Realizing deep-subwavelength negative-index waveguiding by a single-side conformal surface plasmons

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***Abstract*—In this work, we introduce a novel route for achieving negative group velocity waveguiding at deep subwavelength scales. Our scheme is based on the strong electromagnetic coupling within a single side conformal surface plasmon structures. Simulation results show that the single side conformal surface plasmon system can be geometrically tailored to yield negative index dispersion. These results can assist in the development of ultrathin surface circuitry and represent a further step within the general endeavor of radiation control for the microwave and terahertz regimes.**

***Keywords*—negative group velocity; conformal surface plasmons**

I. Introduction

The so-called spoof surface plasmon modes propagating on a textured conducting surface of subwavelength scale, emulating optical surface plasmons at much lower frequencies has opened novel routes for wave control of far-IR, microwave, and terahertz radiation[1-3]. Recently, a more practical structure, the ultrathin corrugated metallic strip, has been proposed to propagate conformal surface plasmons (CSPs) on arbitrarily curved surfaces[4,5], which is proved to be a potential candidate for surface plasmonic device and circuit applications in the microwave and terahertz frequencies [6-8].

One of the enabling elements for the development of such technology is the realization of negative-index (negative group velocity) CSP waveguides. The realization of such waveguides would represent a further step within the general endeavor of radiation control using negative-index metamaterials and plasmonic structures. Recent studies have been made to explore the backward wave propagation of both optical surface plasmons[9] and the lower-frequency CSPs[10-11], which reveal that properly designed tri-layer waveguide, either a metal-insulator-metal (MIM) or an insulator-metal-insulator (IMI) plasmonic structures, can support the backward wave propagation or negative-index in the higher-frequency branch (anti-symmetric mode, or odd mode). However, realization of the negative-index in the fundamental mode (or even mode) has not been reported.

In this work, to achieve the negative-index in the fundamental mode of the CSPs, we proposed a modified CSP structure, which is composed of a single-side corrugated metallic strip by integrating interdigital structure in each slot to further enhance and concentrate electricmagnetic (EM) field in the strip. The resulted CSP waveguide could have fundamental guiding mode with dispersion curve possessing negative slope.

II. Results and Discussions

As shown in Fig.1(a), the traditional single-side CSPs is composed of a corrugated metallic strip with period d, the groove depth h, the groove width a, and the strip thickness t. We first simulate the EM field distribution (|Ez|-component at f_t=7.95 GHz) for the fundamental mode in the traditional single-side CSP strip waveguide and find that the corresponding EM energy $[|E|=(|Ex|^2+|Ey|^2+|Ez|^2)^{1/2}$ at f_t=7.95 GHz] is merely confined at the two edges of the CSP strip as shown in Fig. 2(a) and Fig. 2(b). The EM energy can be hardly penetrated into the slots in the metallic strip leading to an always forward wave propagation in the CSP waveguide. However, in order to couple the EM wave into the slots, we modify the traditional CSP strip by adding small metallic grooves in the slot as shown in Fig. 1(b). The resulted interdigital structure inside each slot further enhances the capacitive coupling of the EM fields in the strip and the power flow could then penetrate into the slot region. This is clearly illustrated in the electric field distributions (|Ez|-component of the fundamental mode at f_m=3.13 GHz) shown in Fig. 2(c) and the corresponding EM energy $[|E|=(|Ex|^2+|Ey|^2+|Ez|^2)^{1/2}$ of the fundamental mode at f_m=3.13 GHz] in Fig. 2(d), which accord with the field pattern of a transverse magnetic (TM)-polarized CSP mode. In the simulations, as increasing the length (l) of the small grooves of the interdigital structure, the EM field is more and more enhanced inside the slots and the EM energy is more and more concentrated in the strip region. The EM energy inside the strip region may become greater than that in the two edge regions. As a result, the dispersion relations of the modified CSP waveguide structure move to lower frequency (e.g. the asymptotic frequency reduced from f_t=7.95 GHz to f_m=3.13 GHz), and after a certain critical point the dispersion curve of the fundamental mode begins to present negative slope at large wavenumber. This means the fundamental guiding mode will support backward wave with anti-parallel phase and group velocities.

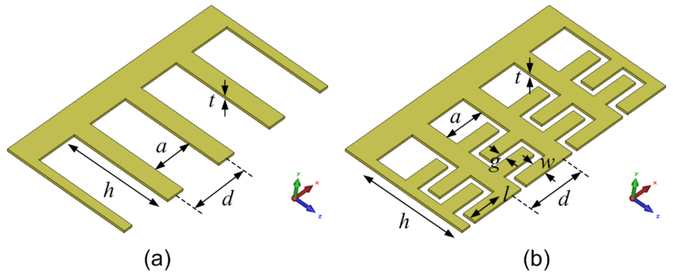


Fig. 1. (a) and (b) Traditional and Modified CSP unit cells, where the period d=5 mm, groove depth h=8 mm, groove width a=4 mm, strip thickness t=0.018 mm. For the interdigital structure, the length of the small grooves l=3 mm, the width w=0.3 mm, the interval g=0.1 mm respectively.

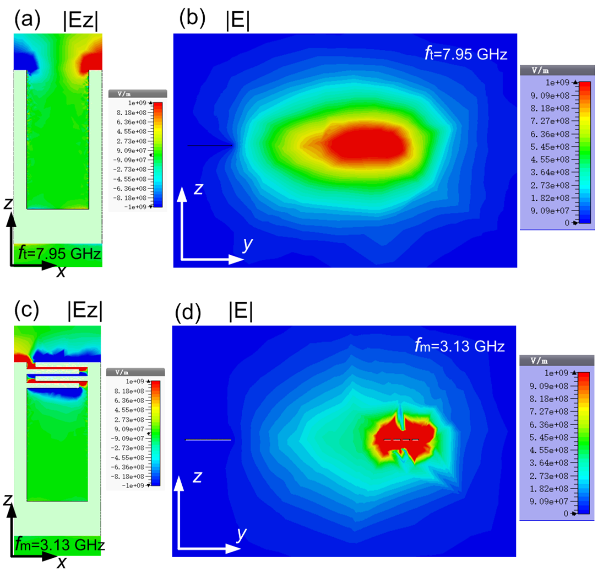
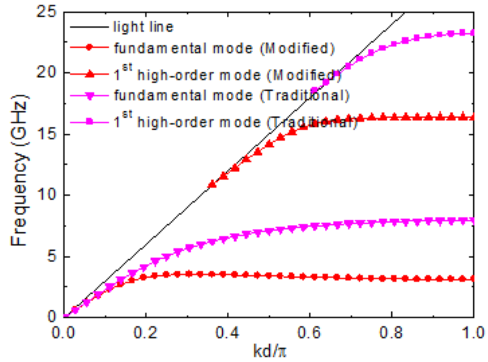
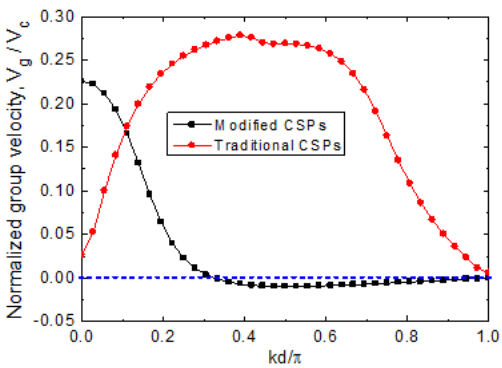


Fig. 2. The simulated |Ez| distributions on the xz plane and the electric field amplitude |E| distributions on the yz plane corresponding to the fundamental mode of the traditional and modified CSPs at asymptotic frequencies f_m=3.13 GHz and f_t=7.95 GHz respectively.

To quantitatively demonstrate the negative-index in the proposed single-side CSP waveguide and compare with the traditional single-side CSPs, the guide-mode dispersion relation and the normalized group velocity (Vg/Vc, Vc=3e8 m/s is the velocity of the light line in free space) for the fundamental mode and the first high-order mode of the traditional and modified single-side CSPs are calculated numerically and displayed in Figs. 3(a) and 3(b) respectively. It is noted that the dispersion curve of the CSPs for the higher-frequency branch does not start at the origin, as only non-radiative modes are taken into consideration. From which, we can obviously observe that the calculated dispersion relation (red line with circle dots in Fig.3(a)) demonstrating an fundamental mode with dispersion curve possessing negative slope, and when the wavenumber kd/π>0.33, the normalized group velocity for the fundamental mode of the modified CSP Vg/Vc<0, indicating the negative-index appears in the proposed single-side CSP waveguide.



(a)



(b)

Fig. 3. (a) Dispersion relations of the traditional and modified CSPs for the fundamental and first hogh-order modes, in which the black line is the light line. (b) The normalized group velocity (Vg/Vc) corresponding to the fundamental mode of the traditional and modified CSPs.

III. Conclusion

In summary, we have presented clear demonstration of backward CSP wave propagation in a specially designed plasmonic metamaterial. To achieve the negative-index in the fundamental mode of the CSPs, we modified a single-side corrugated metallic strip by integrating interdigital structure in each slot to further enhance and concentrate EM field in the strip. The resulted CSP waveguide could have fundamental guiding mode with dispersion curve possessing negative slope. We remark that the demonstration of the backward wave propagating in the plasmonic metamaterial of single-side metallic structure with strong field confinement has not been reported, to the best of our knowledge. Backward wave is the fundamental of many peculiar EM phenomena such as the negative refraction or the sub-diffraction imaging, therefore our findings can lead to many exciting applications based on the backward surface wave propagation in plasmonic metamaterial. We also believe that the proposed planar plasmonic structure can be easily extended to higher frequency regime and may be very promising for further development of practical ultrathin surface circuitry for microwave and terahertz radiation.

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