Investigation of Modal Characteristics of an Electromagnetic Band Gap Structure Comprised of Metallic Open Rings

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***Abstract*— A numerical study of an electromagnetic band gap (EBG) structure is presented. It is comprised of 3D lattice of metallic open square rings (OSRs) in air through investigation of the modal resonant frequency, magnetic field distribution within a unit cell, and current distribution on the OSRs. Furthermore, the EBG structure band gap dependence on the geometrical parameters is analyzed. Different geometries, designed properly, exhibit resonant frequencies at X-band and Ku-band. The thorough investigation establishes the potential of EBG composed of OSRs in the development of novel microwave circuits and components.**

***Index Terms*—Electromagnetic Band Gap (EBG), Open Square Rings (OSRs), Resonant eigenmodes, Dispersion diagrams.**

I. INTRODUCTION

Electromagnetic band gap (EBG) materials are periodic structures in which electromagnetic waves are forbidden in a certain range of frequencies, i.e., band gap. EBGs can be realized using metallic or dielectric elements arranged in one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D) periodic lattices.

Up to now, two types of EBG are widely used. The first conventional type consists of dielectric rods or cylindrical holes within a dielectric substrate [1-3] and the second is metallic pads (with/without grounding vias) [4-6] within a substrate. A high dielectric constant material must be used in all these designs. The via-based EBGs suffer from electric loss and fabrication complexity (i.e., non-planar fabrication processes) whereas the dielectric rods and holes are structurally complicated, which significantly restricts their operation at sub-mm and THz range [7,8]. The use of high dielectric constant materials (ε_r in range of 12 to 90) yields an improved electromagnetic performance (wider fractional stopbands) and smaller physical dimensions. But the microfabrication process is more challenging because of intractable small feature dimensions that call for tight manufacturing tolerances, while the dielectric materials tend to be more brittle [7]. To overcome the fabrication complexity of the mentioned EBGs, a novel EBG consisting of a multi-layer periodic square lattice of metallic open square rings (OSRs), as shown in Fig. 1, was initially proposed in [9]. The structure was later extended in [10] to design and develop EBG slab waveguides [11-13] for TE modes (electric field parallel to the x-y plane of periodicity, and the magnetic field normal to the plane).

The present work focuses on the impact of geometrical parameters (Fig. 1(b)) of multi-layer OSRs on the band gap.

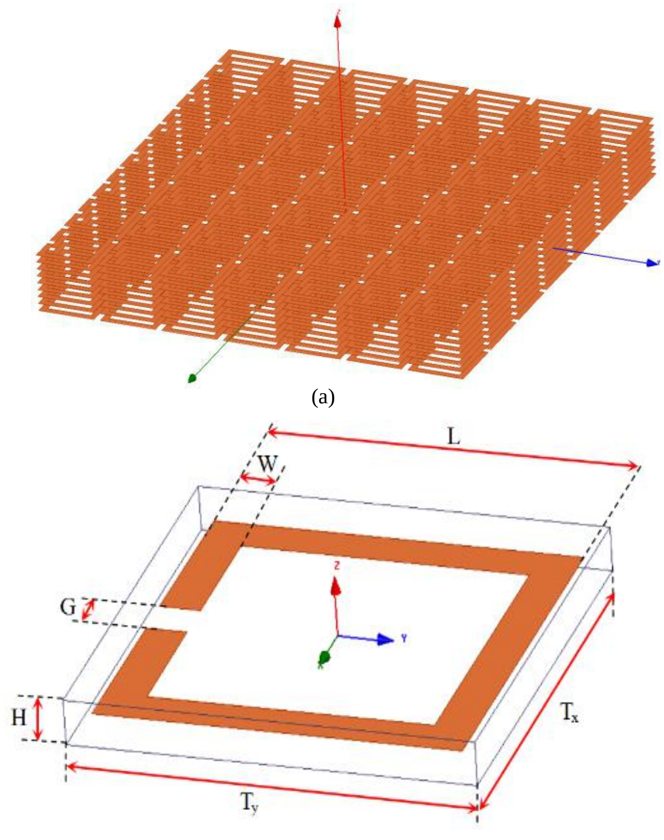


Fig. 1. (a) Schematic of periodically arranged multi-layer OSRs; (b) single unit cell with geometrical parameters**:** *H = 0.5 mm*, $T_x = T_y = 5$ *mm*, *G = 0.5 mm*, *W = 0.5 mm and L = 4.5 mm* [9].

The structural parameters are varied one at a time and the modal characteristics are studied through presentation of magnetic fields within a unit cell and variation of ring circumference, ring width *W* and vertical spacing between rings *H*. The detailed presentation of the impact of gap size *G* and lattice constant *T* can be found in [10] and [12], respectively.

The numerical simulations were performed using the eigenmode solver of the commercial full-wave software Ansys High Frequency Structure Simulator (HFSS™), which is based on the finite element method (FEM). The schematic of the periodic OSR layers and the geometry of a single unit cell used in the simulation are shown in Figs. 1(a) and (b), respectively. The unit cell is composed of a single perfect electric conductor (PEC) ring in an air box. The surrounding surfaces of the air box are assigned master/slave to establish periodicity in the X, Y directions while a perfect magnetic conductor (PMC) was imposed at the top and bottom walls to establish periodicity in the Z direction and restrict the modes to TE.

The origin of the band gap in the ring lattice will be explained in Section II, while Section III is devoted to the effect of geometrical parameters on the resonance frequency of the eigenmodes. Concluding remarks are presented in Section IV.

II. Origin of The Band Gap in The OSR Lattice

It is well known that a metallic open ring interacts with a magnetic field that is normal to its plane [14]. The magnetic field induces circulating electric currents around the ring which lead to charge accumulations across the gap and magnetic fields inside and outside the ring for the first and second modes, respectively [15]. The OSR can be considered as a resonant *LC* circuit, exhibiting a resonant frequency $\Omega_{LC} = \sqrt{L_{self} C_{self}}$, where L_{self} is the self-inductance and C_{self} is the self-capacitance of the ring and is inversely proportional to the size of the ring [16]. Additional capacitance C_{mut} and inductance L_{mut} developed between the rings contribute to the total capacitance and inductance of the OSR system. The currents of modes 1 and 2 correspond to half wavelength $\lambda/2$ (first-order) and wavelength λ (second-order) resonant eigenmodes of the OSR, respectively [15]. The first mode concentrates its magnetic field inside the ring to maintain a low frequency while the second mode has its magnetic field outside the ring in order to rise its frequency [10] and this leads to the emergence of a band gap between these two modes. Given the above explanation, it is obvious that the band gap in the ring lattice is generated by the ring element resonance and periodicity.

III. Change of Modal Resonant Frequency of Multi-layer Lattice of OSRs

A. Effect of Size of Open Square Ring

In this section, the effect of the ring size *(L)* on the band gap is presented. Since the lattice constant *(T)* is fixed, decreasing the size of the rings will increase the separation between the rings. Fig. 2 displays the dispersion characteristics of EBG for $L = 4.5$ *mm* and *3 mm*. Along Γ-X, the phase $k_x T_x$ (k_x is wavevector and T_x is lattice constant along x-direction) is changed from 0 to 180º along x-axis, while $k_y T_y$ is fixed at zero. This produces the frequencies for the wave propagation in the Γ-X segment of the Brillouin zone. Then the $k_x T_x$ is fixed at *180º* and the phase constant along the segment *X-M*, $k_y T_y$, is changed from *0* to *180º*. Lastly, the phase constants of both $k_x T_x$ and $k_y T_y$ are changed in tandem from *180º* to *0º*. Thus, the last range of eigenmode frequencies is found for the M-Γ segment. The same method is used to find the frequency characteristic of the second mode. The width of the bandgap is determined by frequency separation of the extrema of consecutive eigenmodes of the EBG; which in this case is the maximum frequency of the mode 1 and the minimum frequency of the mode 2. The results show

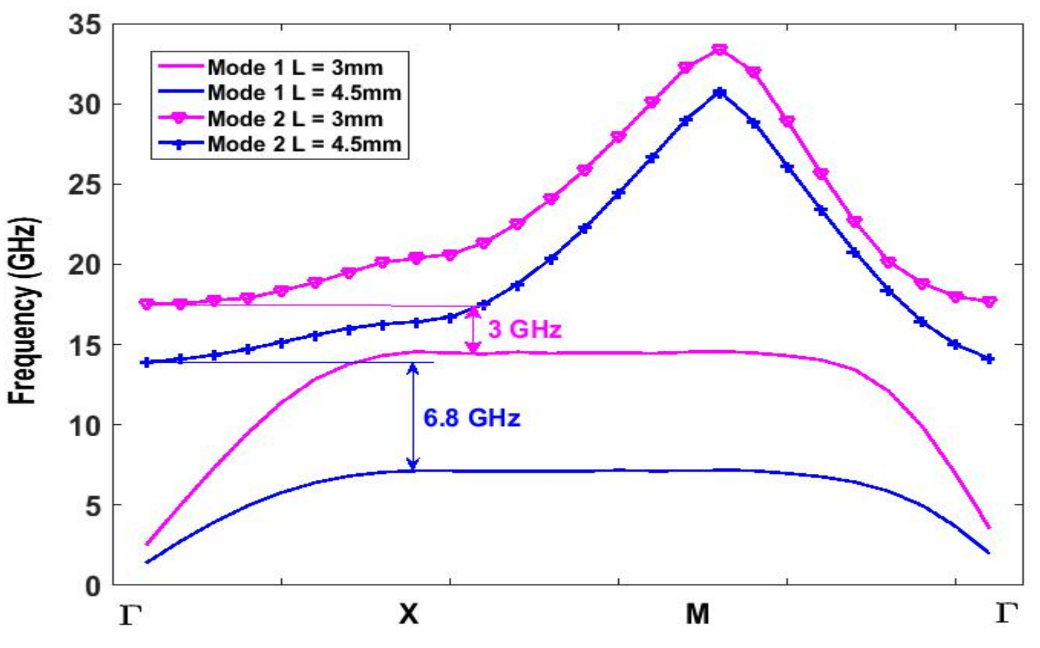


Fig. 2. Effect of modifying outer-ring size *L* on the band gap. 3 GHz, 6.8 GHz, correspond to band gap for *L= 3 mm* and *4.5 mm* respectively. Other parameters are as in Fig. 1(b).

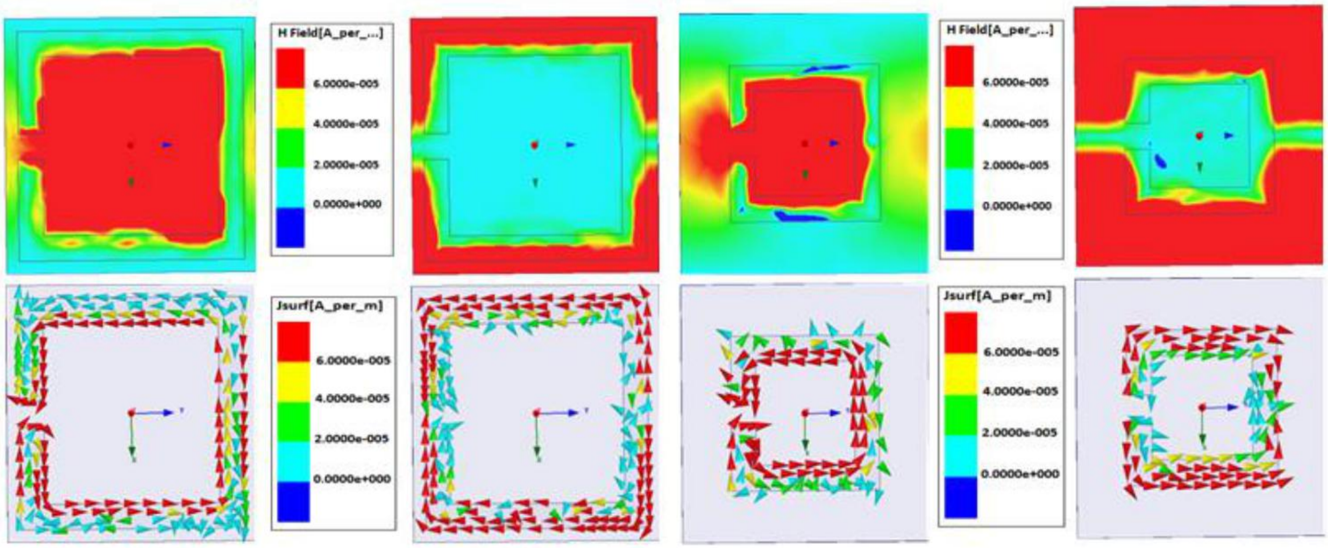


Fig. 3. The magnetic fields H_z (top) and surface currents (bottom) at the X-point for *L = 4.5 mm* (a) and *L = 3 mm* (b) (i.e., other parameters are as in Fig. 1(b)). Modes 1 and 2 are the left and right panels, respectively.

that decreasing the size of the ring results in an increase of the frequency of modes 1 and 2. From the field and current distributions of Figs. 3 (a) and (b) for *L = 4.5 mm* and *3 mm*, respectively, one can see that as the size *L* decreases, the magnetic field of mode 1 is less confined in the interior of the ring (due to decreased self-inductance, i.e., decreased ring geometry) and mode 2 displays more field confinement in the exterior of the ring (similar to mode 2 of increased lattice size [12]). This results in upward shifts for both modes 1 and 2. This trend can also be inferred by focusing on the modal behavior of the OSR EBG that is tightly linked to the resonance behavior of the OSR cell element. Upward shift of the resonance frequency of the OSR as the loop size decreases is compatible with higher modal frequencies of modes 1 and 2 of the single open loop.

B. *Effect of Width of Open Square Ring*

Fig. 4 shows the dispersion characteristic of the ring structure with different metal line width (*W = 0.1*, *0.5*, *1* and *2 mm*) and demonstrates narrower bandgap for a thicker OSR. It is observed that mode 1 frequency increases, while mode 2 stays around the same frequency. The band gap disappears when *W = 2 mm*. Examination of the fields and currents for *W = 0.1 mm* and *2 mm* are shown in Figs. 5 (a) and (b), respectively. It can be seen that *W = 0.1 mm*, mode 1 (associated with low resonance due to *λ/2* current density wave) confines within the OSR and mode 2 (associated with high resonance due to *λ* current density wave) confines in the region between the loops leading to large band gap between

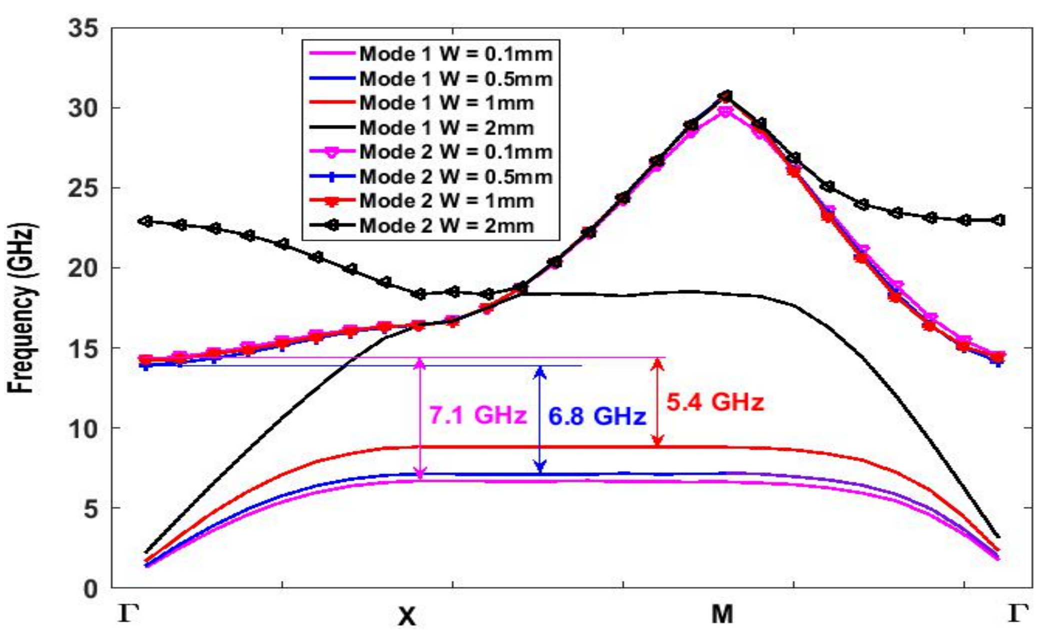
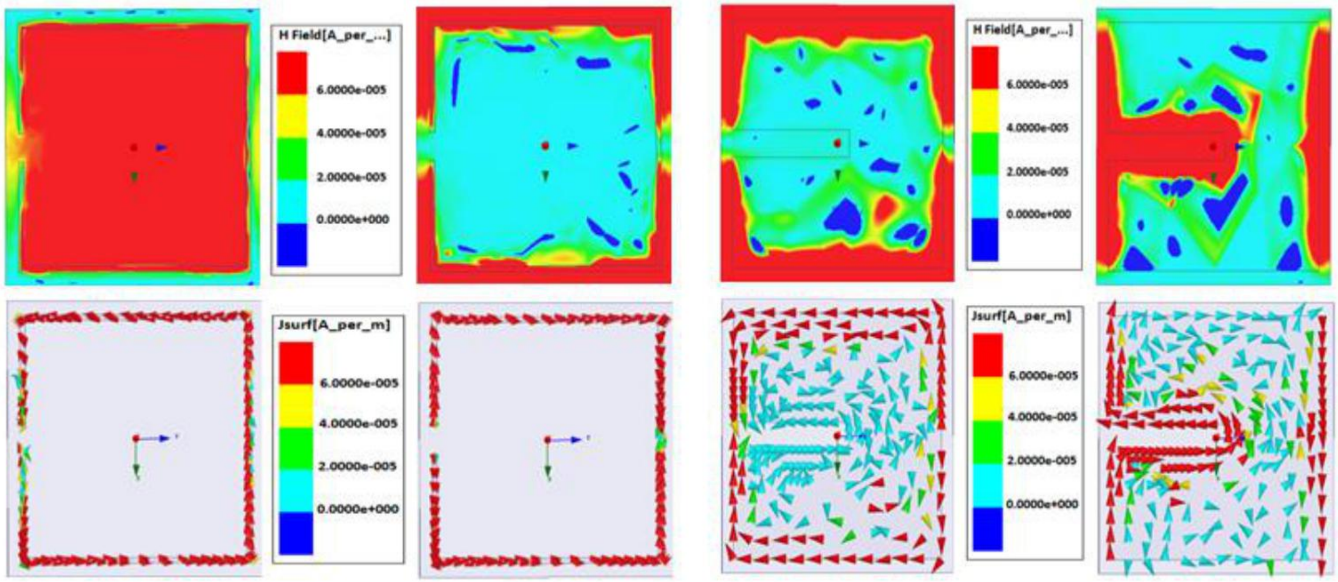


Fig. 4. Effect of modifying metal width on the band gap. Frequencies 7.1 GHz, 6.8 GHz, and 5.4 GHz correspond to band gap between modes 1 and 2 for *W = 0.1 mm*, *0.5 mm* and *1 mm* respectively, but no band gap for *W = 2 mm*. Other parameters are as in Fig. 1(b).



(a) (b)

Fig. 5. The magnetic fields H_z (top) and surface currents (bottom) at the X-point for *W = 0.1 mm* (a) and *W = 2 mm* (b) (i.e., other parameters are as in Fig. 1(b)). Modes 1 and 2 are the left and right panels, respectively.

the two modes. On the other hand, mode 1 is less localized in the interior of the ring for *W = 2 mm* due to low current in the patch, and reduced self-inductance that causes higher modal frequency while mode 2 tends to be further concentrated outside the ring with overall effect of raising its modal frequency. Therefore, both modes show similar energy concentration outside the ring that leads to the absence of band gap.

It should also be noted that as the width of the ring is increased, it approaches a square patch that has generally a higher resonance frequency as compared to a square ring of the same size [17].

C. Effect of Vertical Distance

To investigate the impact of vertical separation between OSRs on the band gap, Fig. 6 presents the band structures with different separation values *(H)* of *0.5*, *10*, and *20 mm*. Examining the dispersion data, one can see that increasing *H*, results in reducing the band gap between modes 1 and 2. The fields for *H = 0.5 mm* and *20 mm* are shown in Figs. 7 (a) and (b), respectively. Increased separation between the OSRs is equivalent to reduced permeability of the equivalent magnetic rods which causes a reduction of the frequency gap width. As *H* increases, the magnetic field of mode 1 displays less confinement within the ring, which leads to increased frequency of the mode. Mode 2 exhibits the same rate of confinement as mode 1 (the magnetic field spreads-out to the interior of the ring), which leads to narrower bandgaps between these two modes.

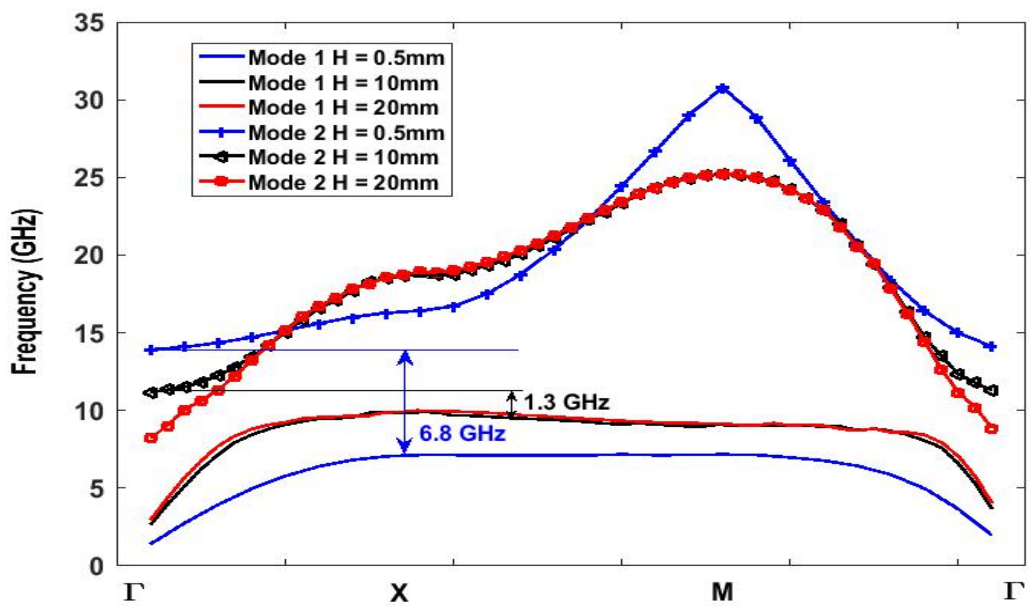


Fig. 6. Effect of modifying separation H. Frequencies 6.8 GHz, and 1.3 GHz correspond to band gap between modes 1 and 2 for H = 0.5 mm and 10 mm respectively. No band gap for *H = 20 mm*. Other parameters are as in Fig. 1(b).

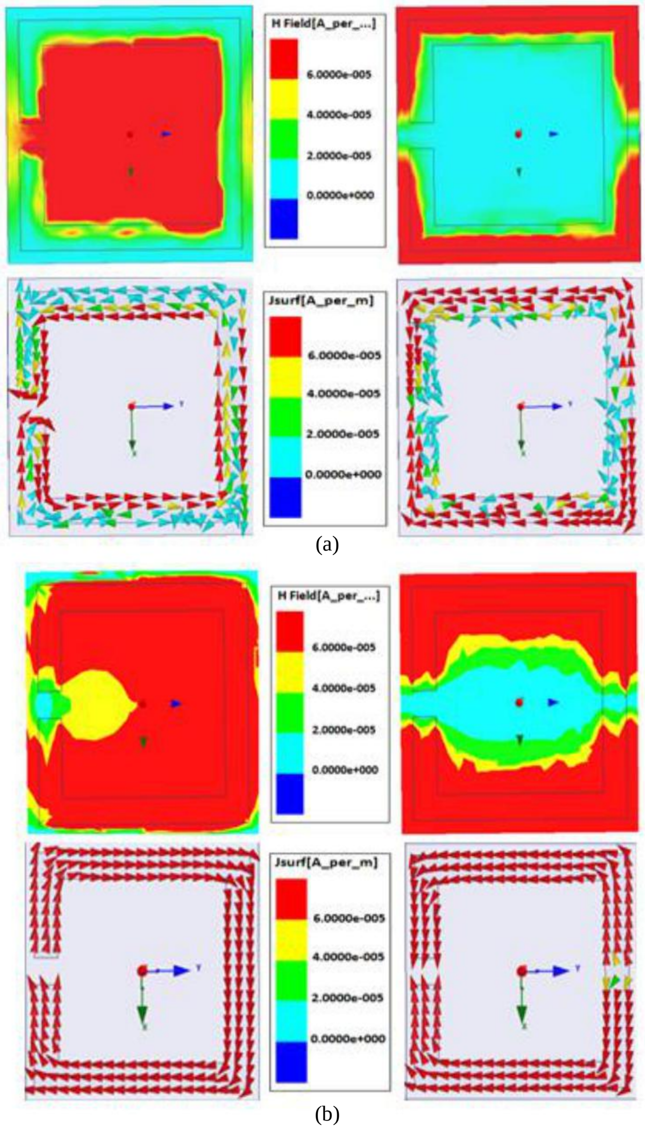


Fig. 7. The magnetic fields H_z (top) and surface currents (bottom) at the X-point for *H = 0.5 mm* (a) and *H = 20 mm* (b) (i.e., other parameters are as in Fig. 1(b)). Modes 1 and 2 are the left and right panels, respectively.

IV. CONCLUSIONS

Dispersion diagrams, resonant frequencies and confined modes in a multi-layer periodic metallic open square ring structure were studied through computer simulations. The effects of ring outer size L, ring width W and vertical spacing between rings H were investigated. From the results, it was shown that the lattice exhibits a band gap at X-band or Ku-band which depends on the geometrical dimensions of the cell element. Increased metal width and vertical separation of rings lead to a narrower band gap, while increased ring size leads to a widening of the band gap. Such design information is useful in assessing implementation trade-offs and tailoring the OSRs to specific applications. The structure is promising for novel microwave components such as waveguides, couplers and antennas.

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