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# Micro-Analysis of the Radiation Mechanism of High-Gain Pyramidal Horn Antennas

**Sushant Kumar Chhotray**

skchhotray@rediffmail.com

Independent Researcher https://orcid.org/0009-0002-3408-5527

**Research Article**

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# Abstract

The conventional model of horn-antenna radiation requires further examination to understand important aspects of the radiation process, particularly the formation of the far-field radiation pattern, the configuration and evolution of the electric field, and the formation of the closed-loop spherical wavefront. To address these aspects and examine the limitations of the conventional model, a new radiation model for a long pyramidal horn antenna is proposed. This model provides a qualitative and logical framework for describing the transition of the electromagnetic field from the guided region to the radiated field and for examining the formation of the resulting radiation pattern. The model consists of two complementary parts: (i) an electrostatic model, which describes the charge and electric-field distributions associated with the antenna structure at a given instant, and (ii) a dynamic radiation model, which describes the time-varying electromagnetic field structures and their propagation into free space through the horn antenna. The proposed new model establishes that the radiation mechanism of a pyramidal horn antenna solely depends on the radiation produced by an equivalent array of dipoles distributed along the inner surfaces of the horn antenna and responsible for radiation pattern formation.


# I. Introduction

The high gain pyramidal horn antenna [1–8] is a simple yet important passive microwave antenna, widely used for the efficient wireless transmission and reception of electromagnetic waves. Its simple construction, high gain, good directivity, and relatively wide bandwidth make it particularly useful at microwave frequencies. The origin of horn antennas can be traced to Sir J. C. Bose, who used a horn-type [9–11] arrangement in his pioneering experiments on the generation, propagation, and detection of centimetre and sub-centimetre electromagnetic waves. He demonstrated his work on the propagation and refraction of electric waves before the Royal Society in 1897. Since then, horn antennas have become important components in microwave transmission and reception systems. They are widely used as standard-gain antennas for antenna measurements, calibration, and radiation-pattern characterization, as well as feed antennas for parabolic reflectors, radar, satellite communication, remote sensing, and radio astronomy. Their low loss, good impedance matching, and high-power handling capability further enhance their importance in microwave engineering and electromagnetic measurements. The theoretical and experimental studies of horn antenna become a part of text book for graduate level studies.

The conventional representation of the radiation mechanism of a pyramidal horn [1, 2] antenna shown in Fig. 1. An RF source is connected to one end of a rectangular waveguide, while a pyramidal horn antenna is attached to the other end.

An important feature of the surface charge distribution is its spatial variation along the direction of propagation on the inner surface of the waveguide. For the dominant mode considered, successive regions of opposite charge on the same conducting wall are separated by approximately half the guided wavelength ($\lambda g/2$). The opposite charges on the facing walls are separated by the transverse waveguide

dimension, which is much smaller than λg/2. This difference in spacing is important for understanding the electric-field distribution. At any instant, the electric field is predominantly established between the nearby opposite charges on the facing walls, extending across the waveguide cross-section.

Several aspects of the pyramidal horn antenna are re-examined, particularly the formation of the far-field radiation pattern, the electric-field distribution at the horn aperture, and the free space impedance matching. The examination suggests that the conventional model may not provide a sufficiently detailed physical interpretation of these aspects. Therefore, a suitable model is needed to address these questions and provide a logical explanation of the observed radiation pattern.

This review article proposes a new model to explain the radiation mechanism of a pyramidal horn antenna. Section II presents the statement of the problem concerning the unresolved aspects of the radiation mechanism of horn antennas. It examines several key issues, including the formation of closed-loop wavefronts, the formation of radiation beam patterns, the emergence of spherical wavefronts from the horn aperture and free space impedance matching. These aspects require further investigation to establish clear and satisfactory physical explanations for the underlying radiation mechanisms. Section III proposed a new horn antenna radiation model, which consists of two parts: an electrostatic model and a dynamic model. The electrostatic model uses electrostatic simulations to illustrate the charge distribution and associated electric field characteristics within the horn antenna. The dynamic radiation model provides further insight into the proposed horn antenna radiation mechanism by examining the dynamic behaviour of the surface charge distribution and the corresponding electric field orientations. Together, these two parts aim to provide a logical physical interpretation of the radiation mechanism of the pyramidal horn antenna. The proposed horn radiation model is extended to the long biconical antenna radiation mechanism in Section IV.

## II. Statement of Problem

A horn antenna consists of a gradually flared waveguide that provides a transition between the guided waves inside the waveguide and the electromagnetic waves radiated into free space. The RF source excites electromagnetic fields within the waveguide, typically in the dominant $TE_{10}$ mode for a rectangular waveguide. As the wave propagates through the flared section, the expanding geometry modifies the field distribution and provides a larger radiating aperture. The electric fields at the aperture contribute to the free space radiation in accordance with electromagnetic boundary conditions and aperture field theory. As per the conventional model, the radiated fields from different regions of the aperture interfere constructively and destructively, producing a directional radiation pattern. The aperture dimensions, horn length, flare angles, and field distribution influence the antenna's gain, directivity, and beam width. The horn antenna thereby provides efficient directional radiation with relatively low reflection and improved impedance matching. Several aspects of horn antennas are examined in detail, highlighting key points that require further investigation and more logically consistent physical explanations, as discussed below.

1. **Closed loop formation**

Consider the shape of the spherical wavefront radiated by a horn antenna, as shown in the Fig. 1. The conventional explanation describes a closed-loop spherical wavefront emerging from the horn antenna aperture and propagating into free space [1, 2]. This concept is often illustrated by comparing electromagnetic radiation with water waves generated when a pebble is dropped into a calm body of water. Once the disturbance is initiated, the resulting waves propagate outward and continue travelling even after the pebble is removed. The analogy demonstrates that a disturbance can continue propagating after its source has ceased to act at the point of initiation. However, the physical processes governing water waves and electromagnetic waves are different, and the analogy alone cannot establish the mechanism of electromagnetic closed loop formation.

In a horn antenna, the electric field varies periodically with time according to the applied RF signal, reversing its direction every half-cycle and passing through zero between successive positive and negative peaks. Consequently, the field configuration at the aperture changes continuously, with opposite field orientations occurring at different phases of the signal. This raises an important question regarding the conventional representation of a closed-loop spherical wavefront: how does such a loop form and propagate through free space? In particular, fields emitted at different times with opposite orientations do not necessarily combine to form a closed loop, especially when a zero-field region may exist between regions of opposite polarity.

This raises an important physical question: How does the electromagnetic field emerging from the finite aperture of a pyramidal horn?

1. **Radiation beam formation**

The electromagnetic wave first enters the feeding point of the pyramidal horn from the rectangular waveguide. From the throat toward the mouth, the transverse dimensions of the horn increase gradually, allowing the electromagnetic field to occupy an increasingly larger cross-sectional area. Thus, the horn provides a gradual transition from the confined guided-wave region of the rectangular waveguide to the open space at its aperture. As per the conventional model, the horn antenna aperture radiates spherical waves in to free space. Consider a spherical wave is expressed as,

$$E(r,t) = (r^{-1})\,\mathbf{r}E_0 \exp[i(\omega t - kr)], \quad (1)$$

Here, $E_0$ is the wave-amplitude constant, ω is the angular frequency, and **r**, with r = |**r**|, denotes the position vector and its distance from the origin, respectively. The fields exhibit oscillatory radial and temporal dependence, while their amplitudes decrease inversely with distance from the origin. Thus, as the spherical wave propagates outward and its radius increases, its field amplitude decreases proportionally to (1/r). The wave vector k specifies the direction of wave propagation. Since the expression for an ideal spherical wave depends only on the radial coordinate r and is independent of the

polar and azimuthal angles, its phase propagates radially outward, and the spherical wavefront expands as the radius increases.

Yet measurements of a pyramidal horn antenna radiation clearly show a directional radiation pattern, with maximum radiation concentrated around the horn axis and progressively decreasing radiation away from that axis. A narrow beam is associated with high directivity and, consequently, high antenna gain.

The radiation emerging from the horn aperture is represented as a spherical wave spreading radially outward. However, there is no obvious mechanism by which such a spherical wave, after leaving the horn, should spontaneously "self-concentrate" into a narrow beam in free space. How, then, does the radiation subsequently exhibit a directional pattern and form a beam without an explicitly explained physical mechanism? This apparent contradiction suggests that the conventional description of horn-antenna radiation may not, by itself, provide a complete physical picture of the radiation mechanism.

1. **Electric field configuration at antenna aperture**

It is well established that the dominant or fundamental mode of a rectangular waveguide is determined by its cross-sectional dimensions. When these dimensions change, the cut-off frequencies of the possible modes also change. If the dimensions become sufficiently large, higher-order modes may become capable of propagating in addition to the fundamental mode. Consequently, the power carried by the waveguide may no longer remain confined to a single dominant mode but can be distributed among several modes. This multimode propagation can alter the field distribution and may affect the efficiency and radiation characteristics of the system.

The same issue deserves consideration in the case of a pyramidal horn antenna. In a pyramidal horn, both the broad dimension, a, and the narrow dimension, b, increase progressively from the feeding point towards the aperture. Therefore, the local waveguide dimensions continuously change along the horn, and the corresponding modal conditions also change continuously. This raises an important question: Can higher-order modes be generated or excited as the wave propagates through the expanding horn? If such modes are present with significant amplitudes, the electromagnetic field at the aperture will no longer represent a pure fundamental-mode distribution. The resulting aperture field could consequently influence the radiation pattern, beam width, directivity, and radiation efficiency.

Nevertheless, many conventional analyses [1–5] of pyramidal horn antennas assume that the field entering the horn is predominantly the dominant mode of the rectangular waveguide at the feeding and use this mode as the basis for determining the aperture field and far-field radiation.

This assumption therefore deserves careful examination, particularly when explaining the physical mechanism by which a horn antenna produces a highly directional radiation beam.

1. **Free space impedance matching**

A horn antenna is commonly described as an impedance transformer [1–3] because it provides a gradual transition between the electromagnetic field confined within a waveguide and the radiated field in free space. The horn antenna also described as a impedance matching device between the terminal and the space. As the waveguide flares outward, its geometry and transverse field distribution change, influencing the input impedance, reflection coefficient, and aperture-field distribution. Although an open-ended waveguide can also radiate electromagnetic energy, it may exhibit a higher voltage standing wave ratio (VSWR) due to impedance mismatch. The attachment of a horn antenna generally improves impedance matching and reduces reflections, resulting in a lower VSWR under suitable design conditions. The expanding aperture also influences the radiation pattern, directivity, and distribution of electromagnetic energy in the radiated field. These observations suggest that the horn provides an impedance transition between the waveguide and free space. The wave impedance in a waveguide depends on the mode of propagation. When multiple modes are present within a horn antenna, as discussed in Section II.c, the impedance characteristics become more complex. Therefore, considering the horn solely as an impedance-matching structure may be an oversimplification, particularly when the individual modal contributions and their interactions have not been evaluated.

# III. Pyramidal horn antenna model

A new model of a high-gain pyramidal horn antenna is proposed to provide a qualitative and logical explanation of the propagation of RF energy through a waveguide and its subsequent radiation into free space through the horn antenna. The rectangular waveguide guides the electromagnetic waves towards the expanding horn antenna, which provides a gradual transition between the guided field and the free space radiated field. Surface currents flow along the inner conducting walls of the waveguide and horn, supporting the electromagnetic field in accordance with the boundary conditions. These electric fields are associated with time-varying surface-charge distributions that vary in magnitude and polarity during the RF cycle. Their spatial distribution along the direction of propagation is related to the operating wavelength and phase of the guided wave. The proposed model analyses these surface charge distributions to better understand the radiation process. The radiation model is divided into two parts. The first part of the model, The Electrostatic model, examines the instantaneous charge distribution and the corresponding electric-field configuration on the conducting surfaces of the waveguide and horn. The second part of the model, The Dynamic radiation model, investigates the dynamic behaviour of the electric field as it propagates through the horn. It examines the time-varying surface currents and the electric field distributions along the wall of the expanding conducting structure.

Together, the two parts provide a logical framework for investigating the relationship between surface-charge distribution, dynamic electromagnetic fields, and aperture radiation, thereby supporting a more detailed examination of the radiation mechanism of a high-gain pyramidal horn antenna.

1. **Electrostatic model**

An electrostatic simulation of the waveguide and horn antenna is performed using open-source software [12] to examine the surface-charge distribution along the inner conducting walls. Static charges are assigned to the grounded metal surfaces to represent an instantaneous charge configuration. The charge polarity and spatial distribution are arranged to illustrate the alternating positive and negative surface-charge regions associated with the progression of an RF wave through the waveguide and expanding horn, as shown in Fig. 2. This simulation provides a simplified, instantaneous representation of the charge distribution. However, it does not directly model RF-wave propagation, since a true dynamic electromagnetic simulation must account for time-varying electric and magnetic fields, surface currents, and phase variation.

The simulation shows that positive and negative charges on opposite walls of the waveguide are closer to each other than adjacent charges of the opposite polarity along same wall. The electric field is predominantly directed across the waveguide, from the positively charged region towards the negatively charged region on the opposite wall. A similar charge configuration is observed near the feeding point of the horn antenna, where the waveguide transitions into the flared section. As the structure expands, the separation between the opposite walls increases progressively. Consequently, the transverse distance between the illustrated charge regions also increases along the horn. The electric-field pattern is redistributed and realigned, with the field concentrated between successive, closely spaced charges of opposite polarity along the same wall, rather than between charges on the more distant opposite wall. The electric field becomes negligible in the central region of the horn aperture, as shown in the simulation. The resultant electric field is determined by the superposition principle, whereby the individual electric fields produced by all charges combine vectorially.

1. **Dynamic radiation model**

The dynamic radiation model is developed from the surface-charge distributions illustrated in the electrostatic model discussed in the previous section. This model, as shown in Fig. 3, examines the time-dependent behaviour of the surface charges and electric field as the wave progresses. It is reasonable to expect that the electric field due to the charges at position D (in Fig. 3a.) will be directed more strongly towards the opposite charges at positions C and E, separated by approximately half the wavelength, than towards opposite charges located, at position D ', several wavelengths away.

As the RF wave progresses, the surface-charge distribution changes along the waveguide and horn antenna. As discussed earlier, the separation between opposite walls remains constant in the waveguide and increases gradually along the flared section of the horn. Accordingly, the proposed model illustrates a redistribution and realignment of the electric field, with the field influenced by the relative positions of nearby and distant charge regions. At (t = 0), as shown in Fig. 3(a), the electric field at position AA' is directed upward, whereas the field at BB', is directed downward. The increasing separation between the horn walls is represented schematically by the bending of the electric-field lines, shown as dashed lines at BB'. Near point B, the field pattern is then illustrated as being redistributed, with part of the field

directed towards the opposite charge at B' and the remaining field directed towards the opposite charge region at C. This electric field distribution is based on the superposition principle.

Consider the electric-field configuration at (t = T/2), shown in Fig. 3(b), where (T) is the period of the RF signal. At this instant, the polarity of the surface-charge distribution is reversed compared with its configuration at (t = 0). Here, the negative-charge region at position A in the waveguide undergoes a polarity reversal as the RF signal progresses along the structure, illustrating the periodic evolution of the surface-charge distribution. The associated electric-field configuration also changes with time as the electromagnetic wave propagates from the feeding point towards the aperture. At position B, the resultant electric field is determined by the combined contributions from the surrounding regions of opposite charge, including those at B' and C. The superposition of these electric-field contributions determines the resultant field orientation at that instant. Consequently, the field direction is reversed relative to its initial orientation at t = 0. Similarly, the electric fields at positions B, C, D, etc., and B', C', D', etc., maintain their respective orientations according to the instantaneous charge polarities at these locations. As the RF signal continues to propagate, the surface-charge polarities and the associated electric-field orientations undergo periodic reversals. It is important to note that the electric fields are now oriented between oppositely charged regions on the same surfaces, rather than between the facing surfaces, as observed in the waveguide. When the signal completes one full period (t = T), the surface-charge distribution and electric-field configuration return to their initial states, corresponding to t = 0. This process represents one complete RF cycle. For a signal operating in the gigahertz frequency range, these periodic changes occur billions of times per second.

A closer examination of the time-varying electric-field configuration reveals a qualitative resemblance to an array of oscillating electric dipoles, as illustrated in Fig. 3. The electric fields at positions B, C, D, etc., and B', C', D', etc., exhibit periodic oscillations corresponding to the alternating surface-charge distributions, resembling the behaviour of individual dipole elements. In this interpretation, these regions of alternating surface charge are represented by equivalent oscillating dipoles distributed along the horn structure. Each equivalent dipole contributes to the overall radiation, with the dipole elements oscillating synchronously in response to the propagating RF signal. Their individual radiated electromagnetic fields combine through the principle of superposition in the far-field region. Depending on their relative phases and spatial distribution, these fields reinforce one another in certain directions while partially cancelling in others. The resulting constructive and destructive interference contributes to the formation of the directional radiation pattern of the horn antenna. Thus, the proposed model provides an equivalent dipole-array representation to examine the radiation mechanism and understand the formation of the far-field radiation beam.

The equivalent dipole-array distribution proposed in the horn antenna radiation model is illustrated in Fig. 4. The spacing between the dipoles is non-uniform and depends on the RF frequency and the flare angle of the horn antenna. The equivalent dipoles in the array may not be exactly vertical, as they are distributed along the slanted surfaces of the antenna. The dipoles have unequal amplitudes, which arise from the gradual increase in the horn antenna’s cross-sectional dimensions towards its aperture and the

surface-charge density decreases successively along the expanding structure, resulting in unequal field strengths associated with the equivalent dipoles. Thus, the dipoles do not contribute equally to the radiation process, even though they are arranged at equal intervals. The resulting radiation pattern is formed by the combined and synchronous radiation contributions of this unequal-amplitude dipole array.

# IV. Biconical antenna radiation

The proposed radiation model for the pyramidal horn antenna can also be applied to investigate and understand the radiation mechanism of a large biconical antenna. A biconical antenna [1–3] is a wideband antenna consisting of two conducting cones arranged symmetrically, with their vertices facing each other and connected to a coaxial feed, as illustrated in Fig. 5(a). It exhibits radiation characteristics similar to those of a dipole antenna, particularly when the antenna dimensions are small compared with the operating wavelength. For an antenna length, (h), smaller than the signal wavelength ($h < \lambda$), the radiation pattern is approximately omnidirectional, with the radiated electromagnetic field spreading outward in the form of spherical waves. However, as the antenna length increases beyond the wavelength ($h > \lambda$), the radiation pattern can become increasingly directional (the directionality also depends on the antenna geometry, cone angle, and operating frequency).

In the case of a large biconical antenna, the extended conducting surfaces provide a larger region for the distribution of alternating surface charges and associated electric fields. The spatial distribution and orientation of these fields vary along the conical surfaces as the electromagnetic wave propagates from the feed point towards the open ends of the cones. These characteristics bear similarities to the surface-charge distribution and electric-field configurations discussed in the proposed model of the pyramidal horn antenna. Therefore, the equivalent dipole representation and the associated radiation mechanism proposed for the pyramidal horn antenna may also provide a useful framework for examining the radiation behaviour of a long biconical antenna. As the cone angle increases, the spacing between the equivalent dipoles decreases accordingly. Furthermore, increasing the length of the biconical antenna increases the number of equivalent dipoles, resulting in a narrower radiation beam and potentially higher antenna gain.

# V. Conclusion

A new horn-antenna radiation model is presented to provide physically consistent interpretations of various aspects of its radiation mechanism. The model consists of two parts: the first presents an electrostatic perspective of the charge distribution and associated electric fields, while the second examines the dynamic behaviour of the surface charges and their associated electric fields on the inner surfaces of the horn antenna as the RF wave propagates towards the aperture. The electrostatic simulation provides a clear visualization of the electric-field orientations resulting from the charge distribution on the inner surfaces of the horn antenna. It helps illustrate the field configuration associated with the instantaneous distribution of positive and negative charges along the conducting walls. The dynamic model further illustrates the proposed dipole-type radiation mechanism by showing

how the polarity changes as the RF signal progresses from the waveguide entrance towards the antenna aperture. These periodic polarity changes are considered responsible for the successive radiation contributions represented by the equivalent dipole array. Together, the electrostatic and dynamic models provide complementary perspectives for investigating the proposed radiation mechanism of the pyramidal horn antenna.

The model also proposes that a closed-loop spherical wave shape may not form at the aperture of the horn antenna. Instead, the radiation mechanism is interpreted through the collective radiation of the equivalent dipole array distributed along the horn's inner surfaces. This concept required further mathematical analysis to establish the effects of dipole distribution. The proposed model further explains that the gain of the horn antenna increases with its length. A longer horn accommodates a greater number of equivalent dipoles along its inner surfaces. These dipoles radiate synchronously, and their combined contributions produce the directional radiation pattern. According to this concept, the increased number of synchronously radiating dipoles in a longer horn is responsible for the higher gain. This interpretation provides a new perspective on the relationship between horn length, the number of equivalent dipoles, and the resulting radiation pattern.

The study concludes that the proposed model attributes the radiation mechanism of a pyramidal horn antenna to the radiation produced by an equivalent array of dipoles distributed along the inner surfaces of the horn, which collectively contribute to the formation of the radiation pattern. The proposed model is also extended to analyse the radiation mechanism of a long biconical antenna, demonstrating its potential applicability to other types of antenna configurations. A detailed investigation is required to study and formulate the radiation fields within the framework of the proposed model. The same model can also be applied to E-plane, H-plane, and other similar types of antennas.

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# Figures

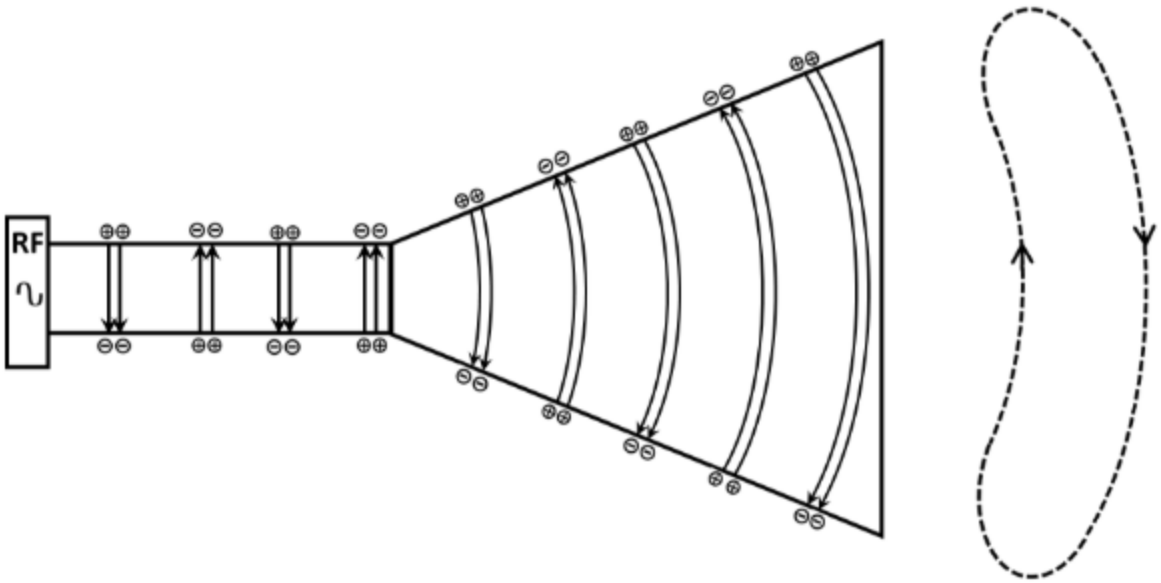



**Figure 1**

Schematic diagram of a conventional high gain pyramidal horn antenna and it’s radiation in free space.

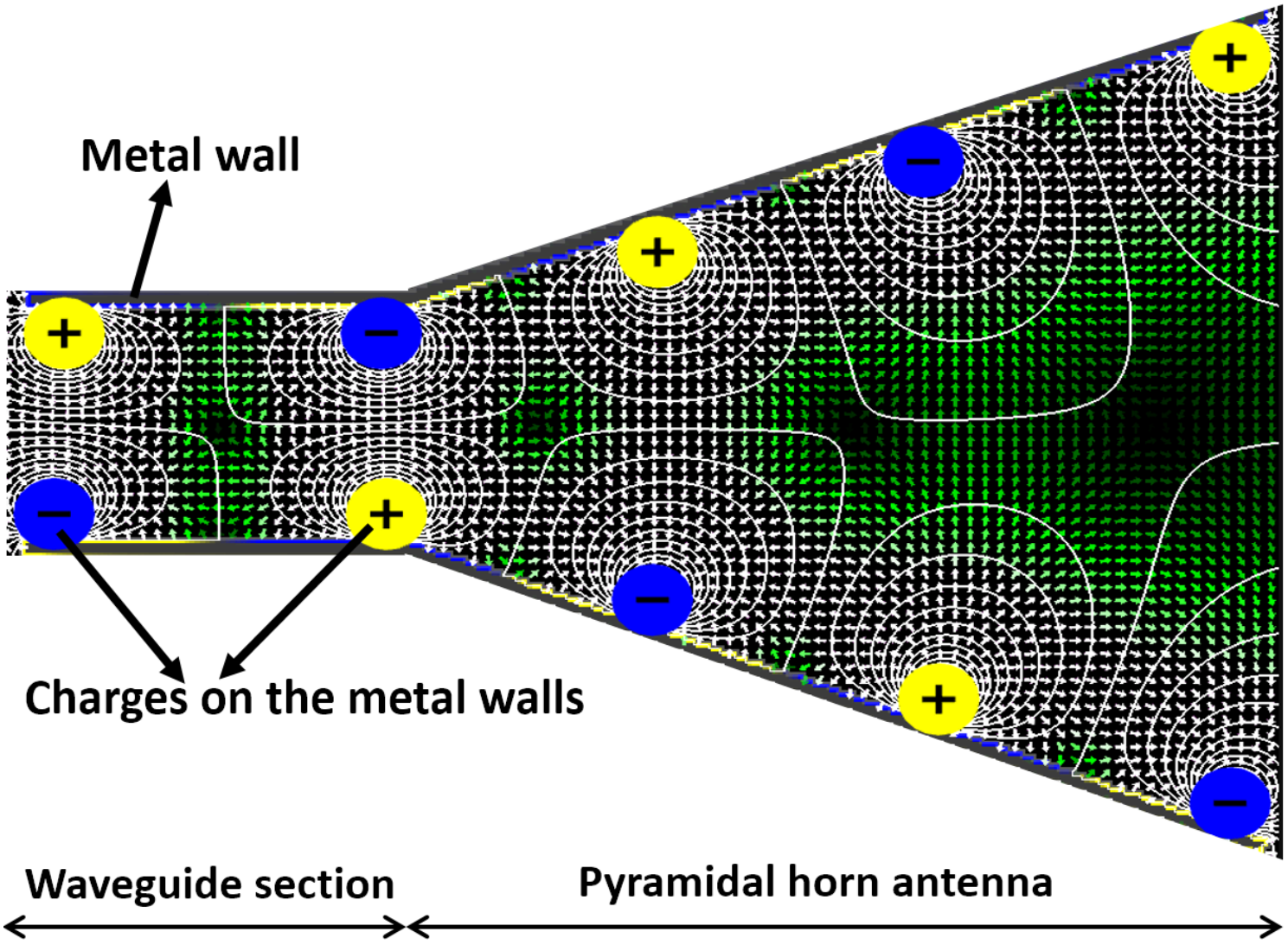



**Figure 2**

The electrostatic model of the pyramidal horn antenna simulation shows the equipotential lines in white lines, while the electric field lines are represented by white and green arrows. The white arrows indicate regions of higher electric field strength than the green arrows.

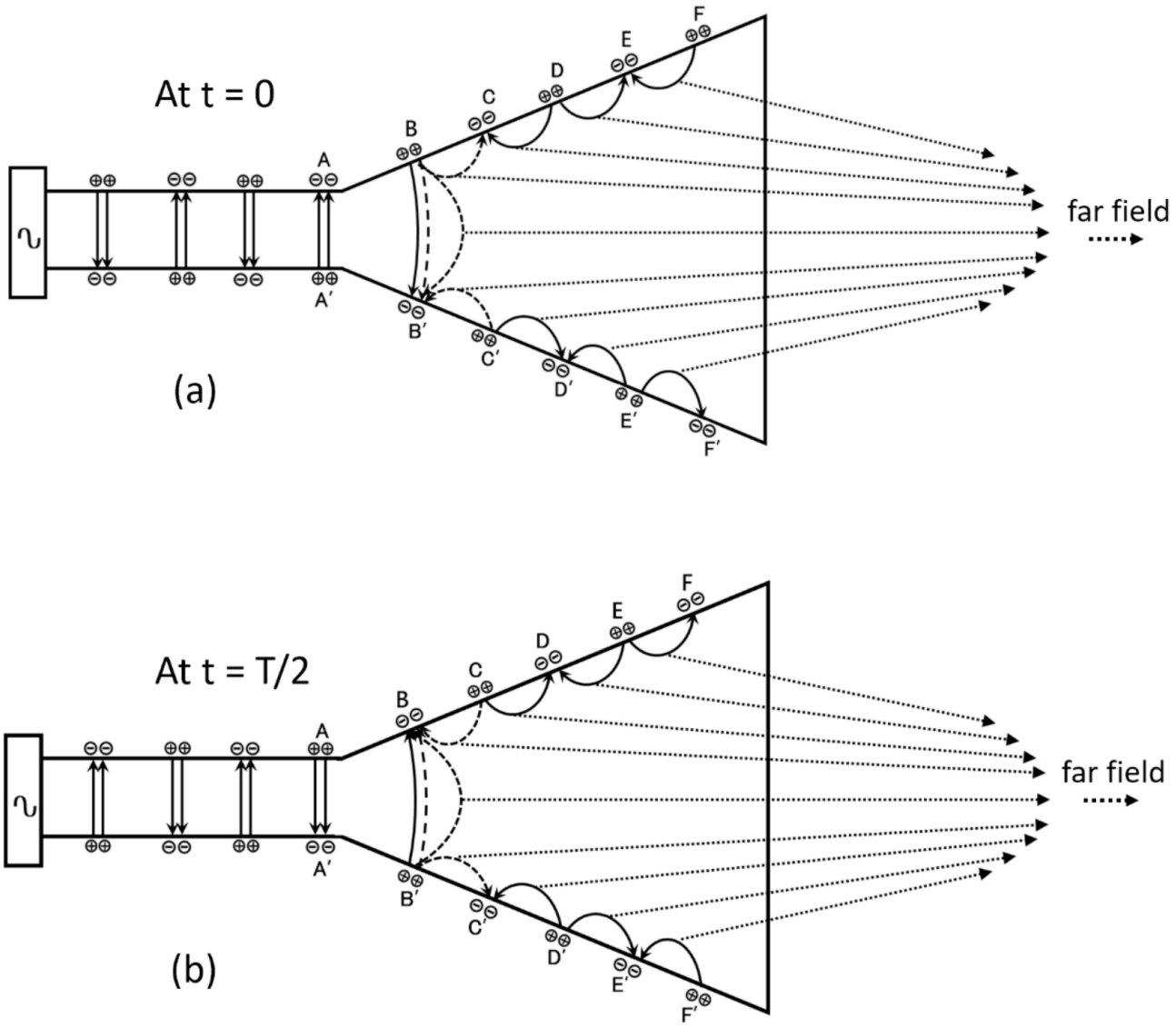



**Figure 3**

The electric fields distribution of pyramidal horn antenna, (a) at time t=0 and (b) at time t= T/2.

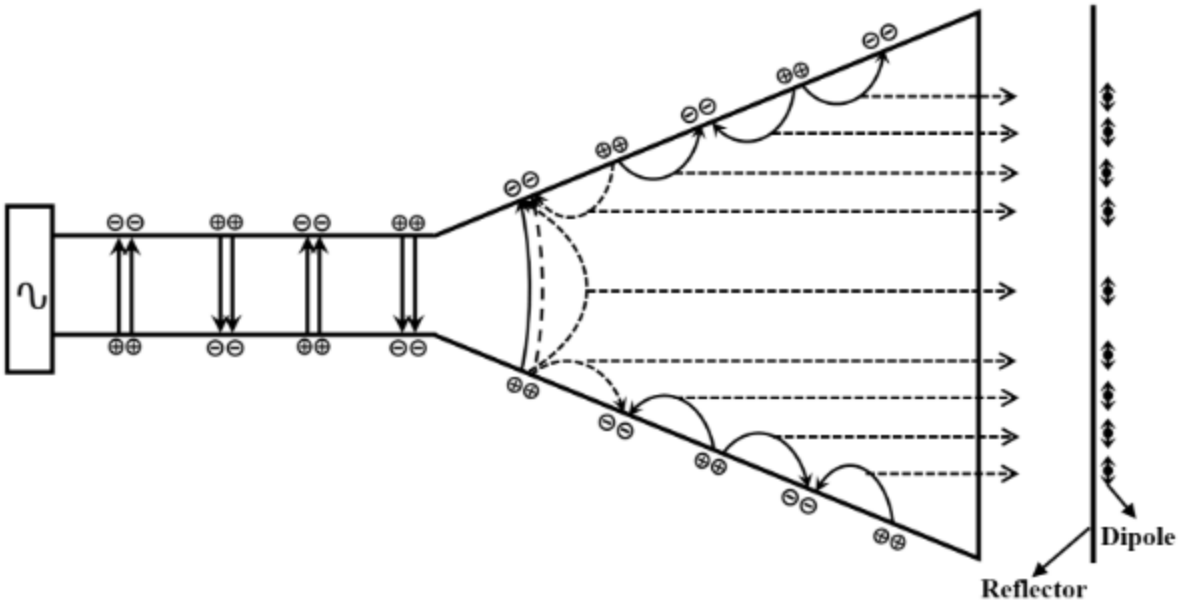



**Figure 4**

The horn antenna radiation and its equivalent dipole array with reflector. The distance between the array elements depends on the radiation frequency and the flaring angle of horn antenna. The dotted arrows indicate the correspondence between the electric fields and their equivalent dipoles.

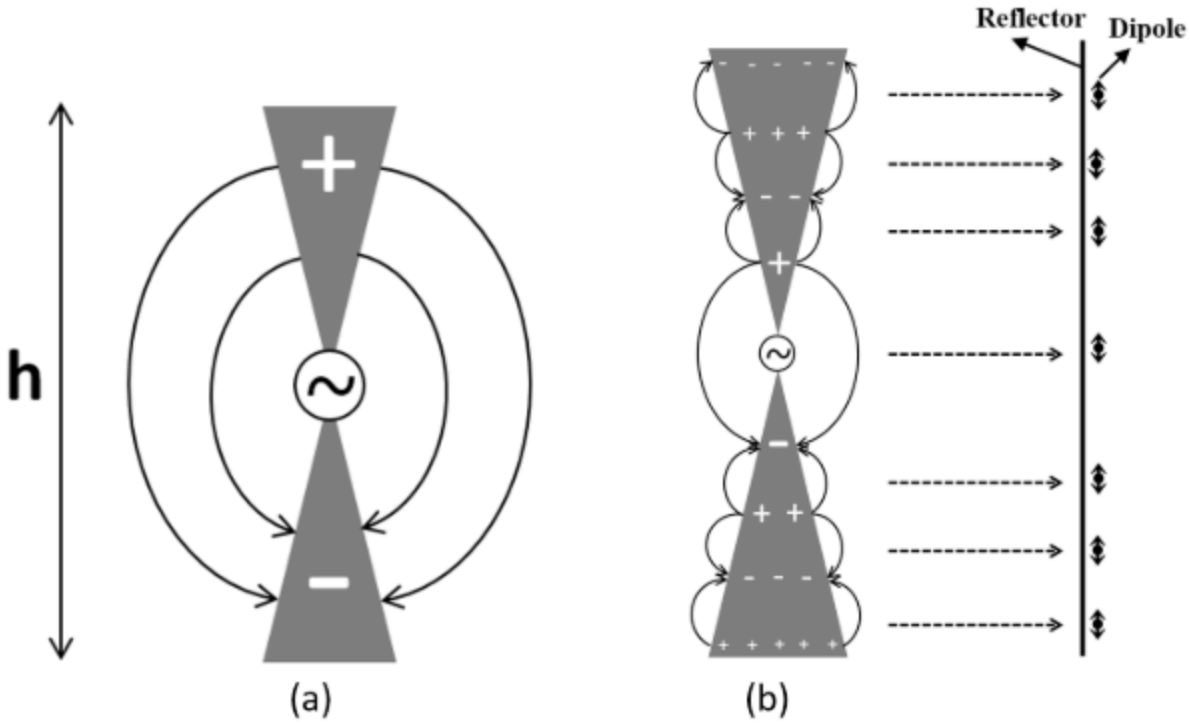



**Figure 5**

The biconical antenna radiation (a) for h < λ, the biconical antenna radiates spherical waves like a dipole, (b) for h > λ, the antenna radiates as an array of dipoles and its equivalent dipole array with reflector. The dotted arrows indicate the correspondence between the electric fields and their equivalent dipoles. The

surface charge density decreases (due to increase in the surface area of the cones) as the charges move towards the end if antenna.