Broadband Electromagnetic Waves Harvesting Based on Effective Surface Plasmon Polaritons

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***Abstract*——In this paper, a novel structure is proposed for broadband electromagnetic energy harvesting based on effective surface plasmon polaritons (ESPPs) under the framework of conformal transformation optics(TO). By inserting a dielectric cylindrical structure with crescent-shaped cross-section into a dielectric-filled rectangular waveguide, the transverse-electric (TE) mode in the waveguide is smoothly transformed into ESPPs at the bottom of the crescent and propagate towards the singularity of the crescent with decreasing velocity down to zero. The ESPPs energy is harvested all the way towards the singularity due to the interaction between compressed ESPPs and the surrounding lossy dielectrics and metallic wires. Simulation results show that broadband transformation and energy harvesting of ESPPs with efficiency about 25% can be achieved in this scheme. This work paves the way for broadband EM energy harvesting at microwave and terahertz frequencies.**

Keywords—effective surface plasmon polaritons; conformal transformation optics; broadband energy harvesting

I. INTRODUCTION

Surface plasmon polaritons(SPPs) are a collective oscillation of free electrons in a noble metal, which reveal how electromagnetic fields can be confined and manipulated at sub-wavelength scales[1-4]. SPPs stimulated at the interface between two materials whose real parts of permittivity functions have opposite values at operating frequencies often occur at the metal-dielectric interface in optical frequencies. Due to their nature of great field enhancement and sub-wavelength field confinement, SPPs have promising applications in biosensors, plasmonic waveguide and miniaturization of photonic circuits.

In 2010, Pendry et al.[5] proposed a metallic nanostructure with a crescent-shape cross section for broadband light harvesting based on conformal TO. The SPPs excited by a plane incoming wave at the flat part of the crescent propagate towards the singularity of this structure where the group velocity vanishes and energy accumulates. In an idea lossless case, energy accumulates towards the singularity with its density increasing infinitely with time. Losses would lead to a balance between energy accumulation and dissipation. However, difficulties in fabrications of these nanostructures and quantum effects at nanoscale make such a scheme only stay at the theoretical level.

At lower frequencies(microwave or terahertz), metal behaves like a perfect electric conductor(PEC) which do not support surface plamons. Since 2004 when Pendry proposed the concept of spoof surface plasmon polaritons(SSPPs), a large number of works have been done to inherit the exotic features of SPPs into their low frequency counterpart. In 2016, Engheta et al.[6] proposed an alternative method to realize plasmonic phenomena at lower frequencies by exploiting Drude-like modal dispersion relations of TE modes in bounded waveguides filled with materials of positive permittivity only. Later in 2017, Li et al.[7] dug into the theoretical origin of and for the first time experimentally verified this structural dispersion induced ESPPs in a rectangular waveguide. Then, Prudencio and co-workers experimentally demonstrated the transmission of ESPPs at a single interface in a parallel-plate waveguide[8]. And the hybridization of ESPPs in multilayer systems was theoretically investigated early this year, showing that the ESPPs can be categorized into odd and even parities in a similar way as natural SPPs supported by the insulator/metal/insulator (IMI) and metal/insulator/metal (MIM) heterostructures in the optical regime[9]. All these works demonstrated that ESPPs are perfect low frequency counterpart of natural SPPs in the optical regime and set up the basis for achieving real ultra-subwavelength field confinement and enhancement at lower frequencies.

In this work, based on the conformal TO and the ESPPs theory, we proposed an alternative structure for broadband EM energy harvesting at lower frequencies. Simulation results show that the harvesting efficiency can reach about 25% across a broadband. The proposed scheme avoids the above difficulties encountered in the optical regime and opens a new avenue for broadband energy harvesting and transformation at microwave and terahertz frequencies.

II. MODEL AND SIMULATIONS

Based on the theory of ESPPs, we designed an energy harvesting structure in a rectangular waveguide as shown in Fig.1(a), in which crescent-shaped dielectric cylinder (blue regime) is inserted into a dielectric-filled rectangular waveguide with length $L = 2a$ and cross-section dimensions of $a \times b = 22.86 \times 10.16 mm^2$. The specific dimensions of the cross-section of the crescent-shaped dielectric cylinder shown in Fig.1(a) with $r = 3.42mm$ and $0.8r = 2.736mm$ respectively. The orange region in the waveguide is filled with a dielectric of relative permittivity $\varepsilon_1 = 4$ and the blue region is filled with a dielectric of relative permittivity $\varepsilon_2 = 2$. To excite ESPPs mode, a series of metallic wires with infinite small radius and period of 0.01mm are placed along the interface between these two regions. It is known that if only TE_{10} mode is considered, one can express the relative effective permittivity of the TE_{10} mode as $\varepsilon_e = \varepsilon_r - \lambda_0^2 / 4a^2$, where ε_r is the relative permittivity of the medium filling the waveguide, a is the lateral dimension of the waveguide and λ_0 is the free space wavelength. Thus, in the frequency regime between 3.28GHz and 3.78GHz, the ESPPs can be supported at the interface between these two regions according to the analysis in[7]. For instance, at 3.4GHz, and the effective permittivity of $\varepsilon_1 = 4$ and $\varepsilon_2 = 2$ are $\varepsilon_{e1} = 0.28$ and $\varepsilon_{e2} = -1.72$ respectively. As expected, when only TE_{10} mode is excited at one port of the rectangular waveguide, it would be transformed partially into the ESPPs waves at the flat part of the crescent structure and propagate towards the singularity of the crescent. Fig.1(b) shows our simulation results of the electric field distributions E_y in the yz plane at four intraband frequencies.

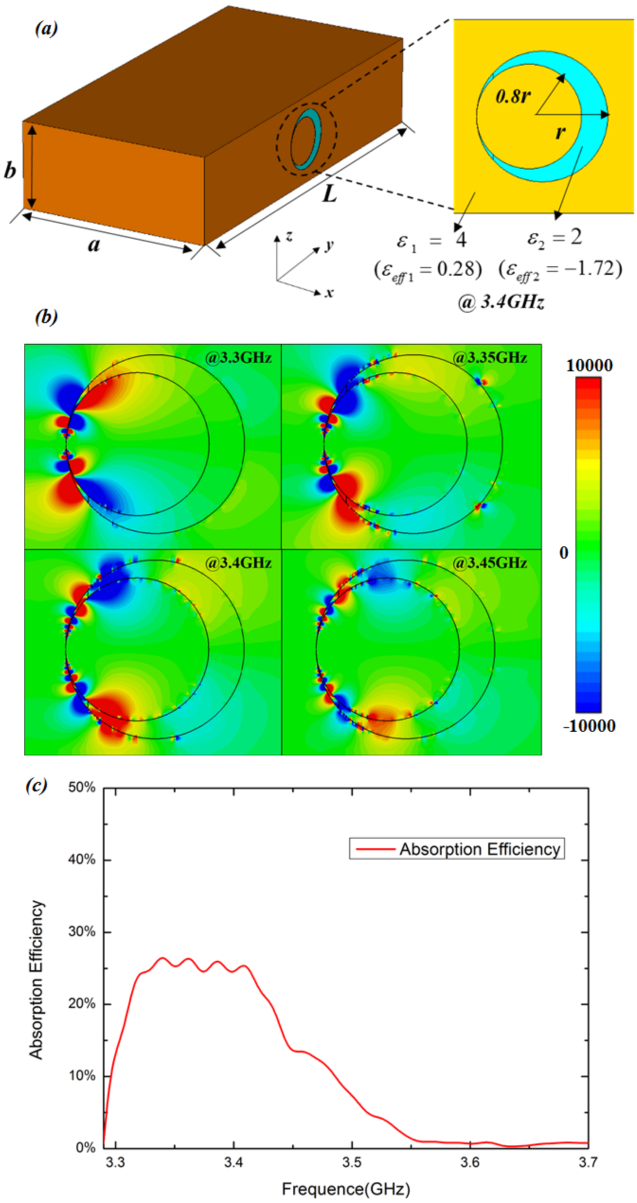

Fig. 1. (a) The schematic drawing of the energy harvesting structure. (b) Simulated E_y (V m^{-1}) distributions in the yz plane(x=0mm) at four intraband frequency points (3.3GHz, 3.35GHz, 3.4GHz and 3.45GHz). (c) Absorption efficiency of the structure.

It can be clearly observed that as ESPPs propagate towards the singularity, their wavelength shortens and the group velocity decreases in proportion. However, these ESPPs waves can never reach the tips or the touching point of the crescent in the same manner of their optical counterpart. In an ideal lossless media, energy accumulates toward the singularity, its density increasing with time without bound. In practice, finite loss will resolve the situation leading to a balance between energy accumulation and dissipation.

We also calculate the absorption efficiency of this structure by normalize the absorption power to the incoming power at the wave-port to verify the broadband energy harvesting effect. As shown in Fig.1(c), a relatively flat absorption spectrum of 40% relative bandwidth between 3.3GHz and 3.5GHz can be observed, in which the absorption can reach 25%. To further broaden the absorption spectrum, one can tune the two relative permittivities of the two regions.

In summary, we have proposed a new scheme for EM energy harvesting at lower frequencies based on the theory of ESPPs and TO. This work opens a new avenue of research and applications of low frequency ESPPs, including broadband energy harvesting, high power nonlinear microwave devices design.

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