Looking into surface plasmon polaritons guided by the acoustic metamaterials

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Abstract: Acoustic metamaterials are introduced as the structures with the alternating elements possessing effective properties that can be tuned seeking for the dramatic control on wave propagation. Homogenization of the structure under consideration is needed aiming to calculate permittivity of metamaterial. We present theoretical outcomes studying an acoustic composite possessing negative effective parameters in the acoustic frequency range. An acoustic metamaterial with an the alternating nanowires arranged in a building block and embedded in a host material was investigated. Propagation of surface plasmon polaritons at the metamaterial interface was predicted.

Keywords: surface plasmon polaritons; acoustic; metamaterial

1. Introduction

Acoustic metamaterials give rise to novel properties of the propagation of mechanical waves. The former are impossible in case of conventional materials. Recently, acoustic artificial structured materials possessing properties not found previously and opening the wide avenues for the diverse potential applications with remarkable functionalities [1-4] have been widely studied. Aiming to have a deeper insight into the properties of the structure under investigation the geometric parameters along with the effective permittivity can be tailored according to the elastic features of the scatterers. These might include either the medium preference [5, 6], or an some external factors, i.e. either electric field [7] or temperature [8].

Aiming to achieve propagation of acoustic waves in metamaterials, both density and stiffness should be negative. Recently, scientists made several suggestions and experiments aiming to attain negative effective parameters for acoustic metamaterials. To do so, different procedures, for instance, implanting soft inclusions in fluids [9], using Helmholtz resonators [10] and pipe-membrane compounds [11] have been employed.

The goal of this study is to demonstrate possibilities to construct a metamaterial exhibiting negative effective parameters and show that acoustic waves can be characterized by unusual behavior. Aiming to achieve this goal we have chosen the structures that are composites of a hexagonal array of metal nanowires in a dielectric medium. An indefinite medium with a metallic nanowire array embedded in a dielectric matrix is not affected by the magnetic resonance and operates over a broad range of frequency with much lower material loss [12]. Such an anisotropic material possesses a negative electric permittivity along the nanowires and a positive permittivity perpendicular to the wires, i.e. indefinite permittivity, resulting in a hyperbolic dispersion. A great number of existing effective-medium theories [13] are limited to the optical response of nanowires that are isotropically distributed in the host material. The predicted response of these systems is not influenced by nanowire distribution and is characterized by the nanowire concentration only. These existing techniques are therefore not applicable for practical composites where the geometry is anisotropic due to fabrication process or as a result of a controlled mechanical deformation. Herein, we deal with a practical homogenized acoustic metamaterial for surface plasmon polariton guiding.

It should be mentioned, that the hyperbolic structures under investigation have already attracted interest before [14, 15]. Similar approaches have already been conducted for the optical frequency ranges [16-18]. However, to the best of our knowledge the enhanced structure based on the hexagonal distribution of the nanowires has not been used for acoustic SPP propagation before.

2. Homogenization of periodic phononic crystals

2.1 Mathematical model

A metamaterial structure under investigation is comprised of the building blocks composed of periodically arranged metallic cylinders made either of silver or gold implanted in a dielectric. These metals are chosen as the metallic nanowire materials for their lowest loss at the investigated frequency range. Figure 1 is as schematical illustration of the nanowire metamaterial. Figure 1 presents the anticipated geometrical drawing of the nanowire structures. Nanowires are implanted in a host material.

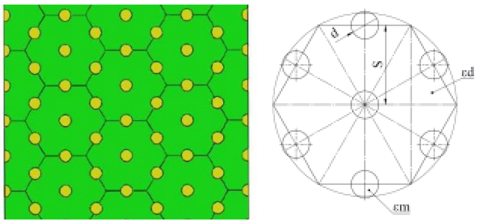

Fig. 1. Schematic illustration of the nanowire composite (a); metamaterial unit cell (b)

Nanowire filling fraction is described as

$$f = \frac{nanowire\ area}{unit\ cell\ area} \quad (1)$$

The nanowire filling ratio is calculated on the basis of the evaluation of the nanowire diameter (d) and spacing (S). It is assumed that the structure under consideration possesses a perfect hexagonal distribution. Doing so, we employ the equation as follows [18]:

$$f = \frac{\pi d^2}{2\sqrt{3}S^2} \quad (2)$$

By proceeding further with this assumption one may obtain a dispersion equation to characterize the modes propagating at the acoustic metamaterial interface.

2.2 Effective constitutive parameters

Herein, we study a composite containing rods with a perfect hexagonal distribution embedded in a fluid host. Nanowires are characterized by a round cylindrical shape and are made of elastic materials. Host material supports propagation of acoustic waves. It is worthwhile mentioning, that in this case wave number is perpendicular to the generatrix of the rods. A composite under consideration is quasi-isotropic. Doing so, geometrical dimensions of the inclusions needed to form the building blocks [19] are much smaller than the wavelength. We have made an assumption that all cylinders are identical. Moreover, they are distributed in a random order. It is worthwhile mentioning that distance between them is approximately equal. Our goal is to calculate the values of the effective parameters of a composite at a frequency range under consideration. Dispersion of the supported acoustic wave is also of particular interest.

Sonic or phononic crystals have provided a fertile ground for dealing with the composites for guiding acoustic or elastic waves. It is worthwhile noting, that in the low-frequency limit, an anisotropic compound exhibits behavior of a homogeneous composite described by outstanding effective features. The plane wave expansion method stands for as an alternative approach to multiple scattering aiming to perform homogenization of highly anisotropic medium consisting of periodic building blocks. The former methodology was for the first time considered by Krokhin [20] for sonic crystals and generalized for non-local phononic crystals in [21].

The system can be efficiently treated as a homogeneous uniaxial anisotropic material with a density parallel to wires ($\rho_{\|}$) and a density vertical to wires ($\rho_{\perp}$) [22, 23] if the wavelength of supported wave is much longer than the period of the array containing distributed nanorods. The derived expressions can be used in the low-frequency limit to get the effective parameters as follows

$$\rho_{\|} = (1-f)\rho_d + f\rho_m \quad (3)$$

$$\rho_{\perp} = \rho_d \left[\frac{\rho_m (1+f) + \rho_d (1-f)}{\rho_m (1-f) + \rho_d (1+f)} \right] \quad (4)$$

In a conventional case of a two-dimensional distribution of nanowire enclosures (parameters labeled with "m") in a fluid background (parameters labeled "d"), f is the filling ratio of the crystal calculated by dividing area of the enclosures by the area of the unit cells. Aiming to modify the frequency range under consideration, one may apply the effective-medium theory designed for the specific frequency range [24].

It is possible to drastically alter the parameters under investigation by the dispersive corrections. For instance, the resonant Lorentz-type dispersion of the density [25] might be considered:

$$\rho(\omega) = \rho_0 \omega_0^2 / \left(\omega_0^2 - \omega^2\right) \quad (5)$$

Herein, $\rho_0>0$ is a constant, and ω_0 is the resonant frequency of microresonators in the compound.

Some important relationship between the permittivity and the bulk density of the air-particle mixture is needed if the dielectric features, of granular or powdered solid materials are taken into consideration. Fundamentally, linearly dependent functions of the real and imaginary parts of the complex permittivity characterizing the specific materials such as pulverized coal, wheat, and whole-wheat flour and their bulk densities has already been found before [26, 27]. The former formalism is based on earlier studies. The linearity of $\sqrt{\varepsilon'}$ was observed by Klein in [28]. Quadratic nature of ε' and ε'' was found by Kent in [29] as follows:

$$\varepsilon' = a\rho^2 + b\rho + 1 \quad (6)$$

$$\varepsilon'' = c\rho^2 + d\rho \quad (7)$$

Herein, ρ characterizes the density of the air-particle mixture, a, b, c and d are constant values for a given particular material. It is worthwhile mentioning, that ε' and ε'' have values of 1 and 0, respectively, for air alone ($\rho = 0$).

3. Surface acoustic wave

It is worthwhile mentioning, that surface waves can not propagate at the boundary between two ideal fluids. The main reason lies in the fact of impossibility to satisfy boundary conditions in this case. Boundary states can be excited [30] if one of the materials possesses a parameter with negative values. The former provides a fertile ground for a direct analogy to surface plasmon states in plasma with $\varepsilon<0$ [31].

Herein, we investigate a wave supported at the boundary separating a pure host fluid and a fluid containing nanowires implanted in a host material. The dispersion relation aiming to have a deeper insight into the properties of a surface wave is calculated as follows:

$$\beta = k\left(\frac{\left(1-\varepsilon_{\|}\right)\varepsilon_{\perp}}{1-\varepsilon_{\perp}\varepsilon_{\|}} \right)^{1/2}, \quad (8)$$

where k – is the wavenumber.

4. Results

In the model employed for calculations the nanowires are considered to be conventional cylinders. Host material is air. Calculations in case of a bulk wave in the composite are presented in Figure 2. At low frequencies effective constitutive parameters have a tendency to approach "classic" values for composites [32]. However, at frequencies close to resonances inside the inclusions the values of dynamical effective parameters are significantly altered.

Fig. 2(a) demonstrates frequency dependence of the dynamical effective density. Because of the complex shear and longitudinal field distribution inside inclusion, resonances of different nature related to shear waves and longitudinal waves might be observed. Thus, there is a significant amount of the frequency ranges where the real part of the dynamical effective density is negative. In Fig. 2(b) permittivity versus frequency is depicted. It is worthwhile mentioning, that dimensions of the nanowires along with the distances between them have been chosen in order to meet the manufacturing requirements [33].

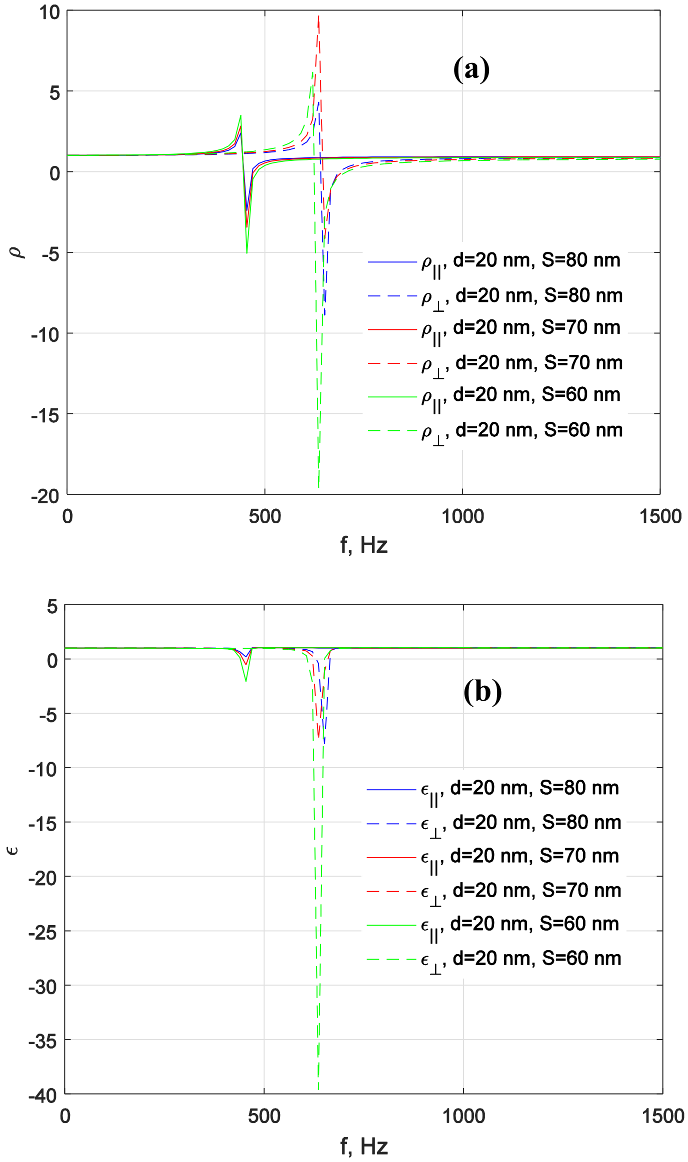

Fig. 2. Effective density (a), permittivity (b) versus frequency for the composite under study.

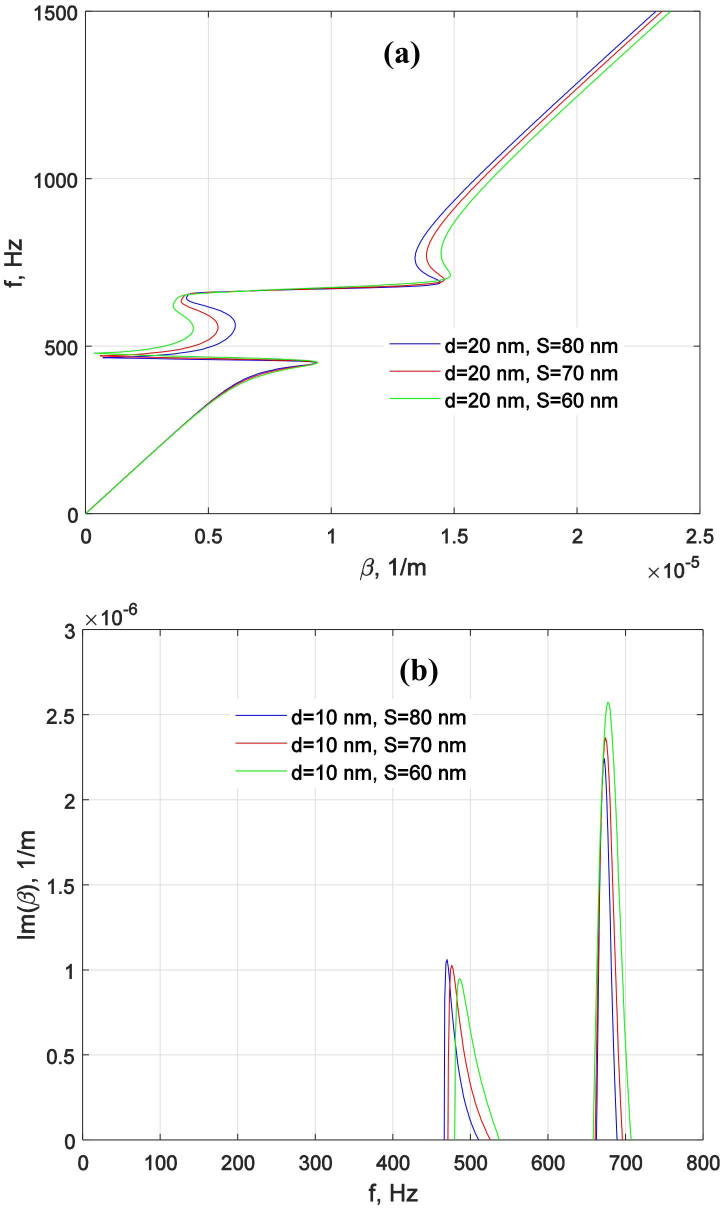

Fig. 3. The dispersion pattern of modes of surface plasmon polaritons supported by a structure under consideration demonstrated in Fig. 1: (a) Re(β); (b) Im(β).

In what follows (Fig. 3), we have studied acoustic surface waves of the Rayleigh type, i. e. surface waves supported by the surface of a semi-infinite elastic metamaterial in vacuum. It is worthwhile mentioning, that the frequency for SPP propagation is determined by negative permittivity. As expected, there exists a common surface waves gap; in addition, when approaching asymptotic frequency from the low frequency direction, all the dispersion curves become very flat and asymptotically reach infinity, exhibiting behavior very similar to that of EM surface plasmon polaritons.

5. Conclusions

Herein, effective dynamic density of composite consisting of nanowires embedded in a host material in terms of coherent potential approximations is calculated. It is demonstrated that there are frequency regions in which dynamic constitutive parameters are instantaneously negative. In this relation, the wave under consideration becomes backward.

Dispersion pattern of the acoustic wave propagating at the boundary separating metamaterial and conventional medium is studied. It is demonstrated that there are frequency ranges in which the surface states are bounded to the interface. Moreover, the exotic behavior of surface plasmon polaritons has been investigated.

In summary, we presented modelling of the acoustic metamaterial. The wide spectral width of the present research for acoustic double negative metamaterials is expected. Moreover, anticipated applications including acoustic superlensing and cloaking [34-37] might be possible.

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Availability of data and material: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability: All simulation parameters of this study are included in this manuscript.

Authors' Contributions: Conceptualization, data curation, and methodology, T.I..; investigation, formal analysis, software, visualization, writing—original draft preparation, writing—review and editing, T.I.; T.G.; E.R.; supervision and revision of the manuscript, validation, T.G.; E.R. All authors have read and agreed to the published version of the manuscript.

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