1st National Conference on Soft Computing of Engineering Science in Industry and Society (ASEIS 2022)
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همایش ملی
محاسبات نرم علوم مهندسی
در صنعت و جامعه

Application of epsilon-near-zero (ENZ) metamaterials on Smith-Purcell Terahertz radiation

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Abstract

For a specific desired frequency, the ENZ metamaterials expose a near-zero reply within the real part of their dielectric permittivity. The performance of the EM field in vicinity of these materials is surprisingly exciting. By means of proximity interaction of moving high kinematic electrons near the surface of an ENZ loaded 1D holed array slab, low-frequency equivalent of surface Plasmon is agitated. Owed to electron-Plasmon momentum attraction force, flow of EM energy grows within the holes and consequently magnifies the energy. This will reduces the working current while the output power upsurges. At correct integer frequency multiplication harmonics of this "spoof" surface Plasmon (SSP), as a result of periodicity of the structured hole-array, a phase change process (ukmlapp process) develops which redshifts the SSP's momentum above the light cone making terahertz wave radiations.

Keywords: Epsilon-near-zero; Smith-Purcell radiation; Maxwell-Garnet effective medium theory; Terahertz source

Introduction

Recently discovered ability to confine, guide and manipulate sub-millimeter waves on apertures smaller than incident wavelengths is a promising key for design of slow wave terahertz circuit structures [1-4]. Although planar metallic surfaces support surface electromagnetic (EM) waves at low frequency regimes, but they are weakly localized and the fields are extensively excluded from the metal and expanded in air [5]. According to Pendry et al. [6], patterning the surface with holes will modify the EM boundary conditions and strongly localizes the sub-millimeter wave which produce surface-Plasmon-like bounded waves –called as a 'spoof' or 'designer' surface Plasmon and have been experimentally confirmed for microwave domain [7]. Despite of the simple prism coupling method which is proven as a useful method for excitation surface Plasmon, both in visible and microwave domains [8]. Here in this paper we use the approximate electron travelling beam method – called as "Smith-Purcell effect" [9-12, 21]– for excitation of spoof surface Plasmon. Providing synchronism condition between beam velocity and phase velocity of surface wave, energy transfers from electrons to surface wave. Due to periodicity of the surface, momentum of spoof wave redshifts to the above of light line [13, 14] and a strong terahertz radiation occurs. Here, we study the effect of loading the structure holes with epsilon-near-zero (ENZ) metamaterials on the quality of radiated terahertz wave.

Materials and Method

As shown in **Fig. 1** low frequency EM waves are not confined to the surface of a metallic slab, but when the surface is coated with any dielectric material (even graphene [15]) and/or is structured [10], a reasonable portion of EM wave confines to the surface. Here in this paper, we show that when loading the holes of the structured slab with engineered ENZ metamaterials, we can even achieve more confinement of EM wave to surface. The ENZ metamaterials are designed to reveal a near-zero response for the real part of the dielectric permittivity at a given frequency or in a specific frequency range [16] and the behavior of the EM field inside these materials is anomalously interesting.

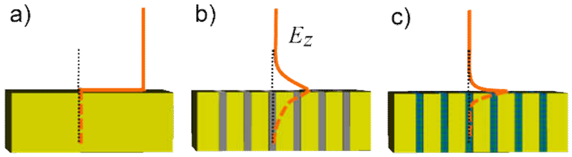

Figure 1. Distribution of EM waves at the surface of a (a) planar (b) structured, and (c) ENZ loaded slab.

A low value of permittivity leads to an increased electric field inside the material thus the phase velocity of EM wave inside such a material may reach near-infinite values and relaxing the link between frequency and wavelength, allowing high frequency waves propagate with long wavelengths through the material [2]. Application of these materials is not straightforward and requires artificial metamaterials exhibiting desired plasma frequency to be synthesized. We stack an appropriate number of thin films embedded with huge distribution of metal nanoparticles. Noble metal nanoparticles size directly affect the surface Plasmon resonance frequency and redshifts it as the size of the nanoparticle increases. Using various synthesis methods, it is possible to shift the absorption peaks toward different excitation frequencies. The permittivity of bulk metals is modeled by the Drude theory, which gives the permittivity as [17, 18]:

$$\varepsilon_m(\omega)=\varepsilon_\infty-\frac{\omega_p{}^2}{\omega^2-i\gamma\omega} \qquad (1)$$

where ω_p, is the plasma frequency and γ is the electron scattering rate, and ε_∞, is given a value of 1 if only the conduction band electrons contribute to the dielectric to the dielectric function. Bulk gold already exhibits ENZ properties in the UV, though for a very narrow range of frequencies. In order to extend the ENZ properties of bulk gold into the visible, we propose synthesizing thin films embedded with gold nanoparticles. To examine the dielectric permittivity of this composite material, we will use the Maxwell-Garnett effective medium theory (MGT), which provides the effective dielectric permittivity as:

$$\frac{\varepsilon_{eff}-\varepsilon_h}{\varepsilon_{eff}+2\varepsilon_h}=f\,\frac{\varepsilon_m-\varepsilon_h}{\varepsilon_m+2\varepsilon_h} \qquad (2)$$

where ε_{eff}, ε_m, ε_h, is the permittivity of composite material, the inclusions, and the host medium, respectively, and f is the volume fraction of the inclusions, $f=V_m/V_{total}$ [16].

Results and Discussion

In **Fig. 2**, we have calculated the usual cold dispersion curves of surface Plasmon for different permittivity loaded inside the slab holes (different filling factors of nanoparticles in the composite). We see that by slight increasing of epsilon (adding nanoparticles and increasing the fill factor of composite) to near epsilon of vacuum, the frequency contrasts between k/K =0.5 and k/K =1 points (k is wavenumber normalized to slab wave number K=$2\pi/L$) decrease and the dispersion curve becomes flatten. Since our device is voltage tunable, we can choose all beam voltages that satisfies the synchronism criterion between electron beam velocity and phase velocity of surface Plasmon for negative group velocity (k/K >0.5 and k/K <1) [19, 20]. We choose the minimum GVD k_{point} of epsilon=0.001 as the operating point. Then from the dispersion diagram, we set the corresponding frequency of this k_{point}. Using this value, we are able to calculate required energy required to excite the corresponding frequency. The phase matched beam must have an energy of 9.02kev and a velocity of β_e=0.185c, where c is the speed of light. This beam intersect with all of dispersion diagrams in the first negative space harmonic region i.e. negative group velocity regions (k/K >0.5 and k/K<1).

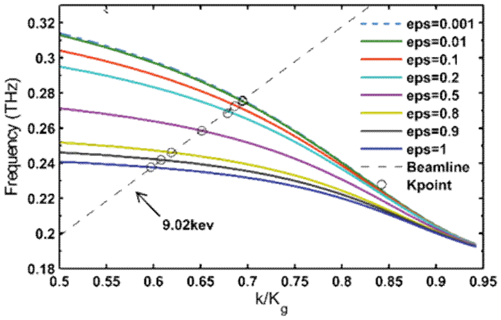

Figure 2. Dispersion relation of surface Plasmon extracted for different permittivity's loaded inside the holes.

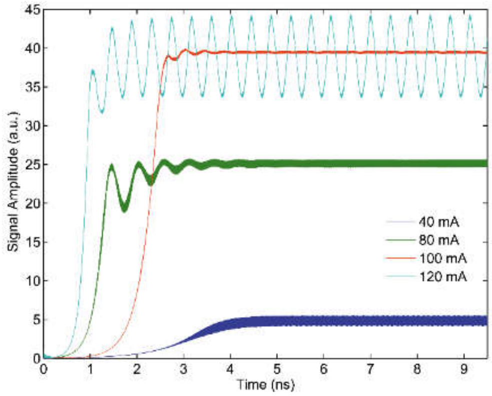

Figure 3. Terahertz radiation amplitude from ENZ loaded slab for different currents of beam with voltage of 9.02kev.

In **Fig. 3**, we have calculated the terahertz wave radiated from ENZ loaded slab for different beam currents. As the results suggests, increasing the current will increase the output power. However this continuous only to 120 mA where the output becomes unstable. The best suggested current is 100 mA. In **Fig. 4**, for 100 mA current, we take fast Fourier transform (FFT) from detected signal which shows 276 GHz component being emitted from our device along with a very tiny component of its second order harmonic.

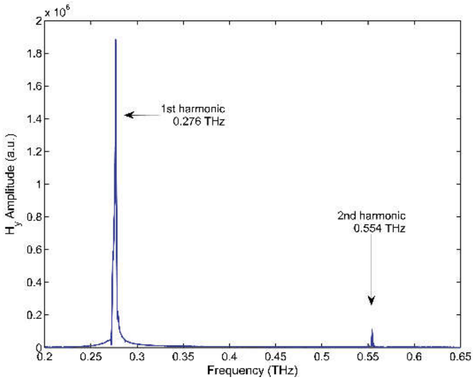

Figure 4. Frequency components of terahertz radiation.

Conclusions

The ENZ metamaterials with a near-zero response in the real part of their dielectric permittivity are really interesting due to their anomalous behaviour. Proximity interaction of travelling electron beam near the surface an ENZ loaded 1D holed array slab excites the low-frequency counterpart of surface Plasmon. Because of electron-Plasmon momentum coupling, a strong recirculation of EM energy expand inside the holes and reduces the operating current while the output power increases. Due to periodicity of the hole-array, an umklapp process develops at the frequency harmonics of "spoof" surface Plasmon (SSP) which in turn redshifts the SSP's momentum beyond light cone forming terahertz region emissions.

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