

“A Fundamental Study of Heat Transfer Phenomenon in Periodic Structures”

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Abstract:

Ever increasing demand from structures makes them to work more in adverse environments. For example, engine components in high performance, high speed new aircrafts are being exposed to much higher temperatures than those in old aircrafts, in different control devices the continuous trend to pack more transistors on a single chip have resulted in an unprecedented level of power dissipation, and therefore higher temperatures at the chip level. Thermal phenomena can adversely affect the performance of these structures. In this project it is investigated whether by designing periodic structures it is possible to manipulate heat transfer directions – increasing heat transfer intensity in one direction while decreasing it in another direction. Such non-uniform heat transfer mechanism utilizing clever design of the periodicity will be useful in designing heat sensitive components. It is shown through numerical analysis that periodicity in structures can steer away the radiation heat energy from its usual propagation direction, thus reducing the energy in one direction while increasing it in another direction. Therefore, structural periodicity can be used to our advantage to manipulate heat propagation directions. Such engineered structures can be used in heat sensitive devices to have more desirable heat transfer characteristics.

Introduction:

Anisotropic materials have different heat conduction properties in different directions. Therefore, depending on the orientation of the anisotropy a material can be a good heat conductor in one direction and a good insulator in another direction. However, in the nature only a limited number of materials (or may be no material) can have a degree of anisotropy that is required for a desired application. If we can engineer

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some structure such that it will have heat transfer characteristics as we want then that will be very beneficial for different applications. We will be able to use these engineered structures in many advanced applications where we want to have the heat dissipating in certain desired direction and not propagating in some critical directions where the temperature variations cannot be tolerated. With this in mind this research was carried out.

Basic Theory:

There are three mechanisms of heat transfer for transferring thermal energy from one point to another. These are Conduction, Convection and Radiation.

Conduction is transfer of thermal energy between two bodies with different temperature due to temperature gradient. Convection transfers the energy by movements of the molecules at different temperatures. Radiation is the electromagnetic wave propagation mechanism. Depending on the frequency of the propagating electromagnetic wave the radiated energy can be light, heat or some other form of radiation such as X-ray, THz ray or T-ray etc. Thermal radiation is continuously emitted from all objects because of the molecular and atomic agitation associated with their internal energy. Examples of thermal radiation are incandescent light bulb emitting visible light, infrared radiation emitted by common household radiators or electric heaters, furnaces, combustion chambers, fires, rocket nozzles, power plants, engines etc. The importance of radiation intensifies at high absolute temperatures because in conduction and convection energy transfer depends on the first power of temperature difference but in thermal radiation it depends on about the fourth power. Another important feature is that for thermal radiation there is no need of any physical medium to be present between two points for the energy to be transferred between them. Therefore, heat energy can transfer through a vacuum only by radiation [1]. Thus in space applications and very high temperature applications the radiation heat transfer dominates and is the focus of this investigation.

Radiant energy propagation can be analyzed by the electromagnetic wave theory. Electromagnetic radiation energy propagates through oscillating electric and magnetic fields, perpendicular to the direction of the energy travel [1]. An ideal body which allows all incident radiation to pass into it and internally absorbs all the incident radiation is called the black body; this is true for radiation of all wavelengths and all angles. Performance of all other materials can be compared relative to an ideal black body.

It has been shown by the quantum arguments of Plank [2] and verified experimentally that thermal radiation for a black body in vacuum is given by the following equation.

$$e_{\lambda b}(\lambda_0, T) = \frac{2\pi C_1}{\lambda_0^5 (e^{\frac{C_2}{\lambda_0 T}} - 1)} \quad (1)$$

In which σ and c are constants, T is the absolute temperature and λ is the wavelength at vacuum. Based on equation 1 Figure 1 is plotted which shows how the peak wavelength and total radiated energy vary with temperature.

In order to relate a non black body emitted energy to a black body emitted energy given in equation 1, a material property is defined. The emissivity of a material is the ratio of the emitted energy from this material to the amount of energy that would have been radiated if it was a perfect black body; this relation is called Kirchhoff's law [3].

(2)

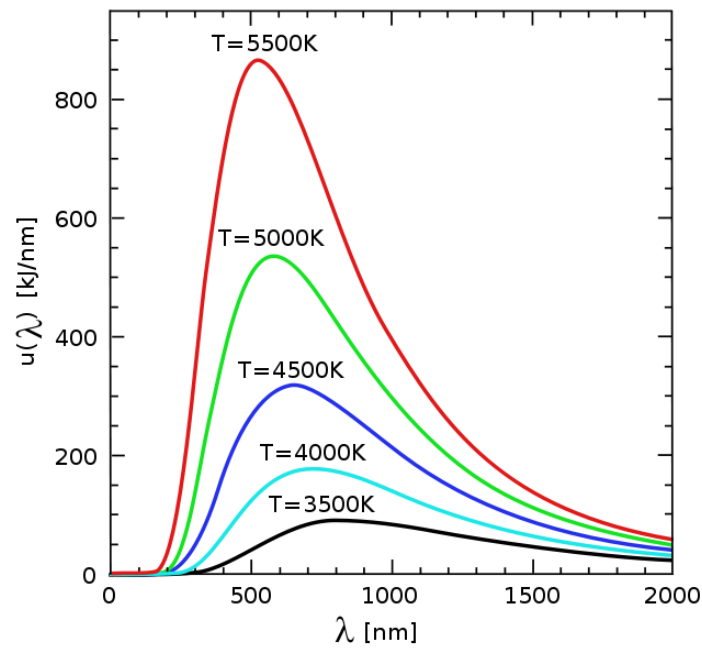


Figure 1: Emissive power of a black body as a function of wavelength for different temperatures.

Electromagnetic wave: Electromagnetic radiation (often abbreviated as E-M radiation or EMR) is a form of energy propagation exhibiting wave-like behavior as it travels through space. EMR has both electric and magnetic field components, which oscillate in phase perpendicular to each other and perpendicular to the direction of energy propagation.

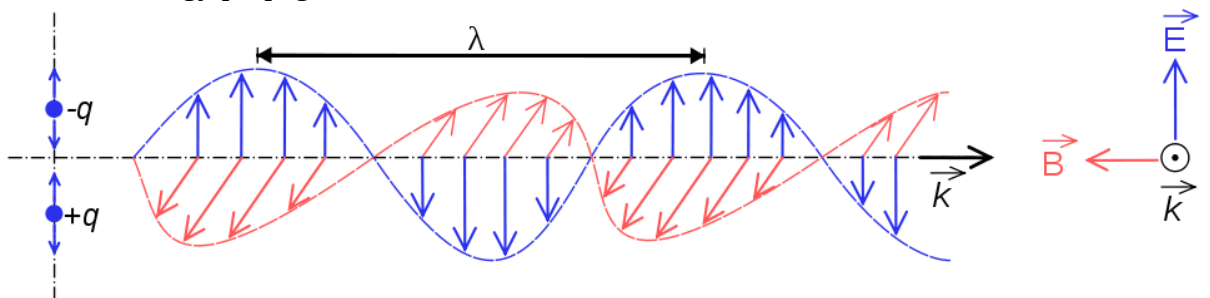


Figure 2: Electromagnetic radiation

The physics of electromagnetic radiation is electrodynamics. Electromagnetism is the physical phenomenon associated with the theory of electrodynamics. Electric and magnetic fields obey the properties of superposition. Thus, a field due to any particular particle or time-varying electric or magnetic field contributes to the fields present in the same space due to other causes. Further, as they are vector fields, all magnetic and electric field vectors add together according to the vector addition law. For example, in optics two or more coherent light waves may interact and by constructive or destructive interference yield a resultant irradiance deviating from the sum of the component irradiances of the individual light waves.

Using the electromagnetic wave theory, the energy carried per unit time per unit area by an electromagnetic wave is given by the cross product of the electric and magnetic intensity vectors. This is the Poynting vector, $S = E \times H$
Using this cross product and simplifying the equations

$$|S| = \frac{\bar{n}}{\mu c_0} |E|^2 \quad (3)$$

In which $\bar{n}$ is the refractive index in an attenuating medium, μ is the magnetic permeability which is a constant, c_0 is the wave speed in vacuum and E is the electric intensity. $|S|$ is a spectral quantity that is proportional to the quantity defined in equation 1.

Results and Discussion:

Using finite elements the radiated heat energy or the electric intensity at a point can be calculated using the electromagnetic wave propagation theory. The spectral quantity and the radiation emissive power can thus be calculated. COMSOL Multiphysics was used for this purpose.

Uniform periodic structures also known as harmonic crystals were considered. It consisted of cylindrical silicon rods arranged in square grids in air matrix. The diameter of rods (Φ) is 140 nm and lattice spacing, a in both x and y directions is 165 nm (center to center distance of the neighboring rods is 305 nm) as shown in Figure 3. The periodic arrangement of 8×14 matrix (8 rows and 14 columns) of crystal was considered for this simulation, see Figure 3.

In-plane TE wave propagation through the periodic structure shown in Figure 3 has been studied for a wavelength varying from 4.0×10^{-7} to 9.0×10^{-7} m (or 40 to 90 μm). The results are shown in Figures 4 and 5 for two different wavelengths.

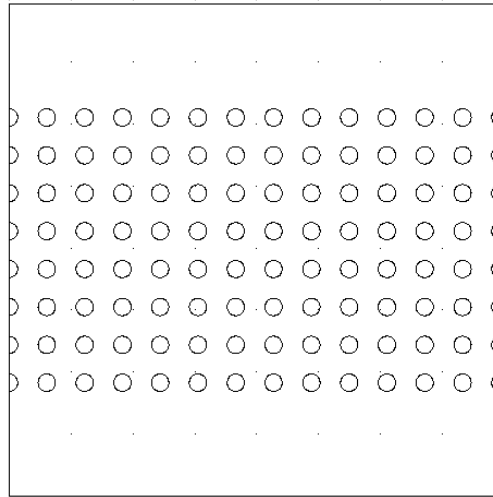


Figure 3: Cross section of 8x14 square lattice array of silicon cylindrical inclusion in air matrix.

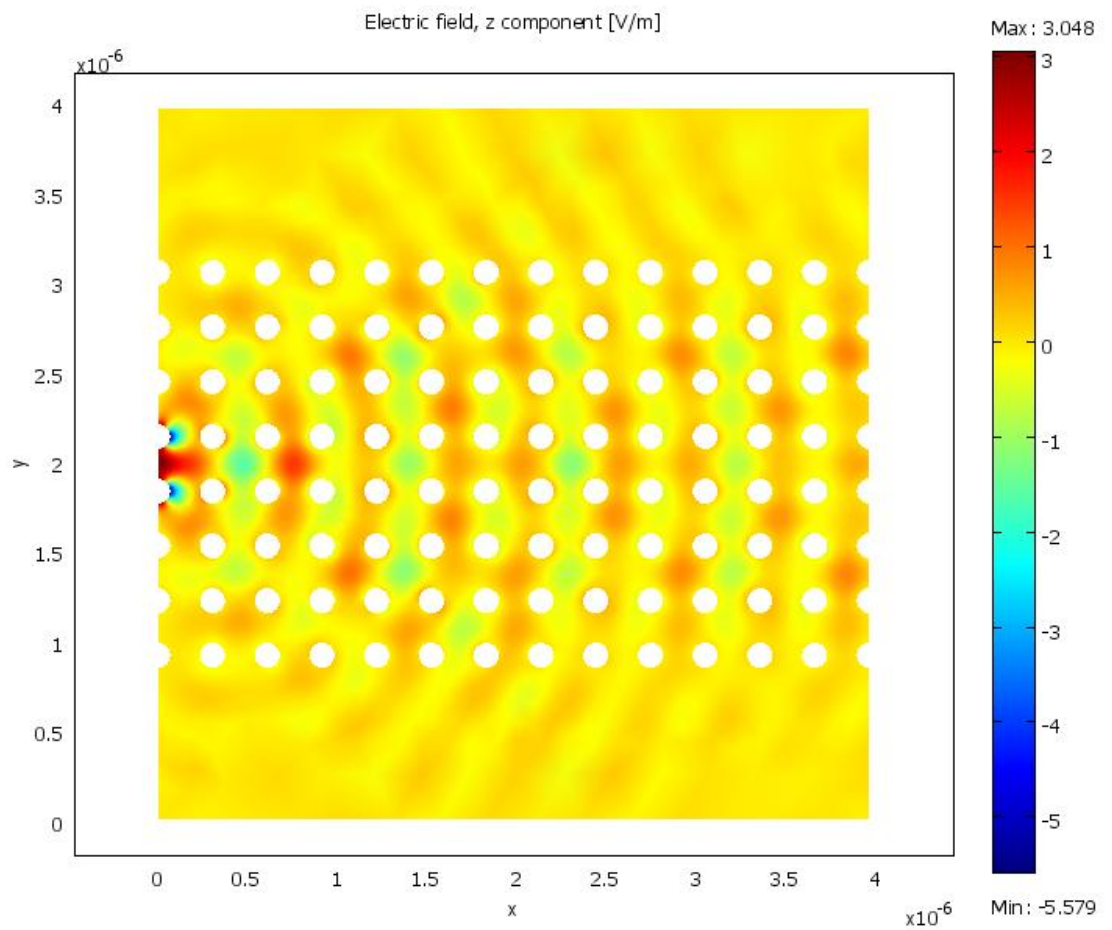


Figure 4: Electric field for 40 μm wave length in the periodic structure of Figure 3

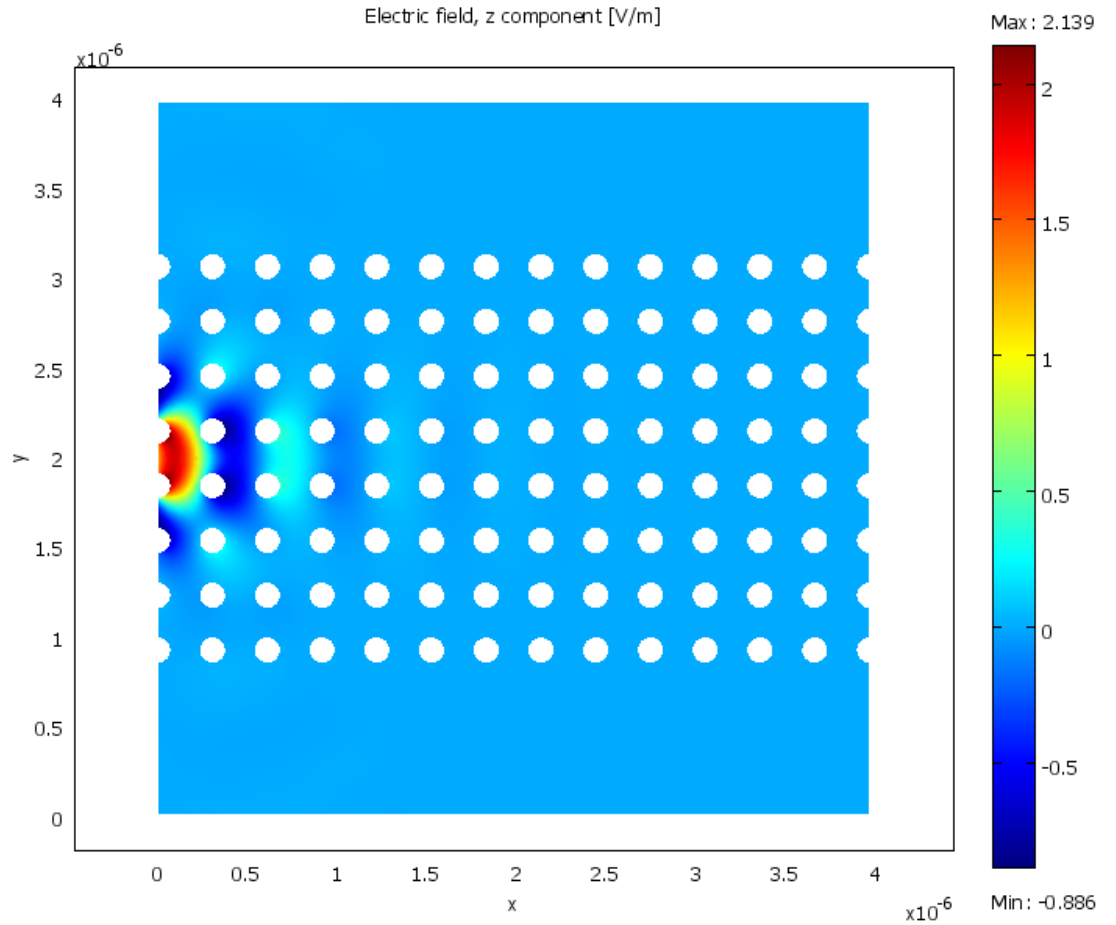


Figure 5: Electric field for 75 μm wave length in the periodic structure of Figure 3

One can see from these figures that for specific wave lengths the electric field is zero on the other side of the periodic structure which means that the radiation energy cannot propagate through this structure at that frequency.

Figure 6 shows the comparison between the electric field on the right boundary integrated over the boundary line for the periodic structure and non-periodic structure (in absence of any periodic inclusion) at different frequencies. One can clearly see from this plot that periodicity reduces the energy propagation through the structure. At some frequencies the periodic structure reduces the z component of the electric field to zero.

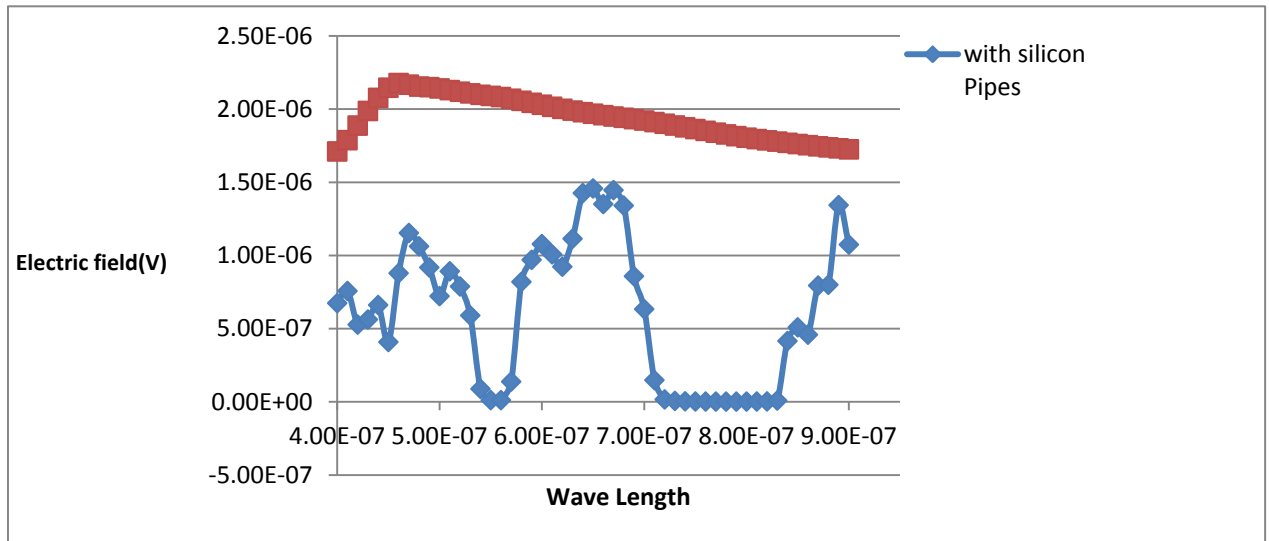


Figure 6: The effect of silicon rod (or solid pipe) inclusion on the electric field on the right boundary

The effect of spacing: The spacing between the rods in the x direction is then doubled to see the effect of spacing on the propagating energy. Figure 7 shows the harmonic structure with the distance between the pipes doubled in the horizontal direction.

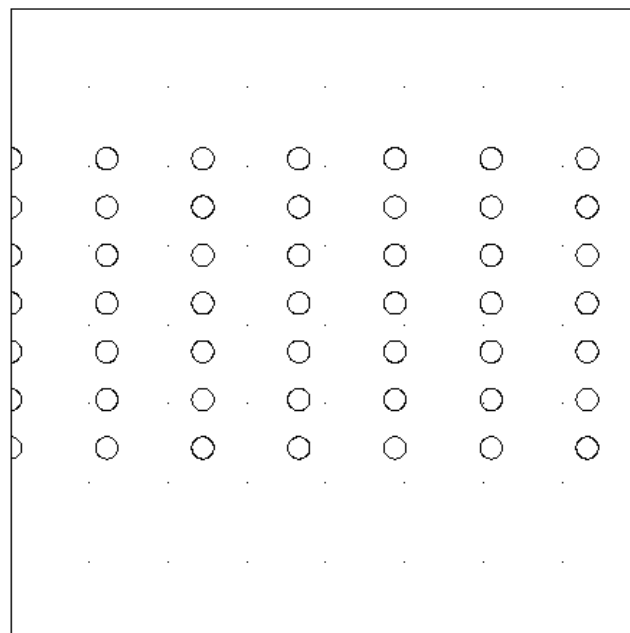


Figure 7: Periodic structure with higher spacing – compared to Figure 3 in this figure the spacing has been doubled in the horizontal direction.

Figure 8 compares the integral of electric field on the right boundary at different frequencies for two different values of the spacing. This figure shows that as the periodic structure changes its spacing the propagation of different wave lengths through the structure is affected. When the spacing is doubled the electric field increased and no zero electric field is observed at any frequency.

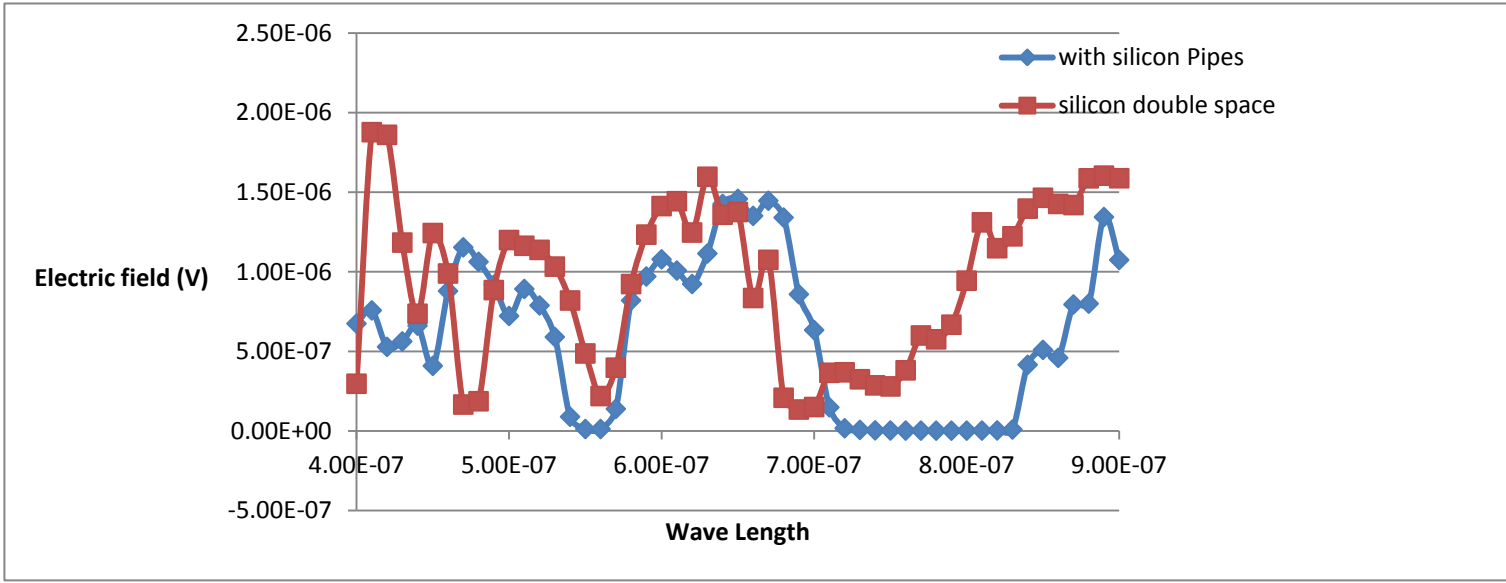


Figure 8: The effect of spacing between solid inclusions in periodic structures.

The effect of radius: In order to study the effect of radius the rod diameter was increased from 140 nm in Figure 3 to 180 nm in Figure 9 but the spacing between the rod inclusions was kept the same.

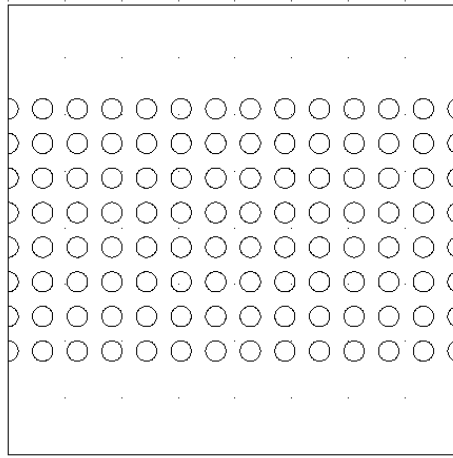


Figure 9: Cylindrical rods of larger diameter forming the periodic structure

Figure 10 shows the effect of the inclusion diameter on the propagated electric field through the periodic structure. Smaller diameter rods (Figure 3) and larger diameter rods (Figure 9) produced different levels of energy on the right boundary. It is clear from Figure 10 that increasing the rod diameter increased the wave length of stop bands (when energy does not propagate) and pass bands (when energy propagates). It also affected the total electric field that passes through the periodic structure.

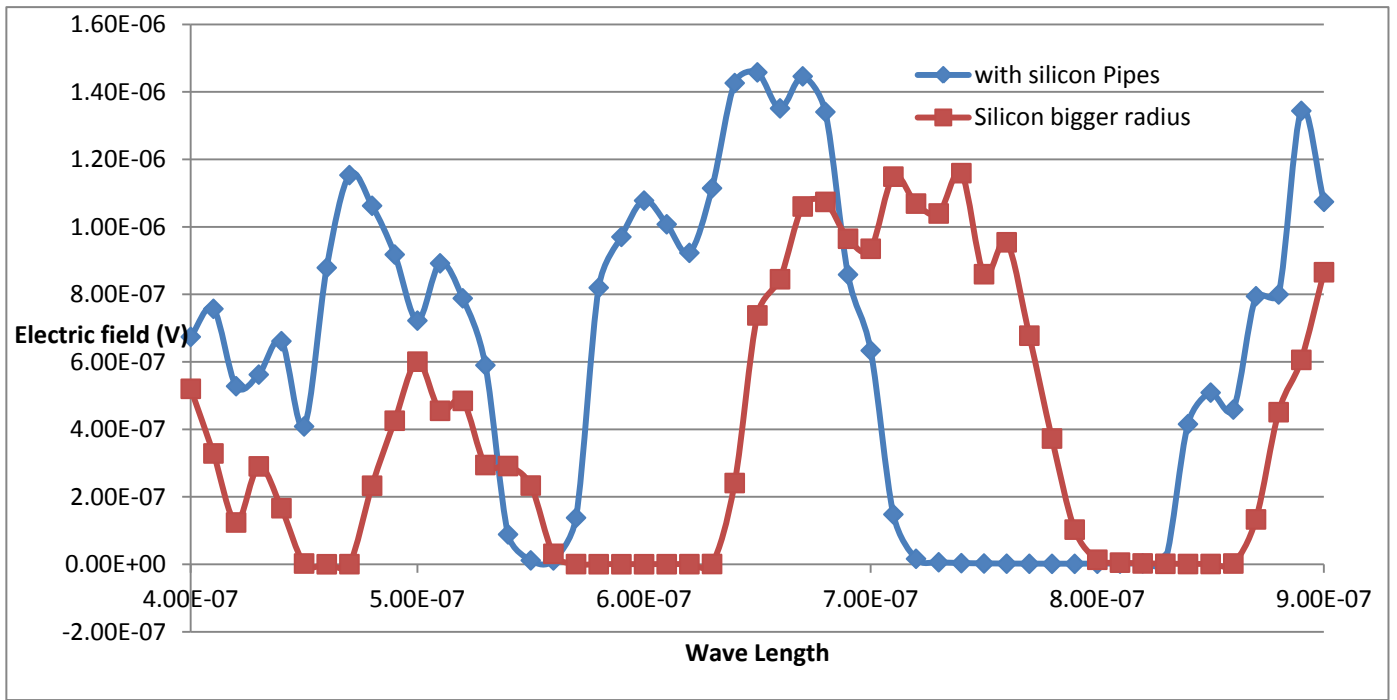


Figure 10: Integral of the electric field on the right boundary of the periodic structure as a function of the wave length for two different diameters of the silicon rod (or solid pipe) inclusion.

Alternative configurations with cavities: Different configurations of the periodic structure with some silicon rod inclusions removed are then investigated. The first configuration that was studied had a Y shaped cavity opening as shown in Figure 11. In this configuration 16 Silicon rods were removed to construct the cavity to see if it can divert the energy in two different directions. The variation of the electric field in the z direction is shown in Figure 12. The cavity facilitates the propagation of the electromagnetic waves through it.

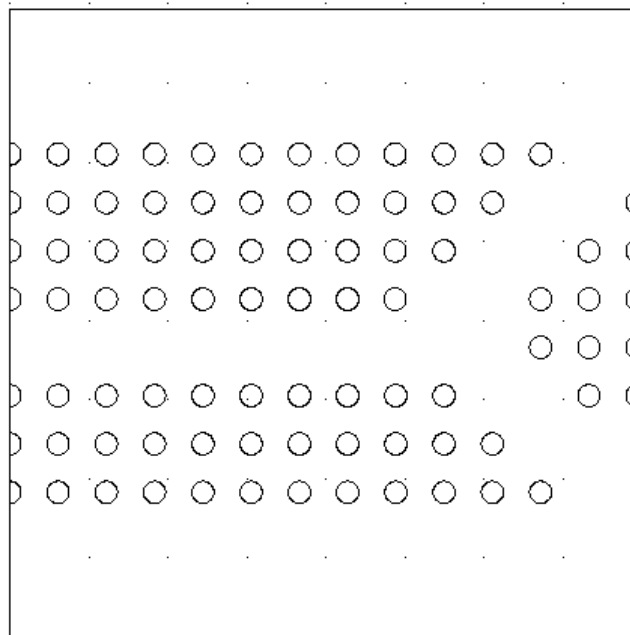


Figure 11: Periodic structure with a Y-shaped cavity.

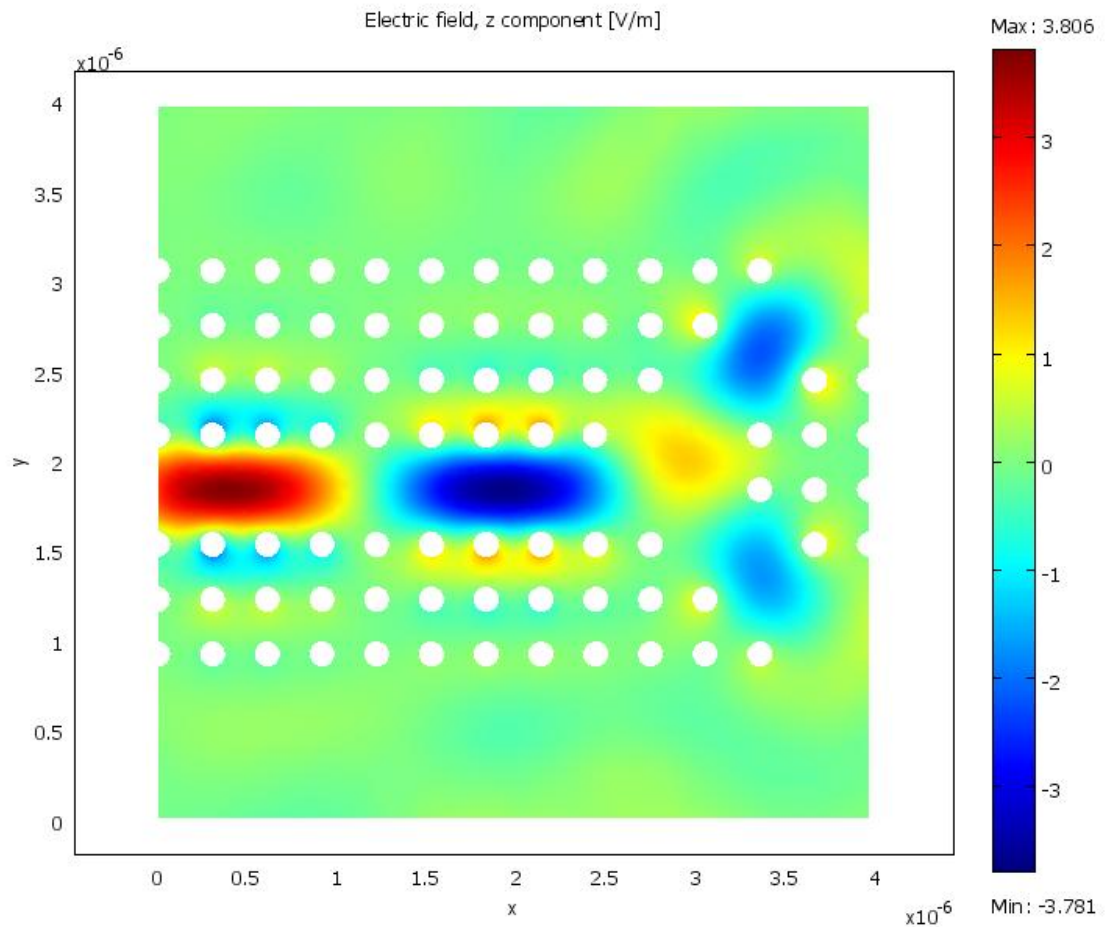


Figure 12: Electric field propagating through a Y shaped cavity in a periodic structure.

Then electromagnetic wave propagation through two more periodic structures having cavities with 90° (L-shaped cavity, Figure 13) and 45° (Figure 15) bents is investigated. Computed fields for these two structures are shown in Figures 14 and 16, respectively. In both cases the electric field could be guided through the cavity opening.

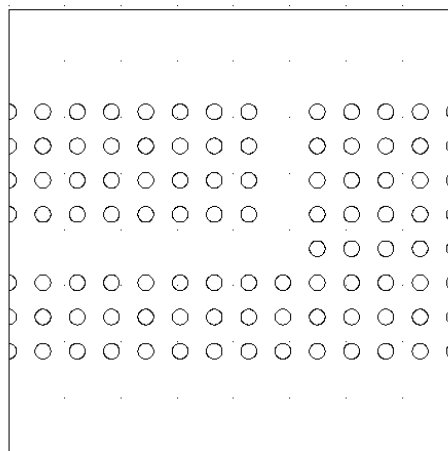


Figure 13: Periodic structure with an L-shaped cavity.

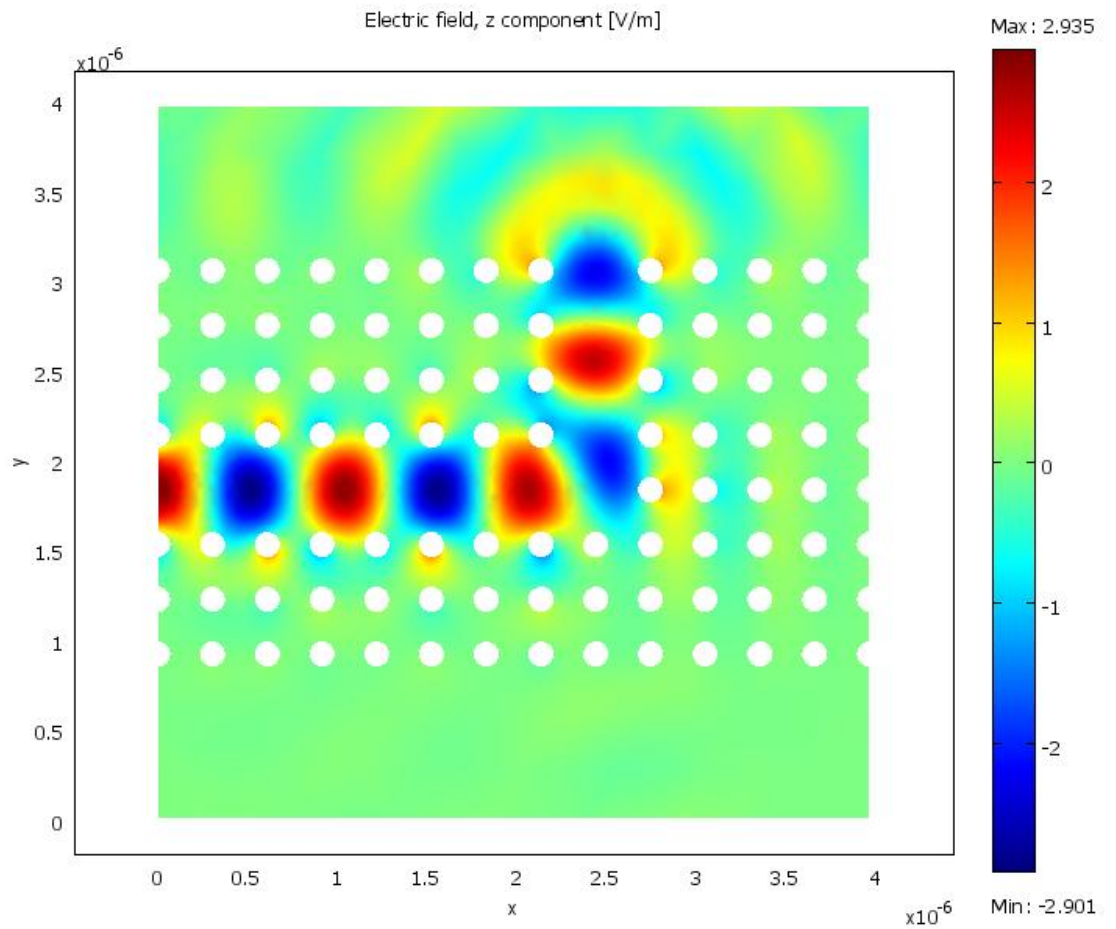


Figure 14: Electric field propagating through a periodic structure with an L-shaped cavity.

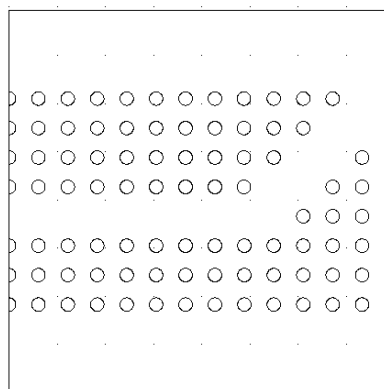


Figure 15: Periodic structure with a cavity having a 45° bent.

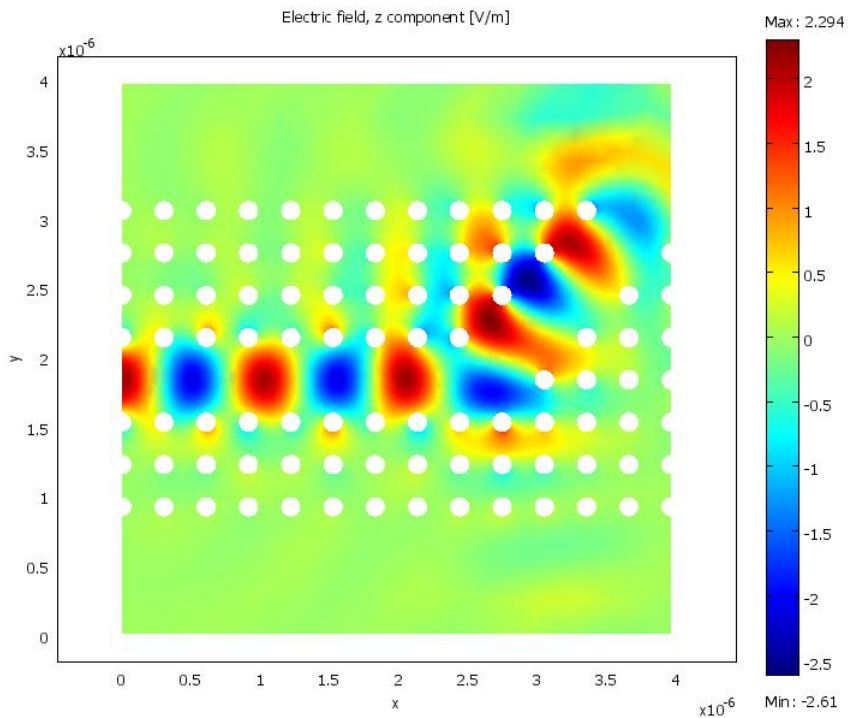


Figure 16: Electric field propagating through a periodic structure having a cavity with a 45° bent.

3D Analysis: Figure 17 shows the z-component of the electric field (wavelength = $7.5 \text{ e-}7 \text{ m}$) generated by a square emitter on one surface of a 3D homogeneous block geometry. The total electric field magnitude is plotted in Figure 18.

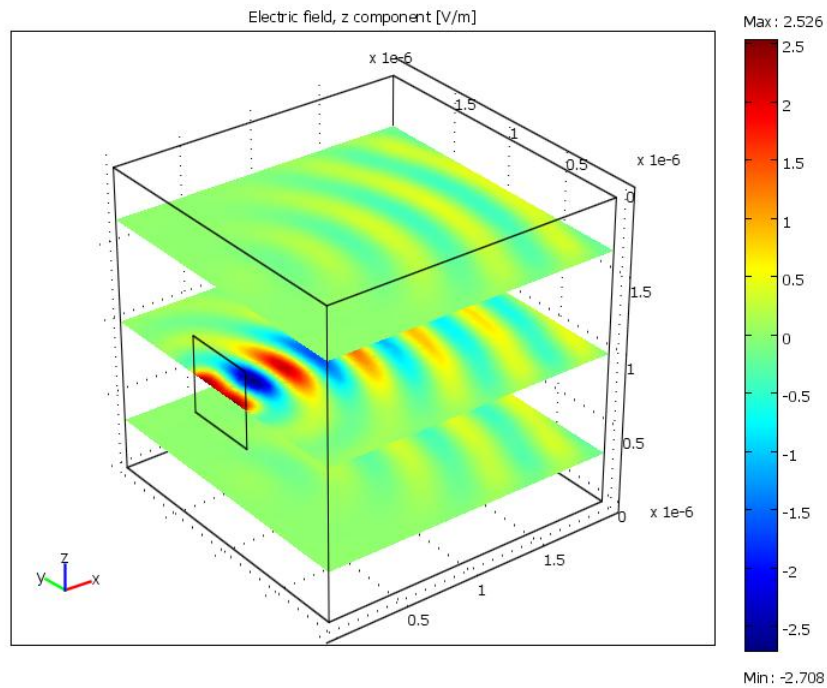


Figure 17: Z component of the electric field in a homogeneous medium (air)

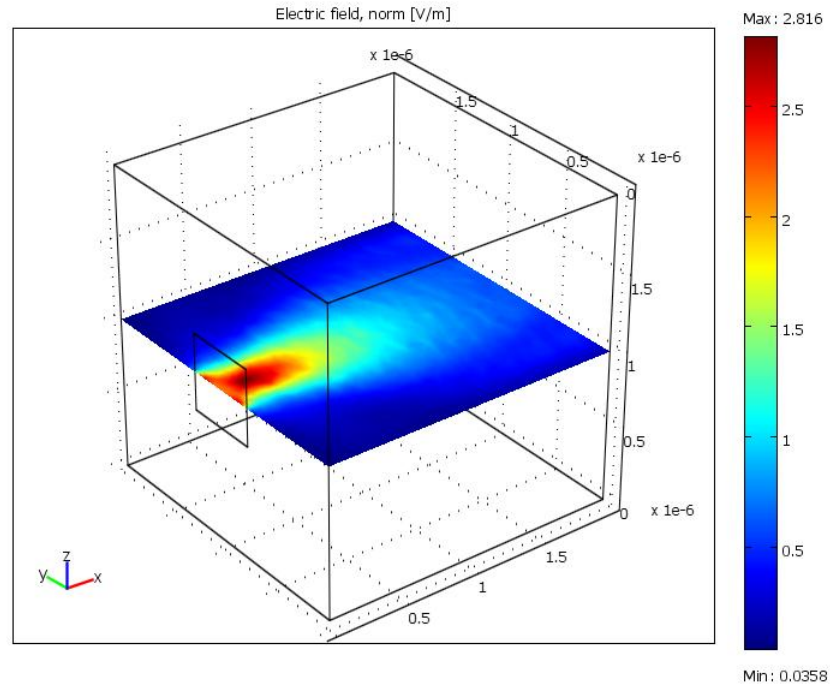


Figure 18: Electric field magnitude in a homogeneous medium (air) generated by a square emitter placed on one surface of the block as shown in the figure

Figures 17 and 18 show that the electric field propagates through the block all the way to the back surface.

Then 125 spherical inclusions ($5 \times 5 \times 5$ array in x, y and z directions) are inserted in the block geometry with air matrix as shown in Figure 19. Spheres are made of silicon and have a radius of 7.0×10^{-8} m and a spacing of 3.05×10^{-7} (center to center) in x, y and z directions.

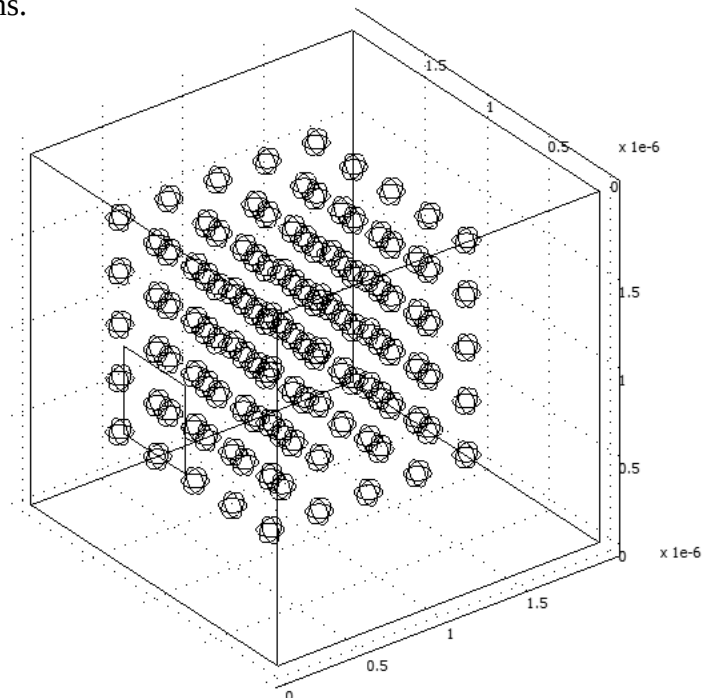


Figure 19: 3D geometry of a periodic structure made of silicon spheres in air matrix

Figure 20 shows the z-component of the electric field (wavelength = $7.5 \text{ e-}7 \text{ m}$) generated by a square emitter on the front surface of the periodic structure. The electric field magnitude is plotted in Figure 21.

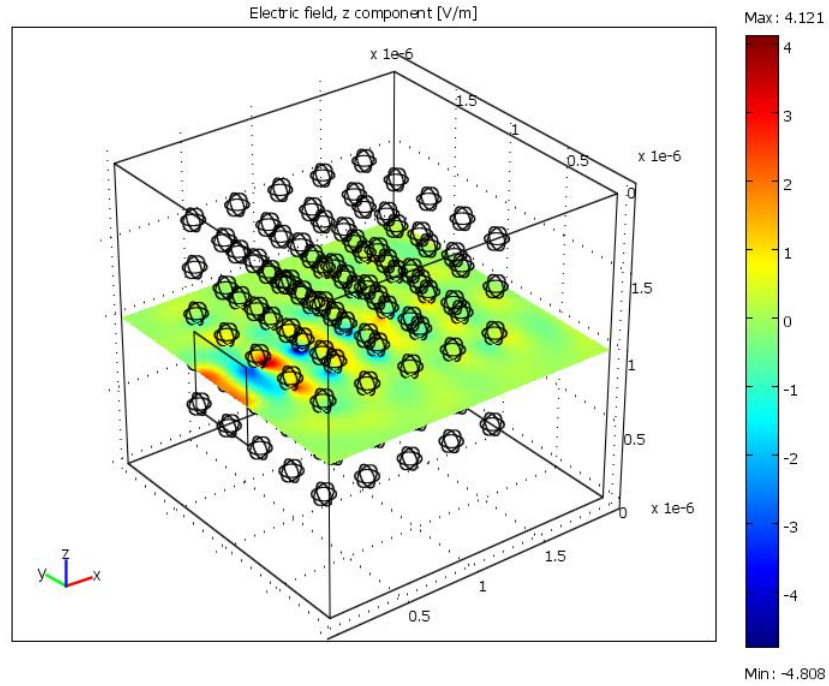


Fig 20: z component of electric field in a periodic structure (silicon spheres in air)

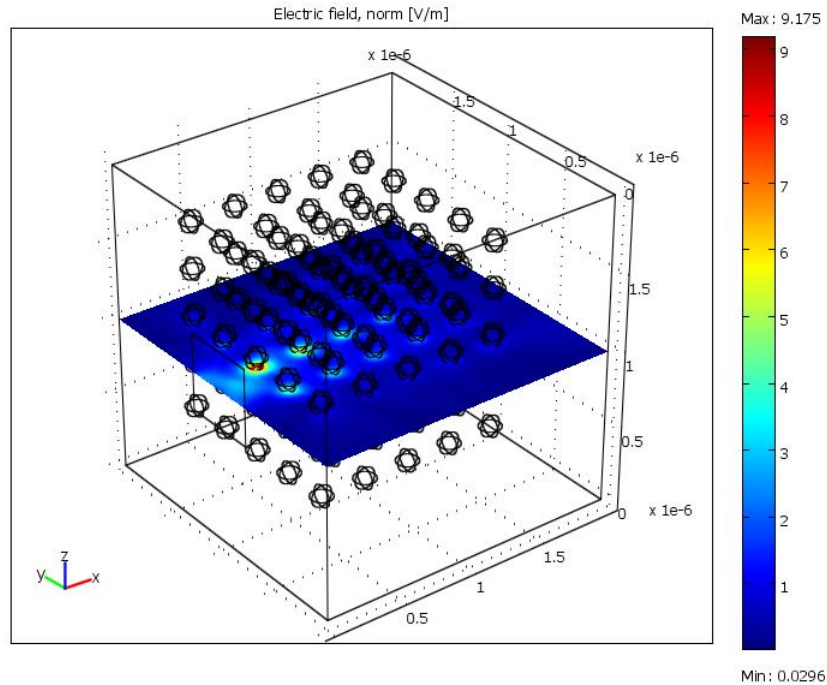


Figure 21: Electric field magnitude in a periodic structure (silicon spheres in air) generated by a square emitter placed on one surface of the block as shown in the figure.

Comparing Figure 17 or 18 (without inclusions) with Figure 20 or 21 (with inclusion) one can conclude that periodic inclusions adversely affect the radiated energy propagation.

The uniform periodic structure is then modified by eliminating the central row of the spherical inclusions as shown in Figure 22. Figures 23 and 24 show the electric field in the z direction and the total electric field magnitude, respectively. The wavelength of the propagating electromagnetic wave is $7\text{e-}7$ m. It should be noted here that the electromagnetic waves easily propagate through the cavity generated by the missing row of inclusions.

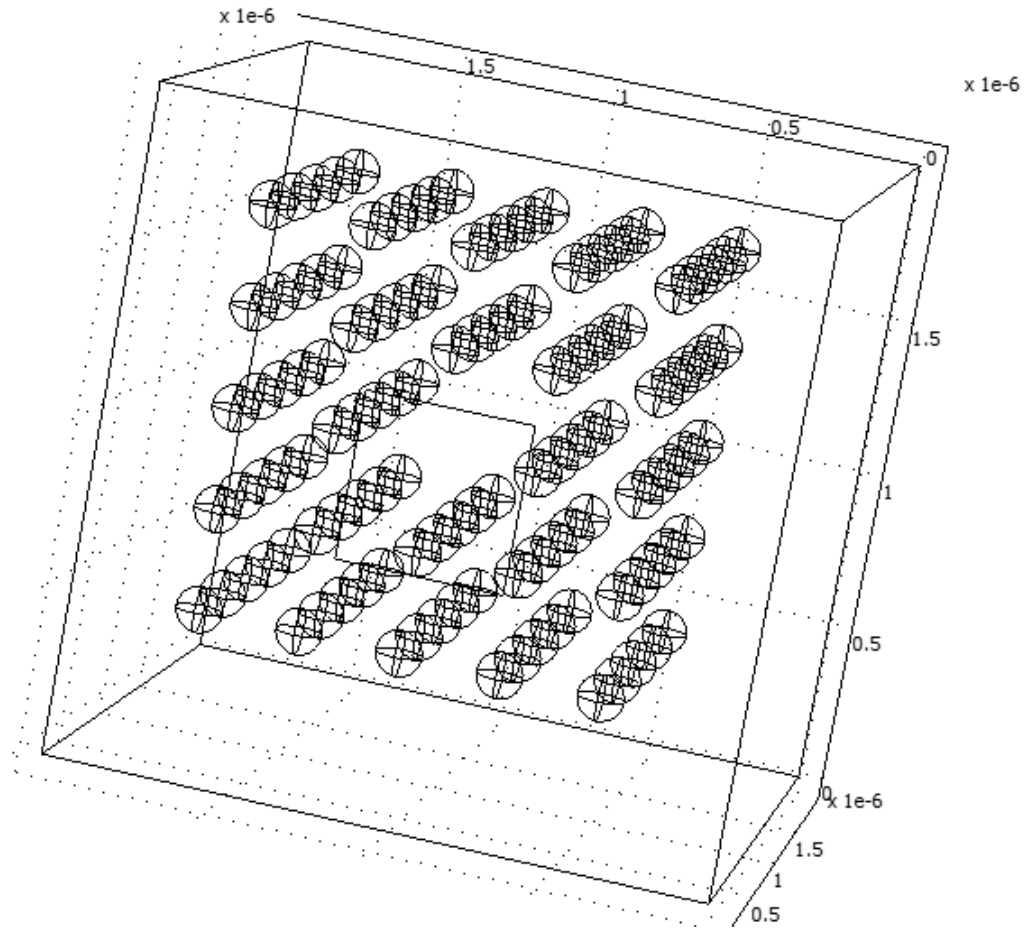


Figure 22: The geometry of the 3D periodic structure with a cavity formed by removing one row of spherical inclusions at the center.

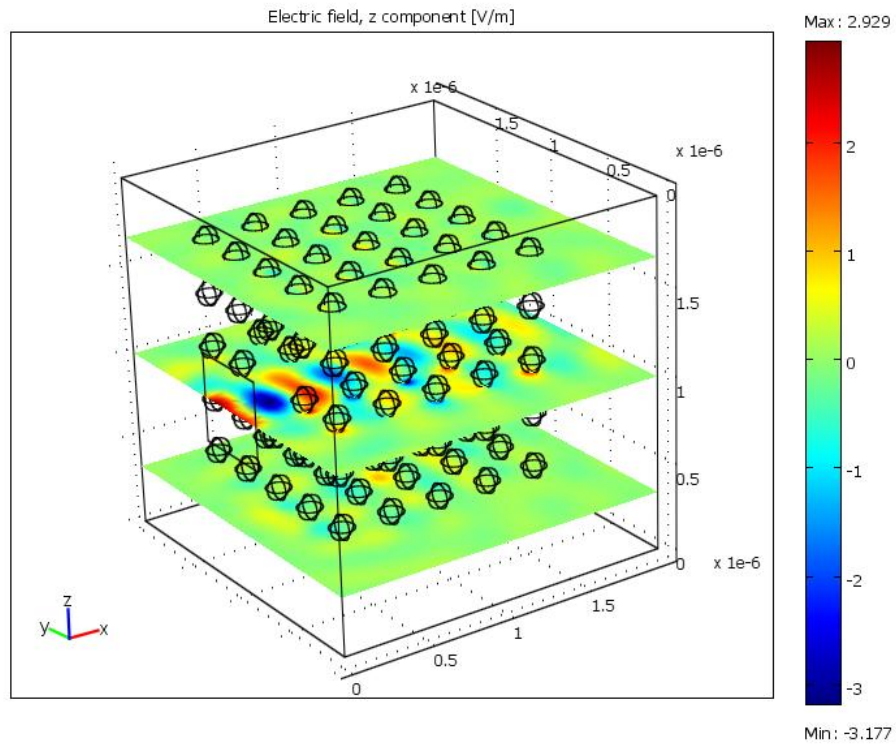


Figure 23: z component of the electric field propagating through a periodic structure with the central row of inclusions missing; wavelength is $7\text{e-}7$ m.

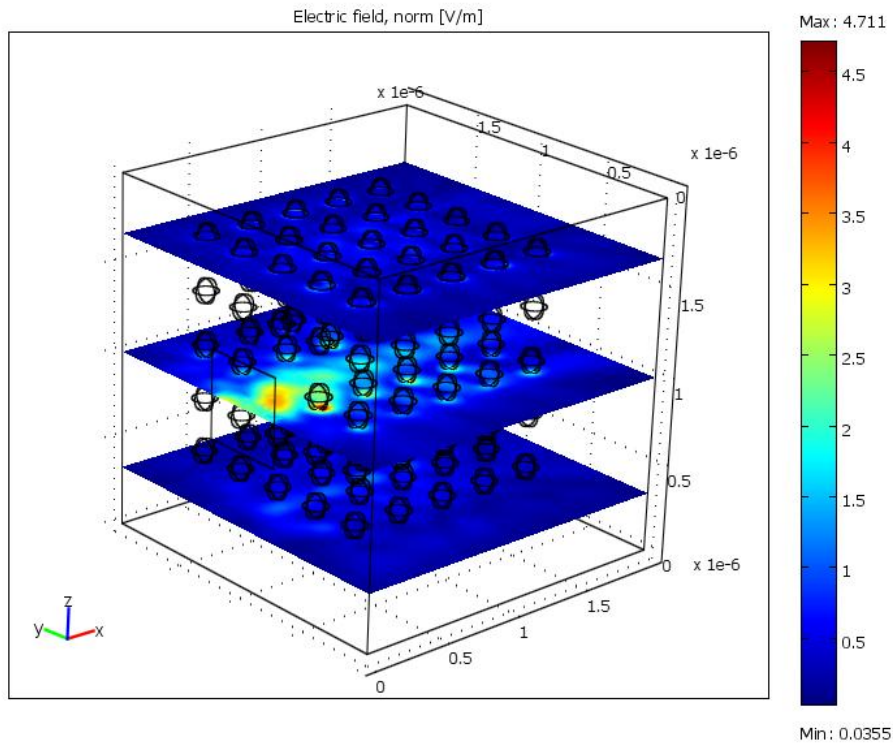


Figure 24: Electric field magnitude of the propagating electromagnetic wave through a periodic structure with the central row of inclusions missing; wavelength is $7\text{e-}7$ m

Next the cavity is moved towards right by removing a row of inclusions on the right side but keeping the central row intact as shown in Figure 25. The electromagnetic wave is then propagated through this structure using the same emitter location, at the center of the front surface (as was done in Figures 17 to 24). Figures 26 and 27 show the generated electric field in the z direction at the central plane (Figure 26) and at two mutually perpendicular planes - one horizontal and one vertical (Figure 27). As before, the electromagnetic wavelength is 7×10^{-7} m. It should be noted here that the energy is no longer propagating centrally. Figure 27 clearly shows that the energy propagation shifted towards right.

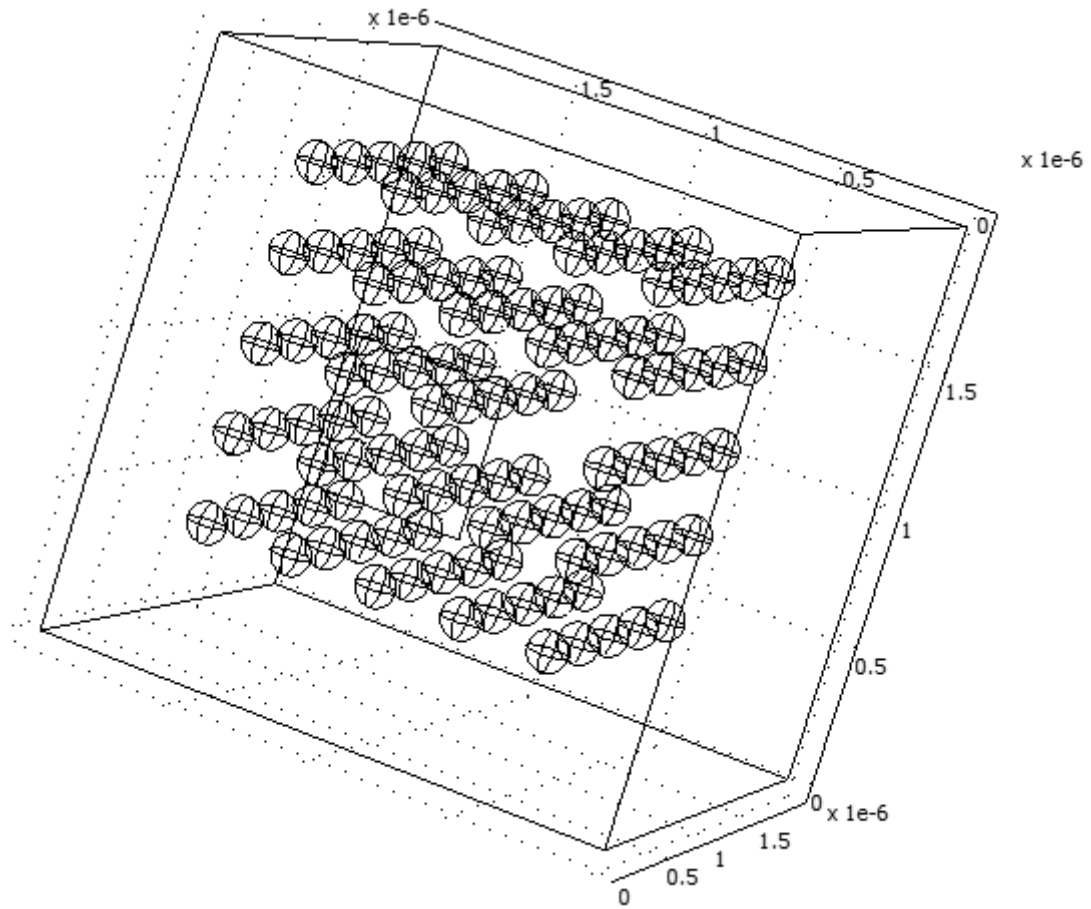


Figure 25: Geometry of the 3D periodic structure showing one row of spherical inclusions missing from the right side.

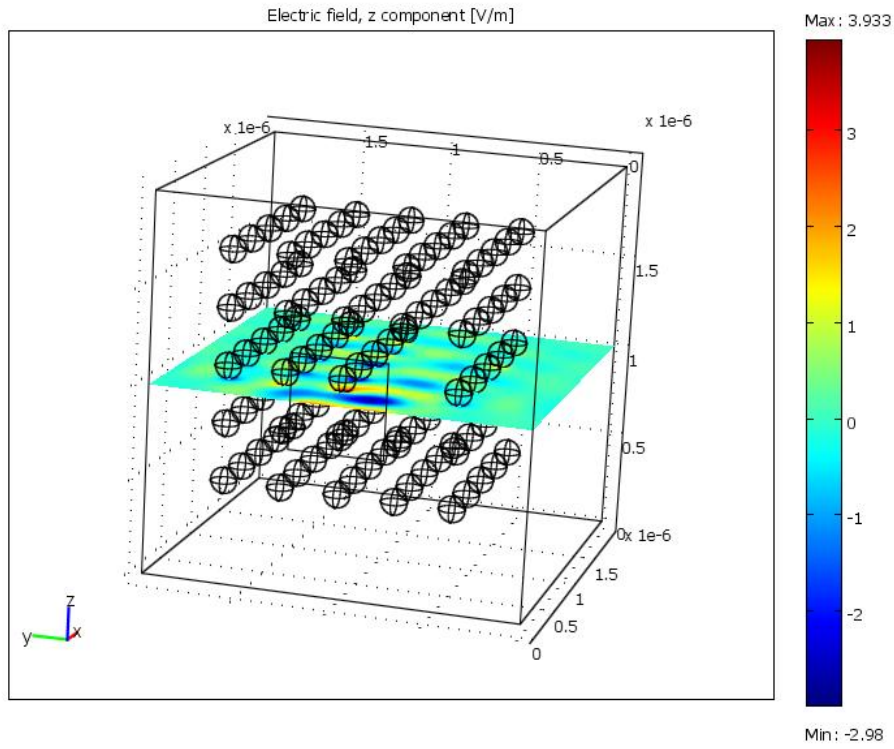


Figure 26: z component of the electric field propagating through a periodic structure with one row of inclusions missing from the right side; wavelength is $7\text{e-}7$ m.

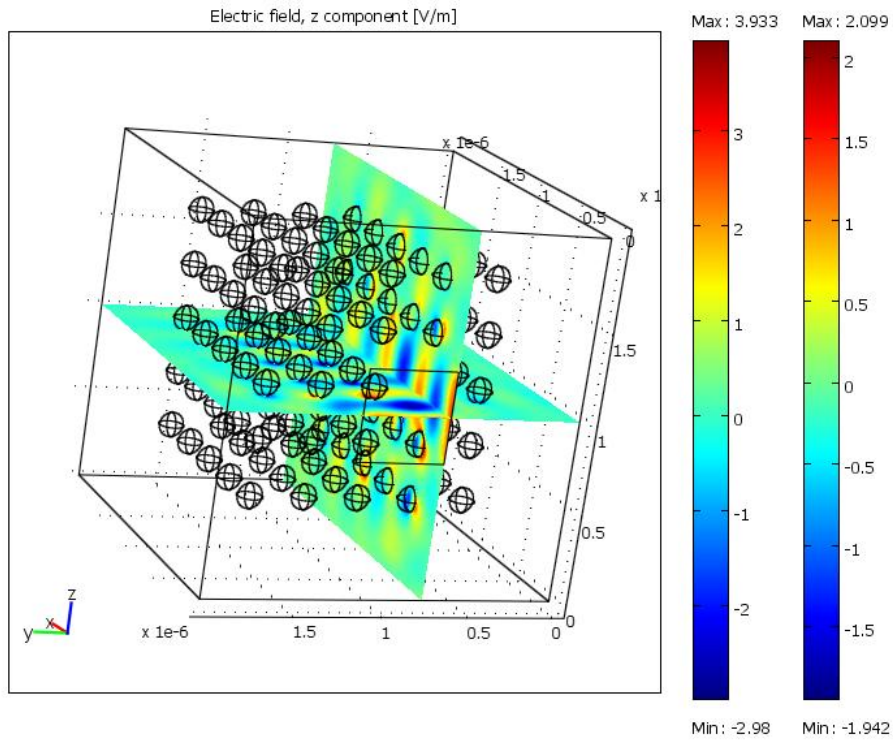


Figure 27: z component of the electric field propagating through a periodic structure with one row of inclusions missing from the right side. Shift of the propagated energy to the right side is evident from this electric field plot on two planes.

Next two rows of spherical inclusions are removed from the periodic structure – one above the central row and one on its right, as shown in Figure 28. The electromagnetic wave is then propagated through this structure using the same emitter location, at the center of the front surface (as was shown in Figures 17 to 24). Figures 29 and 30 show the electric field in the z direction (Figure 29) and the electric field magnitude (Figure 30) generated by the propagating electromagnetic waves in this engineered periodic structure. As before, the electromagnetic wavelength is 7×10^{-7} m. It can be noted in Figures 29 and 30 that the energy is again no longer propagating centrally. Bulk of the energy is now propagating through the two cavities formed by the removal of the spherical inclusions.

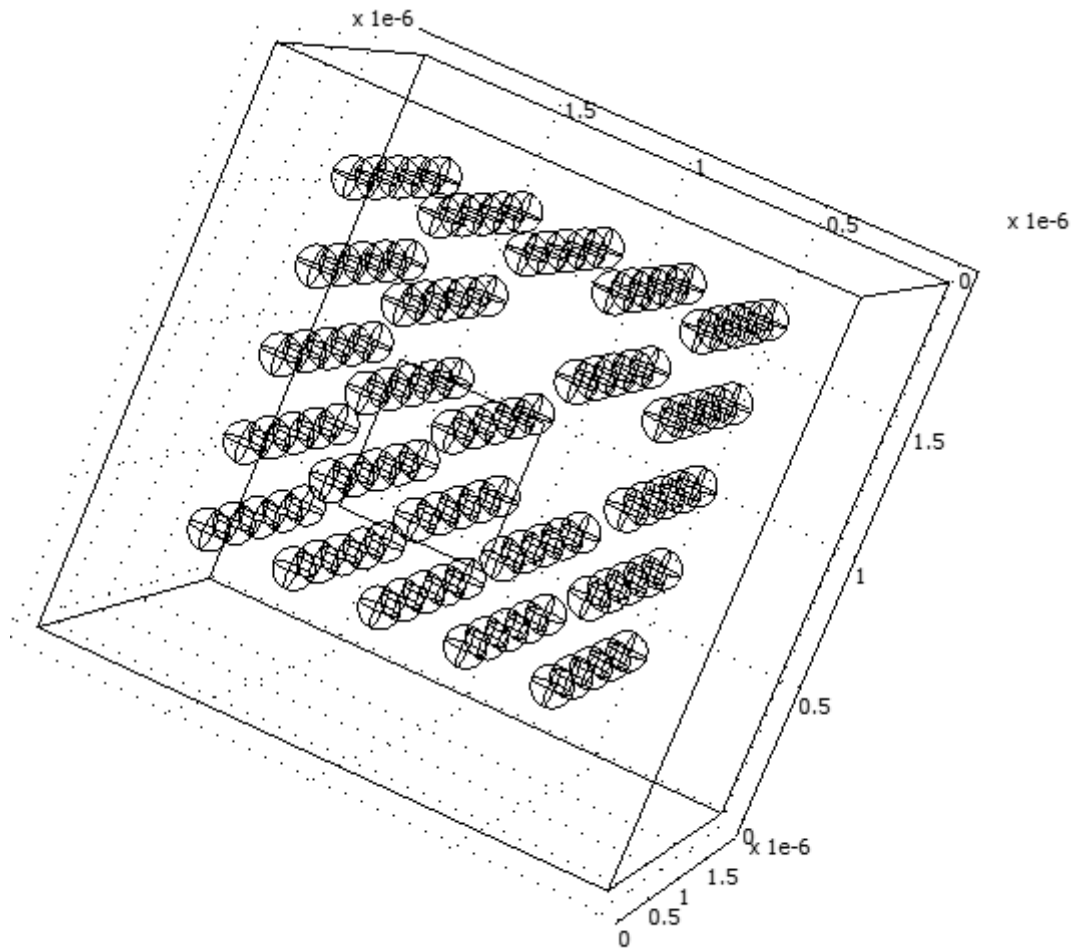


Figure 28: Geometry of the 3D periodic structure showing two rows of spherical inclusions missing – one above the central row and one on the right side.

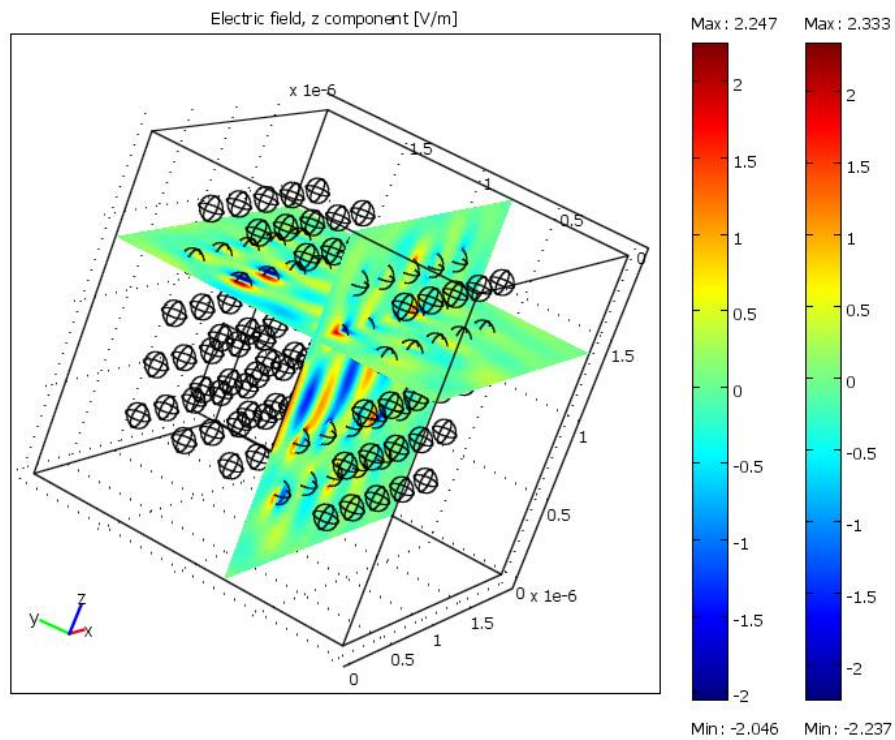


Figure 29: z component of the electric field propagating through a periodic structure with two rows of inclusions missing. The square emitter is placed at the center of the front face.

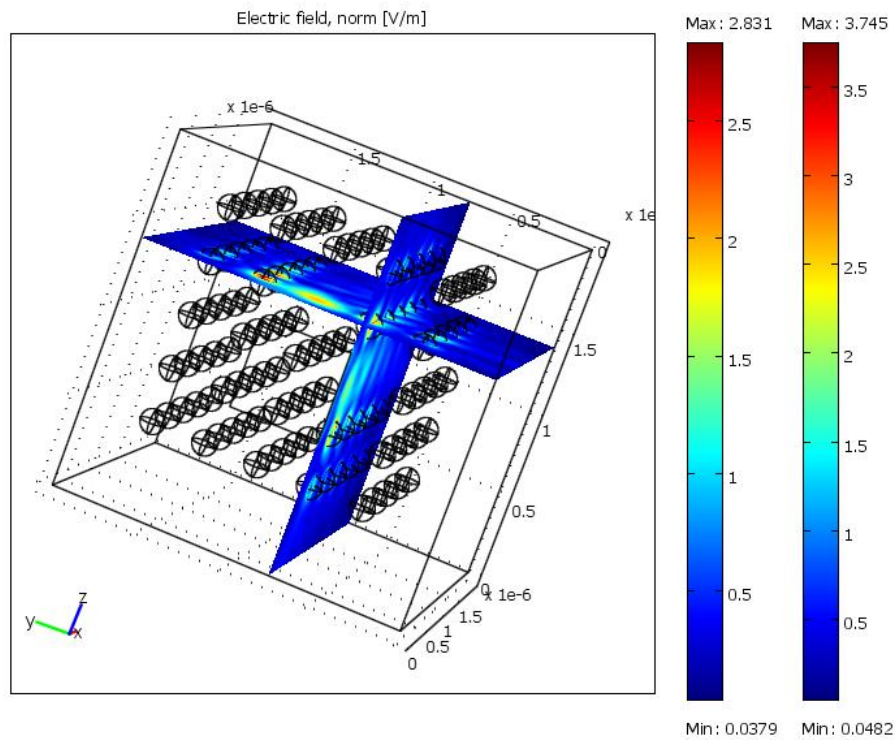


Figure 30: Electric field magnitude generated by the propagating electromagnetic waves through a periodic structure with two rows of inclusions missing. The square emitter is placed at the center of the front face.

Concluding Remarks:

This research showed that by properly designing a periodic structured material it is possible to block the radiated heat propagation in one direction while facilitating its propagation in another direction. The research emphasis here was on the radiated heat transfer for outer space applications. It should be noted that in the outer space, in absence of the air heat mostly propagates through radiation. Radiated heat is an electromagnetic wave and therefore, a good knowledge of electromagnetic wave propagation through periodic structures is needed for studying heat transfer through periodic structures by radiation, as investigated here.

The knowledge advanced through this research can be applied to any other problem related to the wave propagation through periodic structures such as acoustic wave and ultrasonic wave propagation through phononic crystal, or propagation of light wave and other electromagnetic waves such as X-ray, gamma-ray and THz or T-ray through photonic crystals. This research will be also helpful in designing acoustic and electromagnetic metamaterials that rely on the periodicity in the material composition to let the waves of certain frequency pass through the material while stopping waves having another frequency.

Future research on this topic can be on designing more complex distribution of inclusions (instead of forming simple cavities as considered here) for achieving a specific objective such as entrapping the heat energy in certain region while dispersing it in another region and experimentally verifying all these theoretical predictions.

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- [1] Siegel, Robert and Howell John, "Thermal Radiation Heat Transfer" (Taylor and Francis, 4th Edition 2002)
- [2] Planck, Max, "Distribution of Energy in the Spectrum", Ann. Phys., vol 4, no. 3, pp. 465-468-1978
- [3] Rybicki, George B. and Lightman, Alan P., "Radiative Processes in Astrophysics" (John Wiley and Sons, New York, 1979)

List of Publications and Significant Collaborations that resulted from the AOARD supported project:

- 1) A paper for journal publication is under preparation.
- 2) The propulsion and the air vehicle laboratories of AFRL (Air Force Research Laboratory), Dayton, Ohio showed some interest in this research. A future collaboration with them is a possibility

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