied as a line-source of length 70 μm along the y-axis. The temporal variation of the excitation is a step-like function (a quarter period of a sinusoid) with a 1 ns rise time. The simulated laser excitation is applied on the left-hand slab of the sample, and the waves propagating in the $+x$ direction (in the direction of the sub-wavelength bridge connecting the second slab) are monitored (see Fig. 1).

The simulations last for a total duration of 25.4 ns, with a 10.6 ps temporal step. Two-dimensional data representing the surface outward particle velocity is recorded.

3. Experiments and results

Fig. 2 shows the out-of-plane particle-velocity field of the simulated surface acoustic waves for the particular geometry d=1, r=2 and l=1 μm (see Fig. 1). The front propagating to the right (along $+x$) is the one of interest. Acoustic

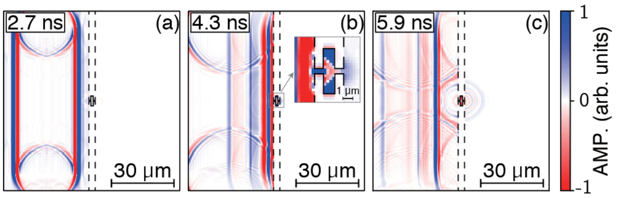

Fig. 2: Simulation of the surface outward particle-velocity associated with acoustic wave propagation in a sub-wavelength bridge of d=1, r=2 and l=1µm, (a) 2.7 (b) 4.3 and (c) 5.9 ns after excitation. Dashed lines represent the block boundaries.

transmission into the sub-wavelength bridge is visible at time t=4.3 ns (Fig. 2b) and after. Figure 2c also exhibits transmission into the right-hand part of the sample.

In order to analyse the frequency response, two equal-area zones R_1 and R_2 (Fig. 1) are defined. They both correspond to a 70×5 μm^2 area. In zone R_1, the wave field is filtered to conserve the only waves propagating in the positive x direction. Once the filtering is achieved, a temporal Fourier transform is applied. The amplitude transmittance T is then empirically obtained from the ratio of the sum of the moduli of the temporal Fourier transforms (FT) over these regions, i.e.:

$$T(f)=|\mathrm{FT}(R_2)|\,/\,|\mathrm{FT}(R_1)|. \qquad (1)$$

From the transmittance T, the extraordinary-transmission efficiency for amplitude is defined as:

$$E(f)=T(f)\,(D/R)^{1/2}, \qquad (2)$$

where D (70 µm) is the length of the zones where the Fourier transform is applied and R (0.25 µm) is the sub-wavelength bridge input aperture (Fig. 1). The square root in Eq. (2) is chosen because T, obtained from the surface wave velocity-amplitude, is a measure of amplitude transmission rather than that of power. For a frequency f, a transmission efficiency $E(f)$=1 indicates perfect transmission. Extraordinary acoustic transmission (EAT) occurs when $E(f)$>1.

Figures 3(a) and 3(b) display results at 259 and 453 MHz, respectively, obtained for the same configuration (d=1, r=2 and l=1 µm). In Fig. 3(b), the extraordinary-transmission efficiency is measured to be E=0.3, indicating the absence of extraordinary transmission for this frequency. Conversely, in Fig. 3(a) at 259 MHz we obtain E=4 demonstrating the phenomenon of EAT for surface acoustic waves at this frequency.

Other configurations can also be analysed by modifying the sub-wavelength bridge parameters. It can be demonstrated that EAT is possible for more than one resonance of the bridge. In Fig. 3(a), the first mode of the cavity is excited, i.e., all the points are moving in phase.

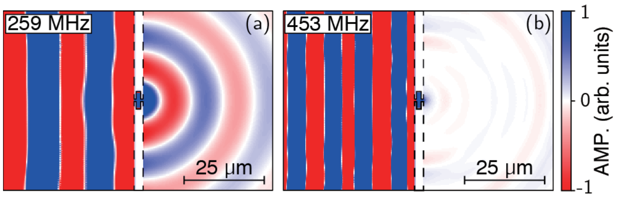

Fig. 3: Amplitude of the Fourier transform (a) on resonance at 259 MHz (E=4) and (b) off resonance at 453 MHz (E=0.3). Dashed lines represent the block boundaries.

4. Conclusion

We demonstrate for the first time that EAT is possible with surface acoustic waves. Extensive study of various cases also demonstrates that GHz resonances of the sub-wavelength bridge (with or without a cavity) are necessary to generate EAT. The extraordinary-transmission efficiency for amplitudes up to ~4 is observed.

In the future, samples should be realized to experimentally demonstrate the EAT with surface acoustic waves, and further simulations should allow optimization of the transmission efficiency.

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