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Visualization of Acoustic Wave Phenomena by Numerical Simulation for Educational Purpose

教育利用を目的とした数値シミュレーションによる音波現象の可視化

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1. Motivation

Numerical simulations have been widely used to design SAW/BAW devices. Moreover, it has the potential to improve quality of education for younger generations. Complex acoustic wave phenomena have been explained by texts and figures but could still be unclear and confusing to the audience. Examples are peculiar wave phenomena such as walk-off (beam steering) and backward propagating waves, which often appear in piezoelectric materials used in SAW/BAW devices.

In this work, we make movies out of numerical simulation results. The dynamic data visualization can figuratively explain complex acoustic wave phenomena such as walk-off angle, phase of evanescent wave, and Goos-Hänchen shift, which deepens comprehension of experienced audience and arouses curiosity of newcomers to the field.

2. Methods

Numerical simulations based on finite element method (FEM) are performed in COMSOL Multiphysics [1]. FEM models are set up with these two features: 1) perfectly-matching layers (PML) for all boundaries to absorb outgoing waves, 2) traveling wave excitation source (TWES) [2] to excite uni-directional wave. For TWES source, spatial profile is set to Gaussian profile instead of step function to suppress unwanted diffraction. For the studies with interfaces, scattering field (SF) can be calculated by subtracting incident field from the total field (TF).

3. Visualization of acoustic phenomena

Three acoustic phenomena are studied and visualized in this work: walk-off angle, phase of evanescent field, and Goos-Hänchen shift (GHS).

3.1 Beam steering

Here, we visualized the power flow angle, which is the angle between wavevector and Poynting vector. The simulation setup is shown in **Fig. 1**, which only has three features: anisotropic material, TWES source, and PML boundary condition. Here, X-cut quartz is used as the material, and the wavevector is in Z-direction. Large walk-off angle of a propagating acoustic wave is shown in **Fig. 2**.

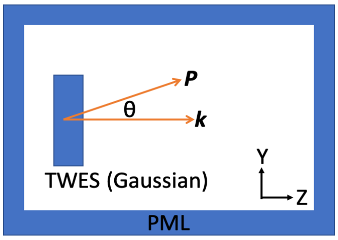

Fig. 1 Simulation setup for walk-off angle visualization. ***k***: wavevector, ***P***: Poynting vector, θ: walk-off angle.

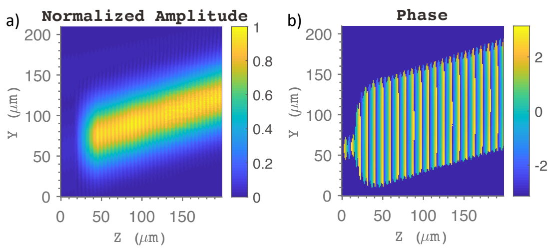

Fig. 2 Visualization of acoustic beam walk off on Z-propagation on X-cut quartz. a) normalized amplitude, b) phase.

3.2 Phase of evanescent wave and GHS

Evanescent wave occurs when the amplitude of the wave decays exponentially from the interface. Total internal reflection (TIR) is one of the most typical examples of source of evanescent waves. The reflectivity of TIR is well known to be unity. For most cases, evanescent wave has pure imaginary wavevector (or slowness) in the direction perpendicular to the interface ($k_\perp$). However, with anisotropy in piezoelectric material, this $k_\perp$ can have a non-zero real part as well. In this study, the phase of evanescent waves with both zero and non-zero real part of $k_\perp$ are visualized by setting a wave incident onto an interface between slow and fast acoustic materials in FEM (**Fig. 3**).

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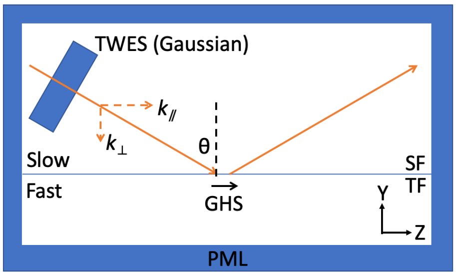

Fig. 3 Simulation setup for evanescent field visualization. θ is the incident angle, which is set at 60° for both studies. Crystalline coordinate system is only valid for study *ii)*, which uses anisotropic material. GHS visualization will be discussed in *iii)*.

i) $k_\perp$ with zero real part

Isotropic materials are used to study standard evanescent wave having $k_\perp$ with zero real part. Here, silicon is used for the slow acoustic material and diamond is used for the fast acoustic material. By removing incident field in the slow material, amplitude and phase of the reflected and refractive fields are studied at the interface (**Fig. 4**). Here, the refractive field is an evanescent field from the TIR. Fig. 4(b) shows the phase of evanescent field, which is not continuous with the phase of propagating wave in the silicon. Furthermore, the phase front is perpendicular to the interface, which suggested the real part of the $k_\perp$ is zero.

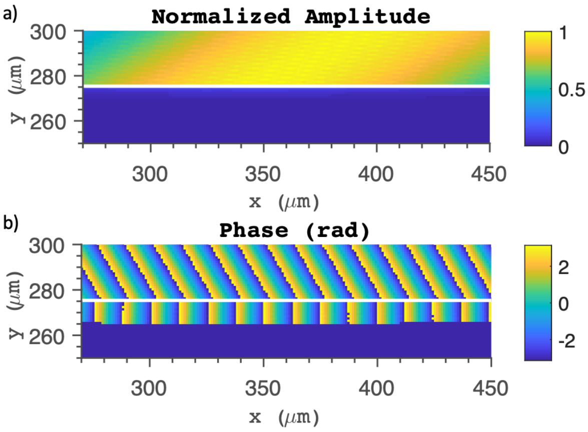

Fig. 4 Amplitude and phase of reflected and refracted fields near the interface. a) amplitude, b) phase.

ii) $k_\perp$ with non-zero real part

To study evanescent wave having $k_\perp$ with non-zero real part, anisotropic materials are required. Here, Y-cut quartz is used as fast acoustic material and the wavevector lies in YZ plane. Copper is used as slow acoustic material due to its low acoustic velocity. As shown in **Fig. 5**. the phase front of the evanescent wave is no longer perpendicular to the interface, which suggests $k_\perp$ having non-zero real part. This type of evanescent wave is similar to a wave propagating in lossy materials.

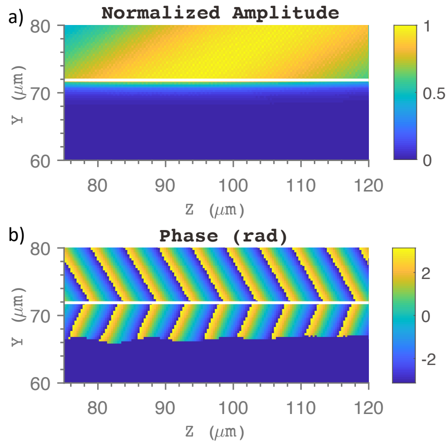

Fig. 5 Amplitude and phase of reflected and refracted fields near the interface with non-zero Re($k_\perp$). a) amplitude and b) phase around interface.

iii) Goos-Hänchen shift

Here, the same model as study *i)* is used to study GHS by calculating center of the incident and reflected beams at different y-locations. The beam centers are shown as lines in **Fig. 6**, where 3.49 µm of positive GHS is measured.

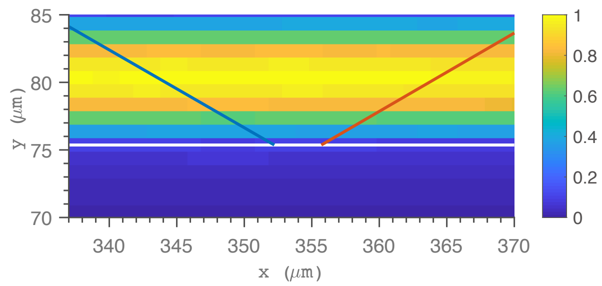

Fig. 6 Goos-Hänchen shift from TIR.

4. Conclusions

In this study, several complex acoustic phenomena are dynamically visualized by numerical simulations. The movies will be shown in the talk. These movies are good tutorials for experienced researchers as well as general audience. The authors will share the movies on our website as free teaching materials.

References

1. COMSOL Multiphysics v.5.4. COMSOL AB, Stockholm, Sweden.
2. X. Li, J. Bao, Y. Huang, B. Zhang, T. Omori, and K. Hashimoto, Proc. IEEE Ultrasonics Symp., (2017).