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GHz extraordinary acoustic transmission of bulk waves through nanostructures

固体ナノ構造における GHz 音響波の異常透過現象

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1. Introduction

Acoustic metamaterials are manmade structures designed to manipulate the propagation of sound not available in naturally occuring materials. One interesting phenomena in this field is extraordinary acoustic transmission, the passage of more acoustic energy than expected through a small sub-wavelength aperture. This has been extensively studied in liquid-solid or air-solid systems [1],[2], but to our knowledge not for waves purely confined to solids. Here we investigate extraordinary acoustic transmission (EAT) in a solid-solid structure at GHz frequencies by simulation.

2. Simulation

The chosen structure is shown in Fig. 1, consisting of a two half-spaces of tungsten joined by a cylindrical pillar surrounded by vacuum. Tungsten is chosen because of its effectively isotropic acoustic behaviour. To enhance the EAT for incident plane longitudinal waves, we also make use of a concentric structure of circular grooves, as shown in Fig. 1, by analogy with similar geometries in optics.

We consider three cases, one in which there are no grooves, one in which there are grooves only on the input side, and one in which there are grooves only on the output side, termed respectively the no-groove case, the input-groove case, and the output-groove case.

The diameter of the pillar is chosen to be 5 nm, and the groove width and depth are both 5 nm. We adjust the pitch of the groove structure (p) and length of pillar (L) to vary the resonant frequency of the surface-wave and pillar longitudinal resonances. The central groove width is also chosen to be 40 nm, measured from the outer diameter of the pillar. Plane longitudinal bulk waves are impulsively excited on the input side, and travel towards the output side. In order to evaluate the extraordinary transmission of longitudinal acoustic waves, we make use of analysis regions for amplitude sampling that are disc-shaped (radius 70 nm, thickness 5 nm, and 100 nm from the source) on the input side and dome-shaped (inner and outer radii 47.7nm and 50 nm, and centred on the output end of the pillar) on the output side. The volumes of these two regions are chosen to be the same. We obtain values of the amplitude transmittance $T(f)$ by making use of the average values of the amplitudes A_{in} and A_{out} in these regions at specific frequencies f. We then find, by analogy with the optical case, the EAT efficiency $\eta(f)$ using the following equation:

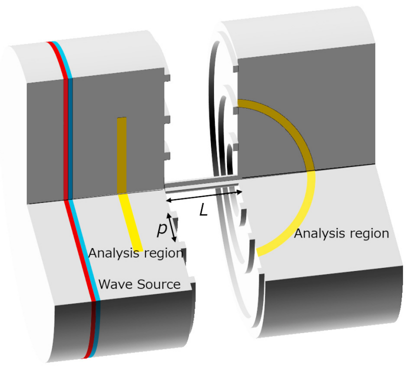

Fig. 1 Simulation geometry (all grooves shown)

$$\eta(f) = T(f)^2 \frac{D^2}{W^2}, \tag{1}$$

where D is the diameter of the disc analysis region and W is the pillar diameter. In our case D^2/W^2=14.

3. Results

In the case of no grooves, EAT is expected to depend on the Fabry-Perot resonance of the pillar at frequency f_n:

$$f_n = \frac{nv_p}{2L}. \tag{2}$$

Here v_p is the wave velocity in the pillar, i.e. the longitudinal velocity of longitudinal acoustic waves

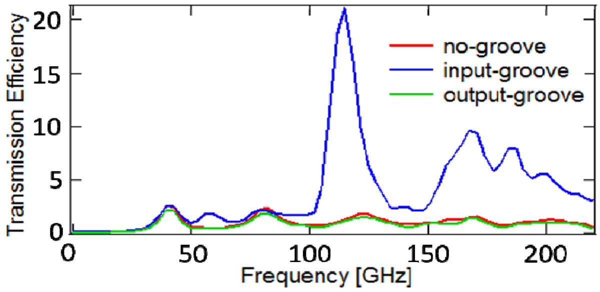

Fig. 2 Transmission efficiency spectra.

in a cylindrical rod, expected from literature values of density and elastic constants to be 4320 m/s for tungsten[3], and n is the mode number. In our simulations we choose L=50 nm. We find f_l= 41.2 GHz from the simulations, in good agreement with 43.2 GHz calculated from Eq. (2).

In the case of grooves of pitch p being present on the input side, it has been observed that resonances are introduced that depend on surface acoustic waves, for example at a frequency[1]

$$f_g \approx \frac{v_{SAW}}{p}, \qquad (3)$$

where v_{SAW} is the surface wave velocity, similar to the Rayleigh wave velocity 2468 m/s for tungsten.

We choose p = 40 nm corresponding to f_g= 61.7 GHz for both the input and output-groove cases. For the no-groove case (red line in Fig. 2), peaks at integral multiples of about 40 GHz are observed, similar to that expected from the estimated value of f_1. For the the input-groove case (blue line), a smaller series of peaks is again observed, this time at integral multiples of about 60 GHz, the first peak similar to that expected from the estimated value of f_g. A particularly strong peak appears in the input-groove case at f = 120 GHz. This frequency corresponds to n=3 for the longitudinal resonance and also to a surface-wave resonance, and the result is to enhance η by a factor >10 to a value η=21. For the output-groove case (green line), we obtain a spectrum very similar to the no-groove case, Peaks at integral multiples of about 40 GHz are observed, and they are not enhanced. We find that the spectrum does not depend on pitch of grooves.

Figure 3 shows the acoustic-amplitude fields for the 3 cases at 82 GHz. For the no-groove case (Fig. 3(a)) and input-groove case (Fig. 3(b)), the waves propagate as spherical waves emanating from the output end of the pillar, and surface waves are strongly excited. In the output-groove case (Fig. 3(c)), surface waves decay by radiation of longitudinal waves, giving a strong amplitude perpendicular to the vacuum-solid surface. We thus find that in this output-groove case the grooves act on the transmitted waves as sound radiators, and thereby modify the wave patterns in the far-field.

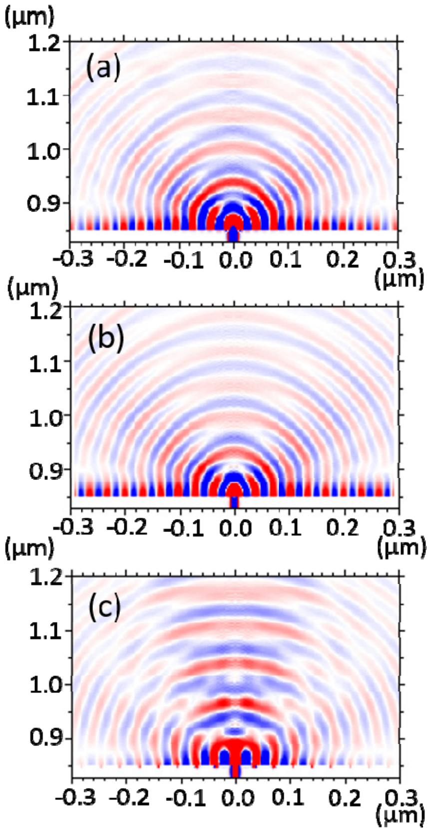

Fig. 3 Acoustic fields for the 3 cases at 82 GHz. (a) No grooves, (b) input grooves, (c) output grooves.

4. Conclusion

In conclusion we have considered the case of extraordinary acoustic transmission in a solid-to-solid system consisting of a cylindrical pillar connecting two solid half spaces. We show that concentric grooves installed on the input surface can dramatically improve the transmission efficiency η. Considerably enhanced values of η>20 can be obtained by tuning the surface-wave resonance to a Fabry-Perot longitudinal resonance of the pillar. In addition, we find that the use of concentric grooves on the output side modifies the the transmitted acoustic waves in the far field but not the transmission efficiency. We hope that in future this work will be verified in experiment using the techniques of picosecond ultrasonics.

References

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