Linear and nonlinear Tamm surface modes in layered metal-dielectric metamaterials

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Abstract

We study dispersion properties of linear and nonlinear Tamm surface modes at the interface separating two metal-dielectric metamaterials. In the linear regime, we demonstrate the existence of three types of surface modes, one being characterized by the negative group velocity. In the case of a thin nonlinear cap layer at the surface of the metal-dielectric nanostructure, we predict the existence of both TE- and TM- surface modes at the finite powers, even in the case when no linear surface modes exist. We analyze the dispersion properties of these nonlinear surface modes and compare our analytical results with the beam propagation numerical simulations.

1. Introduction

The interest in the study of *nonlinear electromagnetic surface waves* has been renewed recently, and it was shown theoretically [1] and experimentally [2] that nonlinearity-induced self-trapping of light may become possible near the edge of a one-dimensional waveguide array leading to the formation of nonlinear Tamm states (see also the review paper [3] and references therein). In particular, it was found that the self-trapped surface modes acquire some novel properties in the nonlinear regime, and they can only exist above a certain threshold power. These modes can also demonstrate bistability when for the same value of the mode power two different surface modes can exist at the same frequency.

Recently, it was shown that strongly confined plasmonic surface modes can be formed at the termination of metal-dielectric metamaterials [4, 5]. Such localized modes demonstrate many properties that can be advantageously for the realization of photonic or plasmonic sources. Indeed, due to their specific dispersion relation and to the hybrid metal-dielectric nature of the structures that support such surface modes, they allow coupling either to the optical mode inside the light-cone or directly to the plasmon mode. More importantly, such surface modes are associated with lower losses than conventional plasmons and can be controlled and laterally confined by a simple patterning of the metal layer. In addition, the surface metallic layer can also allow a simple electrical injection scheme for the realization of plasmonic or photonic integrated sources.

Here we predict the existence of the backward surface states at the interface of two binary metal-dielectric metamaterial nanostructures. Moreover, we study the properties of nonlinear surface states that exist at the interface of vacuum and layered nanostructure with a cap nonlinear layer. We find that there may exist up to *four nonlinear surface modes* defined by the same frequency and threshold power for the TM-polarization case.

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2.Linear surface modes at the interface of metal-dielectric metamaterials

First, we study the surface modes at the interface of two metal-dielectric nanostructures (see Fig. 1).

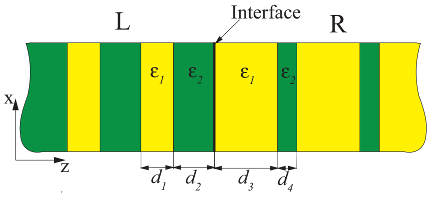

Fig. 1: Geometry of the structure: Two dissimilar metal-dielectric metamaterials are separated by an interface.

In the beginning we apply the effective media approach and find the dispersion of the surface states at the interface of two anisotropic media:

$$\beta = k\left(\frac{(\varepsilon_{\parallel}^{R} - \varepsilon_{\parallel}^{L})\varepsilon_{\perp}^{R}\varepsilon_{\perp}^{L}}{\varepsilon_{\perp}^{R}\varepsilon_{\parallel}^{R} - \varepsilon_{\perp}^{L}\varepsilon_{\parallel}^{L}}\right)^{1/2}, \tag{1}$$

where β is the propagation constant, k - is the wavevector in vacuum and $\varepsilon_{\parallel,\perp}^{L,R}$ are the components of the dielectric permittivity tensors of the left and right media respectively. We also found out that if the metamaterials consist of the identical metal and dielectric layers and we only change the layers' relative widths then then equation (1) simplifies and we obtain

$$\beta = k\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^{\frac{1}{2}}. \tag{2}$$

We can see that dispersion relation in this case is identical to the dispersion of surface plasmon at the interface of uniform metal and dielectric. Thus, the surface mode does not "feel " the composite nature of the media at the both sides from the interface.

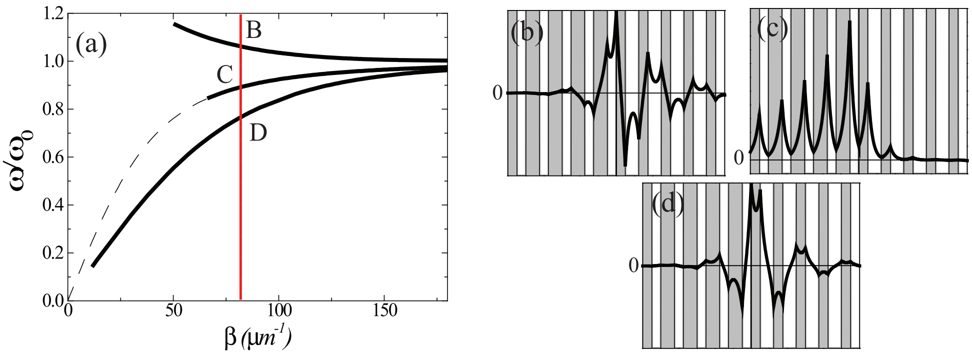

Fig. 2: (a) Dispersion of the surface states. Frequency is scaled to the bulk plasmon frequency ω_0. Dashed line shows the dispersion of the conventional surface plasmons. (b,c,d) Profiles of the magnetic field for the surface states defined by the frequency and propagation constants which are depicted with points (B,C,D) in the plot (a).

We then compare the effective media approach results with the rigorous calculations using transfer matrix method. We find out that together with the surface state predicted by the effective media approach there exist two more additional modes, one of which is characterized with negative group velocity. The dispersion relations and profiles of this modes are depicted in Fig. 2.

3. Nonlinear surface states at the interface of metal-dielectric metamaterial and vacuum

Next, we analyze the dispersion properties of the nonlinear surface modes which may be supported by a cap nonlinear layer at the interface of vacuum and layered nanostructure [see Fig. 3(a)]. We have shown that these surface states are defined by the finite threshold power. If we launch a Gaussian beam along the surface with power less than the threshold power then the beam would diffract from the surface both in vacuum and into the nanostructure [see Fig. 3(b)]. If the beam intensity reaches the threshold value, the beam localizes at the interface forming a stationary nonlinear surface state [see Fig. 3(c)] We have

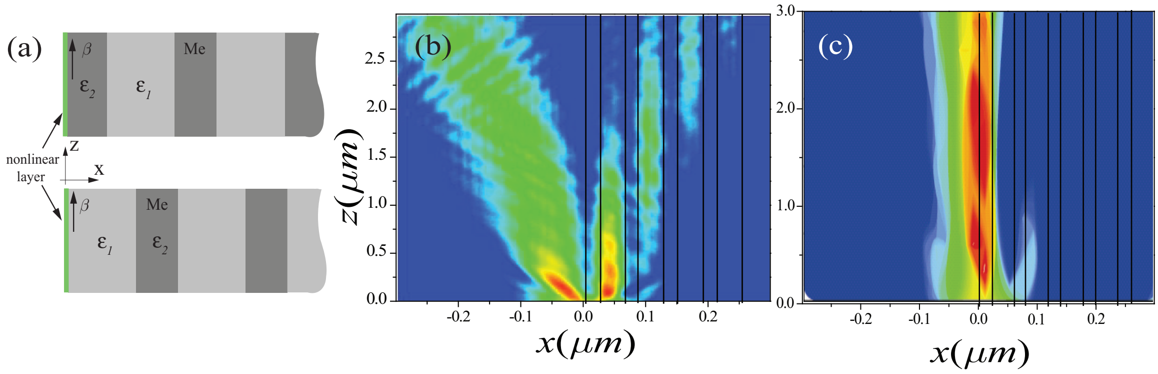

Fig. 3: (a) Geometry of the structure under consideration. (b,c) Beam propagation method simulation results. (b) Field color map for the case when the beam intensity is below a threshold: electromagnetic wave are repelled by the surface; (c) Field color map for the case when the beam intensity near the threshold: wave localizes at the interface.

also shown that there may exist for the case of TM-polarization both discrete and gap modes may exist in the structure even in the case when the wavelength is much larger than the period of the structure.

4. Conclusions

We have analyzed linear and nonlinear surface modes (analog of Tamm surface states in electron theory) which may exist at the interfaces of metal-dielectric metamaterial nanostructures. We have predicted the existence of backward surface modes at the interface of two layered metal-dielectric metamaterials. We have also shown that the nonlinear surface modes may exist at the interface of layered nanostructure and vacuum. We also developed a simple analytical model which allows to calculate the threshold power for these nonlinear states. Finally, we have shown that up to four nonlinear modes with the same frequency and threshold power may exist, which may lead to observation of multistability in such structures.

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