Near-field enhancement using uniaxial wire medium with impedance loadings

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Abstract

Uniaxial wire-medium slab loaded with patches and impedance insertions (as lumped loads) is proposed for the resonant amplification of evanescent waves. The analysis is based on the nonlocal homogenization model for the mushroom structure with a generalized additional boundary condition for loaded vias. It is shown that by appropriately tuning the value of the lumped capacitance, it is possible to achieve a flat dispersion behavior for surface waves resulting in a significant amplification of the near field.

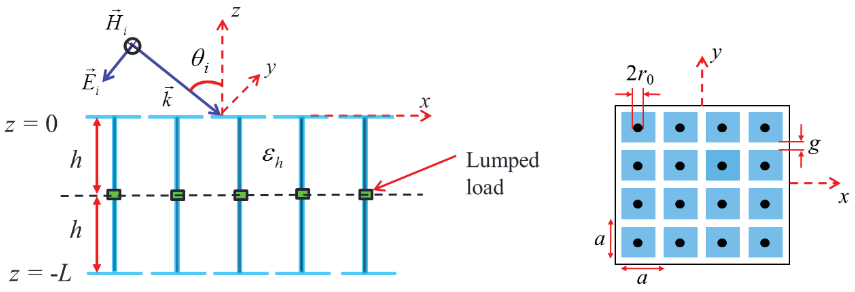
1. Introduction

Since the introduction of the concept of a perfect lens [1], there has been a great interest in the theoretical investigation and practical realization of metamaterial-based lenses, that are able to restore both the propagating waves (focusing of rays by way of negative refraction as theoretically suggested by V. G. Veselago) and the evanescent waves (recovering the fine spatial features by resonant amplification) of a source at the image plane. These lenses, also known as super lenses, exceed the performance of conventional ones which are diffraction limited, and may have important applications in biomedical imaging, sensing, microwave heating, and many other technological areas. In this work we investigate the enhancement of evanescent waves using the mushroom-type structures with loaded vias (lumped loads) through the resonant excitation of surface waves, as a continuation of our previous study on reflection/transmission properties, natural modes, and negative refraction [2, 3, 4]. It should be noted that a uniaxial wire medium (WM) has been used previously to achieve sub-diffraction imaging [5]. However, the imaging mechanism in Ref. [5] was based on the conversion of evanescent waves into transmission-line modes (based on the principle of canalization), and does not involve the enhancement of evanescent waves [6].

Here, the analysis is carried out using the recently developed homogenization models [3] for uniaxial WM with impedance loadings. It is observed that by varying the value of the capacitive load, it may be possible to obtain a flat dispersion for surface waves and to achieve a significant amplification of evanescent waves.

2. Structured uniaxial wire medium

A geometry of the structured WM with loaded vias is shown in Fig. 1 with the TM-polarized plane-wave incidence. The patch arrays are at the planes $z = 0$ and $z = -L$ and the lumped loads are inserted at the center of the vias. Due to symmetry, the response of the structure can be related to the response of a half of geometry with the PEC and PMC ground planes, associated with the odd and even excitations,



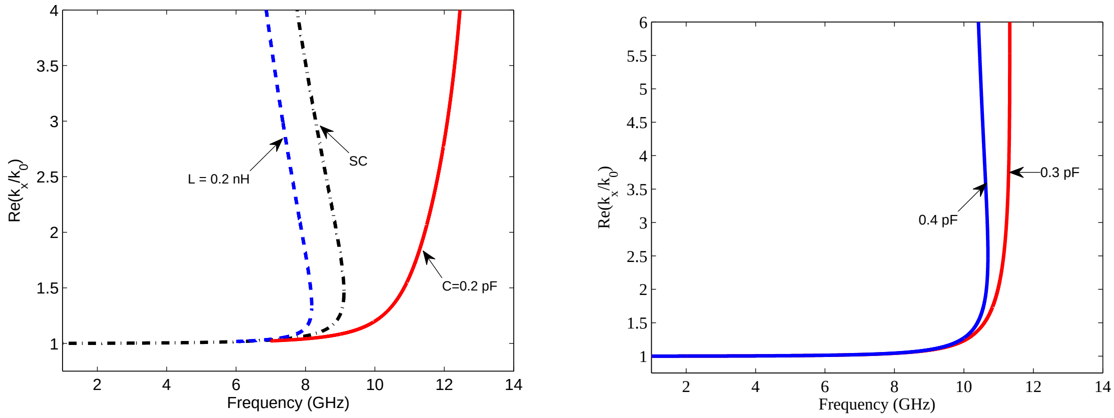
(a) (b)

Fig. 1: Geometry of the mushroom structure with the lumped loads at the center of the vias illuminated by an obliquely incident TM-polarized plane wave. (a) Cross-section view and (b) top view.

respectively. The analytical expressions of the reflection coefficient for the odd and even excitations are given in Refs. [4] and [7], respectively, and the reflection/transmission coefficients of the entire structure (Fig. 1) can be obtained by using the superposition principle.

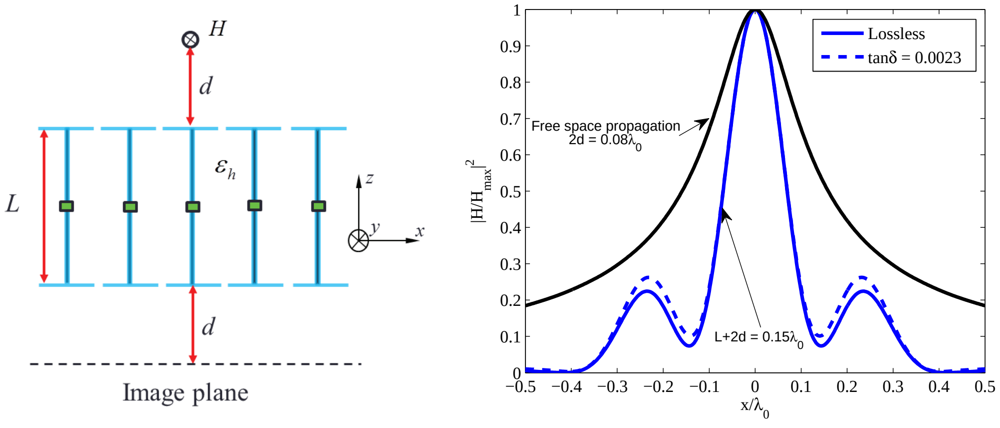
3. Results and discussion

We start with the analysis of the dispersion behavior of TM^x surface (bound) waves for a half of the structure shown in Fig. 1 backed by a PEC ground plane. The structural parameters (with the notations shown in Fig. 1) are as follows: $\varepsilon_h = 10.2$, $a = 2$ mm, $g = 0.2$ mm, $r_0 = 0.05$ mm, and $h = 1$ mm. The homogenization model results for the dispersion behavior of the normalized phase constant, k_x/k_0, of the TM^x surface-wave modes of the mushroom structure with different loads are shown in Fig. 2(a). An interesting observation concerning the dispersion behavior of surface-wave modes for the capacitive loads is that with an increase in the value of the capacitive load the dispersion curve approaches the one obtained for the case of short circuit (SC). This observation is also consistent with the reflection phase behavior reported in [4]. In Fig. 2(b), we plot the dispersion behavior with the capacitive loads of 0.3 pF and 0.4 pF, demonstrating a flat dispersion for a large range of k_x/k_0. Next, we characterize the imaging properties of the structure with the capacitive load of 0.2 pF (equivalent to 0.4 pF for a half of



(a) (b)

Fig. 2: Dispersion behavior of surface-wave modes of the mushroom structure with the vias connected to the ground plane through (a) inductive load (0.2 nH), capacitive load (0.2 pF), and short circuit (SC), and (b) capacitive loads (0.3 pF and 0.4 pF).



(a) (b)

Fig. 3: (a) Geometry of the problem and (b) square normalized magnitude of the magnetic field profile at the image plane calculated for the mushroom structure with the capacitive load of 0.2 pF at the frequency of 10.73 GHz with d = $0.04\lambda_0$.

the geometry with the PEC ground plane), with a magnetic line source along the y-direction, placed at a distance $d = 0.04\lambda_0$ above the structure (set-up is shown in Fig. 3(a)). The homogenization results for the square normalized magnitude of the magnetic field calculated at the image plane are depicted in Fig. 3. The black curve corresponds to free-space propagation, $2d = 0.08\lambda_0$, and the half-power beamwidth (HPBW) is $0.32\lambda_0$. The solid blue curve represents the field profile when the structure is present, and the distance between the source plane and image plane is increased to $L + 2d = 0.15\lambda_0$. The HPBW is equal to $0.14\lambda_0$, thus, clearly showing that the evanescent waves are significantly amplified in the loaded mushroom structure. Also, the evanescent-wave amplification is not significantly affected by the presence of dielectric losses as it can be seen in Fig. 3(b).

4. Conclusion

In this work, we demonstrate a possibility of achieving evanescent-wave amplification by using a mushroom structure with capacitively loaded vias. This is based on the flat dispersion for surface waves which can be obtained by appropriately tuning the capacitive load. The analysis has been carried out using the developed nonlocal homogenization models.

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