Spoof Surface Plasmon Induced Transmission Through a Three-Dimensional Metamaterial

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1. Intruduction

The observation of extraordinary optical transmission reported by Ebbesen et.al. [1] has attracted much research interest. This phenomenon is attributed to re-radiation of localized waves trapped around holes perforated in a metal plate. In the optical frequencies, the localized waves can be achieved by excitation of surface plasmons. The mechanism involving the trapping and re-radiation of the incident wave can be used in applications such as sensing devices, super lenses, and directional beaming. These applications require a thin plasmonic slab so that one or both sides of the slab can support the excitation of the surface plasmons. The applications also require modifications of material surfaces to achieve the coupling between surface plasmons and the incident wave. In the microwave and terahertz frequencies, because of the absence of materials that intrinsically support surface plasmons, localized fields are realized by employing structured surfaces such as corrugated or perforated metallic plate [2]. This structure-induced plasmon like wave is called spoof surface plasmons. However, most of these structures are fabricated on a ground plane to ensure tight confinement on the surface; their applications are restricted to thin waveguides and cannot be used for sensing or for lenses in which excitation of surface plasmons on both sides of metallic slabs is utilized. In this paper, we demonstrate a metamaterial slab based on wire-medium can localize electromagnetic fields on both sides of the slab and the localized field can be coupled/decoupled to a TM-polarized wave by placing diffraction gratings near the surfaces, and which yield spoof surface plasmon induced transmission phenomenon.

2. Numerical simulations

The metamaterial consists of a three-dimensionally connected metallic wire lattice with auxiliary metallic spheres as shown in the inset of Fig. 1. The auxiliary elements serve to reduce spatial dispersion in an effective permittivity of a wire-medium [3]. The geometrical parameters are defined with respect to the unit length a as the radius of the sphere $r = 0.5a$ and the radius of the wire $w = 0.1a$ [5]. The dispersion relation of the structure is shown in Fig. 1. To calculate the dispersion diagram, we employed a three-dimensional finite difference frequency domain (FDFD) method [4]. As we can see in Fig. 1, the two degenerate modes due to the interaction of waves on both sides of the slab will be excited, which is also shown in the inset. It can be also seen that the parallel momentum of the dispersion relations exceeds any wavenumber that radiative waves can have in the air at the same frequency. To compensate the momentum mismatch, we placed diffraction gratings on both sides of the metamaterial slab as shown in the inset of Fig. 2(a).

The grating layer introduces an additional periodicity into the metamaterial structure. Let a be the unit length of a periodic structure along the x direction, and let k_x be a wavenumber along the x direction, dispersion relations are folded at $k_x = 0$ and $k_x a = \pi$. Therefore, the first and second modes appearing from the bound region shown in Fig. 2(b) can be related to symmetric and antisymmetric guided modes folded at $k_x a = \pi$, where a is the unit length of the diffraction grating. The third and fourth modes are related to the first and second modes folded at $k_x = 0$. These modes cross at around $k_x a/2\pi = 0.1$. Therefore, with respect to the normal incidence, for which $k_x = 0$, the first and second lowest modes are

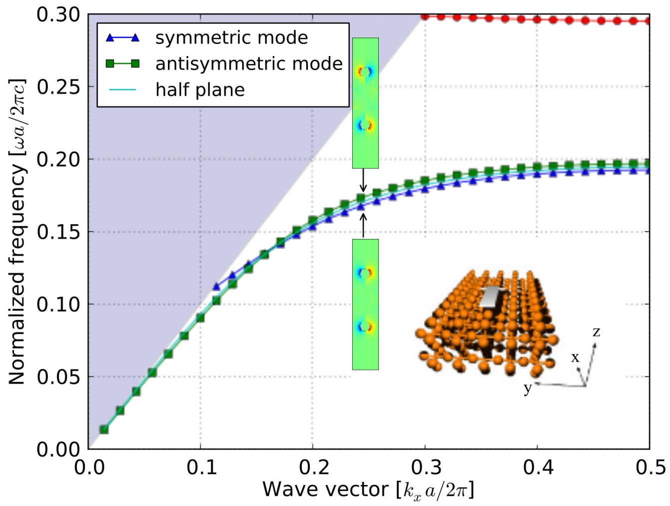


Figure 1: Dispersion relation of the spoof surface plasmons for a half-plane and a finite slab of the metamaterial. The slab has two unit cells along the thickness direction, and the cutting plane of the surface is chosen as shown in the inset. The geometrical parameters are defined with respect to the unit length a as follows: the radius of the sphere is $r = 0.5a$ and the radius of the wire is $w = 0.1a$. In the experiment, the unit length was fixed at $a = 23$mm.

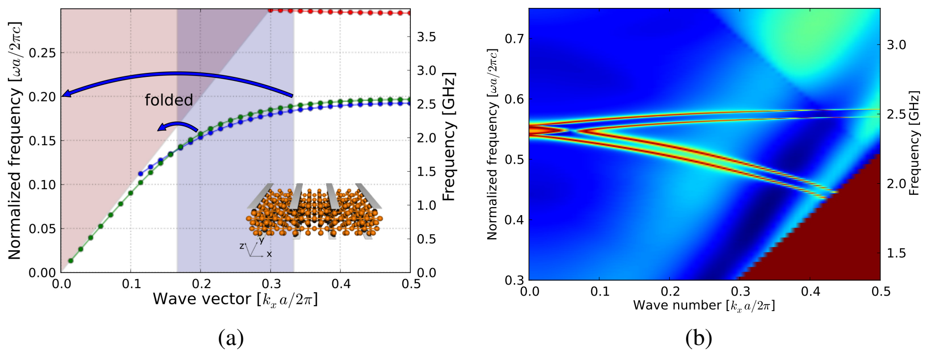
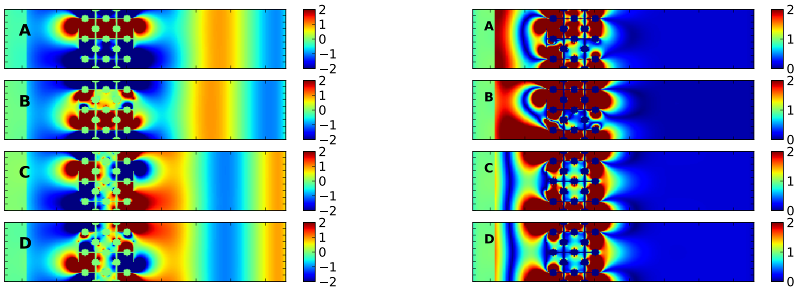


Figure 2: (a) Dispersion relation of the spoof surface plasmons for a finite slab of the metamaterial. Folding lines $k_x a/\pi = n/3$ introduced by gratings are depicted. (b) The calculated transmission spectra for TM-polarized incident waves as a function of frequency and wave number parallel to the surface. This dispersion relation is normalized with respect to the period of the grating.

symmetric modes and the third and fourth modes are antisymmetric modes. It should be noted that a band gap is introduced at $k_x = 0$. Fig. 3(a) shows the spatial distribution of the electric field corresponding to the four transmission peaks at $k_x = 0$. As we expected, the first and second modes involve a symmetric distribution and the third and fourth modes involve an antisymmetric distribution.

3. Experiment

We conducted an experiment using a parallel-plate waveguide (PPW). The height of the PPW corresponds to three periods of the metamaterial, which also corresponds to the period of the gratings. In the experiment, the lattice constant of the metamaterial is $a = 23$mm. The gratings are made of a 23-mm-wide aluminum sheet put on a 3.5-mm-thick foam board. The foam boards are placed tight against the metamaterial face. Fig. 4 shows the transmission for the metamaterial and the grating–metamaterial–grating configuration installed in the PPW. A large transmission is found around 2.45 GHz in the measured result and around 2.35 GHz in the simulated result. In the simulated result, four distinct peaks and



(a) (b)

Figure 3: (a) The electric E_x field distributions at the frequencies corresponding to four distinct transmission peaks in Fig. 2(b) at $k_x = 0$. A, B, C, and D indicate the 1st, 2nd, 3rd, and 4th lowest peaks, respectively. (b) shows the electric E_x field distributions where the diffraction gratings are placed only on the source side.

two band gaps can be seen, while no such distinctions are found in the measured result. As we have seen, these distinct peaks involve highly symmetrical spatial distributions. The experimental observation of such details requires more careful fabrication of the metamaterial. It is worth noting that the spatial symmetry can be exploited [6]; the symmetric modes can be reproduced by placing the PEC plane in the middle of the metamaterial. This can provide another means of experimentally verifying the numerical results and more opportunities for practical applications.

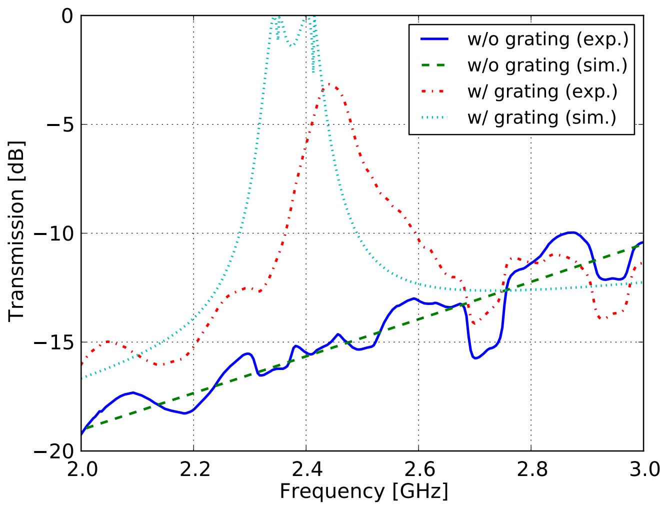


Figure 4: Measured transmission for the metamaterial and grating–metamaterial–grating configuration installed in the parallel plate waveguide (PPW). The height of the PPW corresponds to three unit cells thick of the metamaterial. The cutting plane of the PPW along the height direction and the propagation direction is identical to the plane shown in Fig. 2.

4. Conclusion

We demonstrate transmission enhancement through a metamaterial slab due to the excitation of spoof surface plasmons. Our result shows two essential properties of surface plasmons for practical applications: the field localization involving both sides of the slab and the coupling ability between surface plasmons and diffracted waves. Therefore, we believe that our result has potential for plasmonic sensing, waveguiding, and configurable beam forming.

References

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