SURFACE WAVES ON INTERFACE OF 3D METAL-WIRE DIAMOND LATTICE FOR ACCELERATOR APPLICATIONS

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Abstract

We present the results of our recent research on 3D metallic lattices operating at microwave frequencies, with applications in advanced accelerating structures and radiation sources based on the Smith-Purcell effect. Bulk and surface electromagnetic waves supported by a diamond lattice of metal wires are calculated using HFSS. The bulk modes are determined using calculation of a primitive cell of diamond lattice. The surface mode is determined using simulation of a stack of cells with the perfect-matching layer boundary in vacuum. A plasmonic waveguide is formed as a defect in a diamond lattice. The plasmonic waveguide mode can be employed for particle acceleration.

INTRODUCTION

Photonic (electromagnetic) crystals have found interesting applications as accelerator structures and microwave tube circuits. Recently, we conducted experiments on a 17 GHz photonic band gap (PBG) accelerator structure [1]. The PBG accelerator structure was built as a disk-loaded waveguide of 6 cells. Each cell of this structure was designed as a 2D array of metal rods with a defect in the center. The defect mode serves as a TM_{01}-like accelerating mode. Cold analysis of the PBG structure showed that it can suppress higher order modes (HOM's) which are excited as wakefields from the electron bunch.

This paper includes theoretical studies of a 3D metal lattice structure for accelerator applications. This 3D metal lattice is "artificial plasma" with a negative dielectric constant [2]. Therefore, a surface mode exists on the interface of the lattice and vacuum. This surface mode decays in both directions namely, vacuum and the lattice. Such an effect is possible only if the dielectric constant is negative. This surface mode on the interface of the lattice can be employed in a surface mode accelerator based on the Smith-Purcell effect [3]. Another approach for an accelerator structure would be a slow wave waveguide built of the 3D metallic lattice without any disks. In such a structure, wakefields as HOM's would naturally leak out of the structure without being trapped between the disks.

BULK AND SURFACE MODES

A cubic 3D metallic wire lattice was described as "artificial plasma" in [2]. The plasma frequency f_p is a cutoff frequency for all propagating modes in the lattice. Below the cutoff only a surface mode or a defect mode can be observed. We analyzed in [3,4] the cubic lattice built for microwave applications particularly in an accelerator. We found in [4] that the bulk and surface modes in this lattice are strongly affected by spatial dispersion (SD). Therefore, the "artificial plasma" model is not always applicable for 3D metallic lattices. As a result of SD the surface mode resonance does not occur at $f_p/\sqrt{2}$ as predicted in [2] but tends to f_p at large wave numbers.

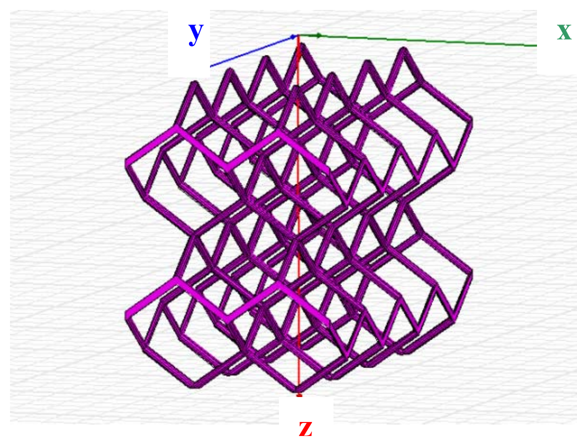

Fig.1. Metallic photonic crystal built as a diamond lattice of intersecting wires.

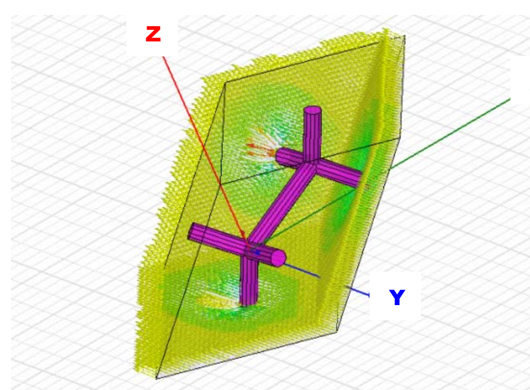

Fig. 2. Simulation of bulk modes in the diamond wire lattice using the primitive cell. A longitudinal plasma mode at 6.25 GHz is shown for the lattice cubic cell length a=2.3 cm and the wire radius r=0.07 cm.

A diamond lattice of metal wires [5] is denser as compared to the cubic lattice and therefore is expected to be more isotropic and demonstrate the properties of "artificial plasma". In this paper we present the simulation results from the diamond lattice carried out using Ansoft's High Frequency Structure Simulator (HFSS).

The diamond wire lattice (Fig. 1) was analyzed for the following parameters, same as in [5]: the cubic unit cell length a=2.3 cm; the wire section length $l=a\sqrt{3}/4=1$ cm; the period in x and y directions $b=a/\sqrt{2}=1.63$ cm; the wire radius r=0.07 cm.

The cutoff (plasma) frequency f_p=6.25 GHz was calculated using the primitive cell of the lattice. The zero-phase advance boundary conditions were implied on the sides of the primitive cell (Fig. 2) to calculate the plasma frequency. The entire Brillouin diagram of diamond wire lattice can be calculated by eigenmode simulation for varied phase advances between the parallel sides of the primitive cell. The calculated Brillouin diagram is close to that calculated using a different approach in [5]. The longitudinal plasma wave at the frequency of 6.25 GHz in the diamond wire lattice is depicted in Fig. 2.

The surface mode on the interface was calculated for propagation in both x and y directions (Fig. 1). A stack of cells with the dimension b x b x 5b was used for surface mode calculation (Fig. 3). The mode uniform in the y-direction and with a phase advance $\varphi_x=k_x b$ was calculated in the x-direction. The low frequency surface mode does not penetrate in to the lattice. The electric field is longitudinal (along the propagation direction) as shown in Fig. 3.

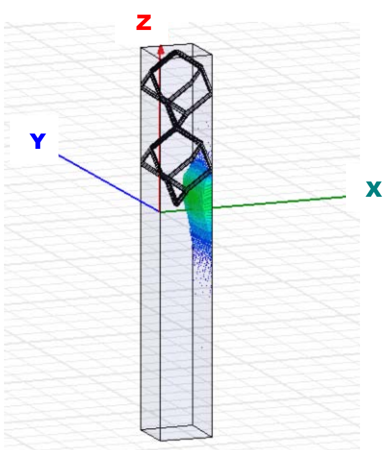

Fig. 3. Simulation of surface mode on the interface of the diamond wire lattice.

Since the interface of the lattice is not symmetrical, the surface modes propagating in the x and y directions are different. The surface mode propagating in the x direction is the one of interest. The dispersion curve of this mode (Fig. 4) coincides with the light cone at low wave numbers k_x and asymptotically approaches the surface resonance frequency of 4.74 GHz at large wave numbers. This frequency is close to $f_p/\sqrt{2}$. The surface mode in the y direction converts into the bulk (plasma) mode of frequency f_p at large wave numbers (not shown in Fig. 4). Using the cell depicted in Fig. 3, the bulk mode can be calculated as well. The bulk mode exists at higher frequencies (Fig. 4) and does not decay in to the lattice.

The surface modes were simulated for different metal rod radii ranging from 0.017 to 0.14 cm. The surface mode resonance frequency was found different to $f_p/\sqrt{2}$ for each particular case, which confirms that the diamond wire lattice is affected by SD though it is more isotropic than the cubic lattice [4].

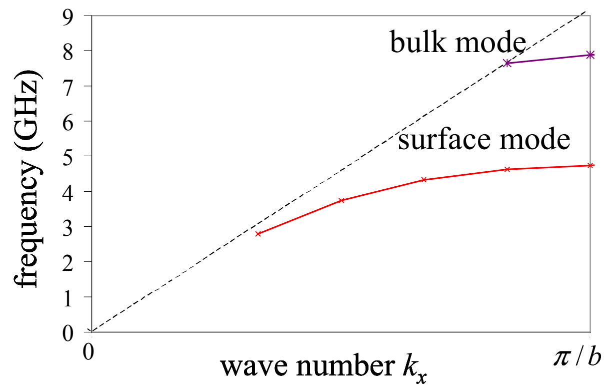

Fig. 4. Dispersion of surface waves on the interface of the diamond metallic lattice. The cubic cell period a=2.3 cm, wire radius r=0.07 cm. The dashed line depicts the light cone.

PLASMONIC WAVEGUIDE MODE

Using mirror reflection of the lattice in Fig. 1 in the x-y-plane and bringing the two parts together a plasmonic waveguide can be designed. The waveguide is therefore formed as a defect in the 3D metallic lattice. Another way to form the same defect is to rotate the half of the lattice at z>0 by 90° over the z-axis.

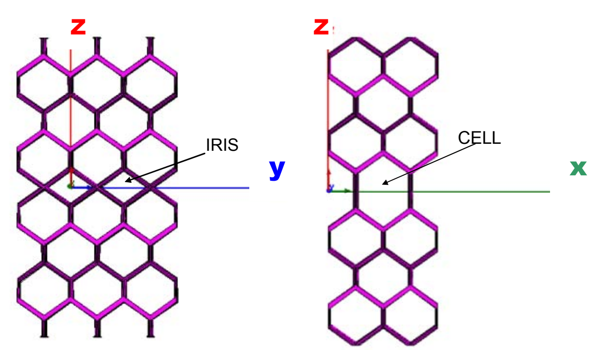

Fig. 5. Accelerator structure using a defect in 3D metallic diamond wire lattice. An electron beam traverses in the x-direction.

We propose that this plasmonic waveguide can be employed as an accelerator structure (Fig. 5). Both irises and accelerator cells are formed in the defect. The iris has the cross-section smaller than the surrounding lattice cells, and the actual accelerating cell (cavity) has the transverse dimension larger than the lattice cells. The defect mode can propagate at the frequencies in the band gap, below the plasma frequency. The operating, defect mode is a TM mode with the electric field on the x-axis.

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The HOM's at the frequencies higher than the plasma frequency are not confined in the defect and leak through the lattice. The plasmonic waveguide is planar in the *x*-*y*-plane. It also can be used to couple the microwave power in to the structure from the side.

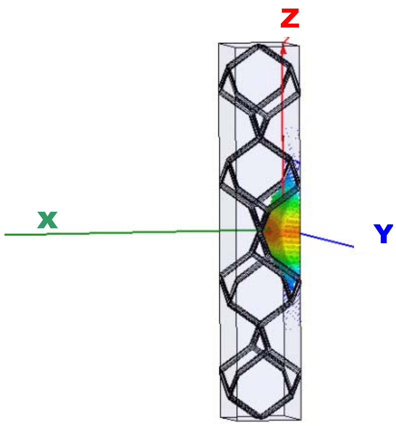

Fig. 6. Simulation of plasmonic waveguide. The defect mode is a longitudinal TM-like mode propagating in the *x*-direction. The electric field distribution is shown.

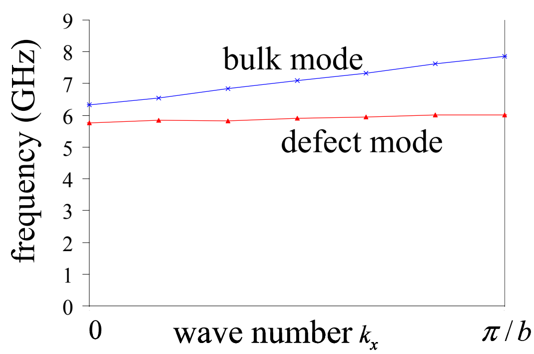

Fig. 7. Dispersion of plasmonic waveguide modes. The defect mode is an accelerating mode. The cubic cell length a=2.3 cm, wire radius r=0.07 cm.

HFSS simulation of the plasmonic waveguide was carried out using one period of the structure (Fig. 6). The structure (Fig. 5) is formed using translation of the cell (Fig. 6) in the x and y directions by multiples of the period b. Similar to the surface mode simulation, the phase advance conditions are set between the parallel cell sides in the direction of propagation x. The TM mode confined in the waveguide was calculated, the modal electric field is shown in Fig. 6. The dispersion of the defect and bulk modes is plotted in Fig. 7. The TM mode has cutoff at 5.77 GHz. The frequency of the mode varies up to 6.03 GHz as the phase advance varies up to 180^o (Fig. 7). Therefore, the group velocity of the mode is small which indicates that the shunt impedance and gradient could be significant. The bulk mode in contrast has a higher group velocity.

The group velocity of the plasmonic waveguide can be negative (backward wave) according to the artificial plasma model. But again this effect has to be examined because of SD. The defect mode was calculated for the rod radius r ranging from 0.017 to 0.14 cm. A low value of negative group velocity was found for r=0.14 cm.

CONCLUSIONS

Three-dimensional metallic lattices are attractive for applications in high gradient accelerator structures. Being frequency selective they suppress and allow easy extraction of higher order mode wakefields generated by the electron beam in a high gradient accelerator. Two-dimensional metallic lattices have been employed at MIT in a 17 GHz linear accelerator. Basic studies of 3D lattices for accelerator applications have been conducted. A diamond wire lattice is found to be attractive. An accelerator structure can be built of the diamond wire lattice without additional disks. A defect in a diamond lattice can form a waveguide with both irises and cavities. Future research will include design of a 17 GHz accelerator structure for testing in the MIT/Haimson Research Corp. accelerator facility.

ACKNOWLEDGMENTS

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