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Frequency separation of surface acoustic waves in layered structures with acoustic metamaterials

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Abstract

We show theoretically that in elastic layered structures containing an upper layer of smoothly varied thickness and a substrate of a highly dispersive metametarial it is possible to significantly enhance spatial frequency separation of surface acoustic waves. Theory of Love surface acoustic waves propagation in waveguides with varied thickness, taking into account mutual modes coupling, is built. Appropriate structure of metamatererial with resonant frequency dependence of material parameters, making frequency separation effective, is provided. Efficiency of spatial frequency separation and modes coupling is calculated for various metamaterial parameters and wave frequencies.

Keywords: Surface acoustic waves; Elastic metamaterials; Splitter; Spatial dispersion

1. Introduction

During the last decade one of the dynamically developing area of physics is investigation of waves propagating in so-called metamaterials [1,2]. Metamaterials are composite media exhibiting properties for propagating waves, that are not usually met in nature. Basic physical phenomena related to wave propagation in metamaterials are defined by the medium as a whole rather than individual components of a metamaterials. One of the examples of electromagnetic metamaterials is the medium with simultaneously negative permittivity and permeability, providing a possibility to obtain negative values of refraction index [3–5]. In these metamaterials it is possible to control electromagnetic radiation [6,7] in unusual manner, namely overcoming diffraction limit of lenses made of metamaterial [8,9], cloaking objects [10,11], reversing Doppler effect [12], measure infrared light intensity with bolometers [13] and many others.

Due to generality of wave propagation in various media, metamaterials for acoustic waves were also

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predicted and developed [14–18]. Similar to electromagnetic metamaterials acoustic metamaterials have negative constitutive parameters, however, in this case effective density and stiffness instead of permittivity and permeability. Acoustic metamaterials also exhibit unusual behavior for propagating acoustic waves, mirroring electromagnetic counterpart: negative refraction [19], superlensing [20], acoustic cloaking [21,22], reversed Doppler effect [16,23] etc.

The nature of negative refraction index and the underlying resonant microscopic elements of metamaterials make them strongly frequency dispersive, providing, in particular, the possibility to use metamaterials for frequency filters and sensors enhancements. Several attempts were made for applying electromagnetic metamaterials to microwave [24] and optical [25] sensing and frequency filtering [26]. However, less attention was payed to acoustic metamaterial applications. On the other hand the using of acoustic metamaterials for development of different devices for signal processing in a wide frequency range analogously to electromagnetic metamaterials is quite important. They can be used, e.g. to reduce losses of existing devices, such as delay lines, filters, resonators, to increase resolution of filters based on surface acoustic waves (SAW).

In our work we have shown that based on recent progress in acoustic metamaterials development [14,17,27–29] they can be used for implementation of SAW spatial-frequency filters. Varying the metamaterials parameters one can make frequency separation in a wide range from kilohertz to hundreds of megahertz. It is well known, that for a various types of open waveguide structures [30,31] there exists a so-called critical waveguide thickness, depending on the wave frequency, waveguide geometrical and material parameters. In such waveguides as their thickness decreases and becomes smaller than some critical value the wave cannot propagate inside a waveguide and leaves it, radiating into the waveguide substrate. In an inhomogeneous waveguide with smoothly varied thickness such wave transformation appears at different waveguide parts for the waves with different frequencies.

In such a way in an inhomogeneous waveguide it is possible to spatially separate the waves with different frequencies. In the present work we consider propagation of Love SAWs [32,33] with the only shear polarization in an elastic layer with smoothly varied thickness, placed on the surface of the acoustic metamaterial. As acoustic metamaterial we have chosen an elastic matrix (epoxy) with cylindrical inclusions of different elastic material (silicon resin). We show, that Love SAW modes can be spatially separated in such a structure and the separation effect is strongly enhanced in the region of the wave strong dispersion. Moreover it is metamaterial-based analogue of channel drop filters in photonic [34] and phononic [35] crystals.

The paper is structured as follows: in Section 2 we consider features of the Love surface acoustic wave propagating in a waveguide with the varying thickness and propose a numerical method for the problem solution, taking into account coupling between Love wave modes. In Section 3 we present results of numerical calculation of the Love SAW propagating in the structure with metamaterial. Section 4 concludes our work.

2. Mathematical model

2.1. Love surface acoustic waves

Let us consider the Love SAW [32] propagating in a structure consisting of an elastic layer placed on a surface of an another elastic medium. General equation of motion for acoustic waves is [36]:

$$\rho\frac{\partial^2\vec{U}}{\partial t^2}=\mu\nabla^2\vec{U}+(\lambda+\mu)\nabla(\nabla\cdot\vec{U}) \tag{1}$$

where $\vec{U}$ is the elastic displacement, μ and λ are the Lame parameters and ρ is the density.

Fig. 1 presents the Love wave propagating in an inhomogeneous waveguide. Love waves are shear waves polarized parallel to layer boundaries. Moreover elastic displacements U_x is not varied along the Ox axis. In this case Eq. (1) can be simplified:

$$\rho(y,z)\frac{\partial^2 U_x(y,z)}{\partial t^2}=\mu(y,z)\nabla^2 U_x(y,z) \tag{2}$$

with where ρ_l, μ_l and ρ, μ are densities and Lame parameters in the layer and in the substrate respectively, $\varphi(z)$ is the layer thickness, U_x is the elastic displacement along the Ox axis.

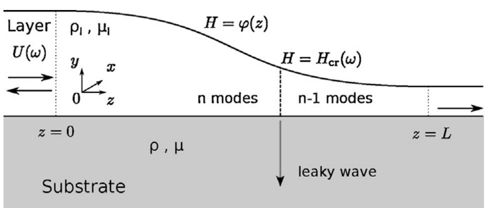

Fig. 1. Love wave propagation in waveguide with varying dimensions.