

Electromagnetic Radiation – ACDC5009

B.Eng.(Hons) in Embedded Electronic Systems

Joshua H – Student Number: 2420839

Table of Contents

Abstract	3
Waveguides in Modern RF Systems	3
Operating Principles.....	3
<i>Communications Applications</i>	3
Defence Applications	4
Task 1a – Vacuum Waveguide	5
Port 1.....	5
Port 2.....	7
Cutoff Frequency Calculations	9
Task 1b - PTFE Wave Guide	11
Port 1.....	11
Port 2.....	13
Cutoff Frequency Calculations	15
Task 1 Analysis.....	17
Safety Standards for RF Energy	17
Task 2 – Dipole Antenna.....	18
Antenna Design	19
Simulation Results.....	20
Simulation Analysis	21
Task 3.....	22
Appendix	24
PEC Waveguide Magnitudes and Vectors	24
PTFE Waveguide Magnitudes and Vectors.....	32
References.....	39

Abstract

This report details where waveguides are used in modern applications, the differences of a vacuum waveguide and a Teflon filled waveguide, safety considerations that need to be addressed when designing waveguide systems, simulated results of a dipole antenna and finally a small summary of how RF systems can be used to detect and track UAVs and the implications of such technologies enter the public world.

Waveguides in Modern RF Systems

A waveguide is a hollow metallic structure that confines and guides electromagnetic waves along its length by means of internal reflection [1]. Unlike coaxial cables, waveguides carry no centre conductor; instead, waves propagate through the interior medium (usually air or vacuum). This makes them the transmission medium of choice wherever low loss, high power handling, and high frequencies are required simultaneously.

Operating Principles

Waves propagate inside a waveguide only above a cutoff frequency, determined by the guide's cross-sectional dimensions. Below this frequency, the wave is evanescent and decays exponentially. Each propagating solution is called a mode; the mode with the lowest frequency is known as the dominant mode [2]. Waveguides are standardised (IEC 60153, IEEE Std 521, EIA WR series) as to ensure interoperability of flanges, connectors, and components. Further standardised waveguide sizes have been collated [3]

Communications Applications

Satellite Ground Stations: High-power amplifier (HPA) output in Ku/Ka-band earth stations is routed via rigid waveguide runs to the feed horn. Waveguides are used in this application due to their low loss nature and efficiency when compared with coaxial cables for Ku/Ka bands [4]

Magnetic Resonance Imaging: Waveguides are used in MRI systems to allow cables, pipes, and other utilities to pass through F) shielded rooms without letting unwanted noise enter the scanner environment. MRI scanners are extremely sensitive to external electromagnetic interference any opening in this shield can act as a pathway for RF contamination, degrading image quality with artifacts or noise [5],[6].

Radio Telescope and Deep-Space Communication: " Over 92% of geostationary satellites use Ka-band waveguide systems" [7]. NASA's Deep Space Network use cryogenically cooled waveguide feed assemblies. Reducing the physical temperature of the waveguide walls to ~15–20 K dramatically lowers thermal noise, enabling detection of signals from spacecraft billions of kilometres away [8].

Defence Applications

RADAR: Waveguides are essential components in RADAR systems because they efficiently transmit high-frequency microwave signals between the transmitter, receiver, and antenna with very low signal loss. Unlike coaxial cables, waveguides can handle extremely high power levels and frequencies commonly used in radar, such as X-band, S-band, and Ka-band, while maintaining signal integrity over long distances [7].

Electronic Warfare (EW): Wideband waveguide horns and TEM cells are used as reference antennas in EW receivers and jammer systems. Travelling-wave tube amplifiers (TWTAs) used in noise/deception jammers are inherently waveguide-coupled devices [9].

Conformal waveguide slot arrays: where the radiating elements are slots cut into the broad wall of a waveguide. Due to their smaller overall size these antennas are able to be fitted to aeroplane nose-cones allowing for a maximisation in payload that typical waveguide antennas can't achieve [10].

Task 1a – Vacuum Waveguide

The waveguide was modelled in CST Studio Suite, with the dimensions 24x10x50mm, with ports being placed upon the Z-axis. A frequency sweep was taken from 2GHz to 30GHz.

Port 1

Mode 1

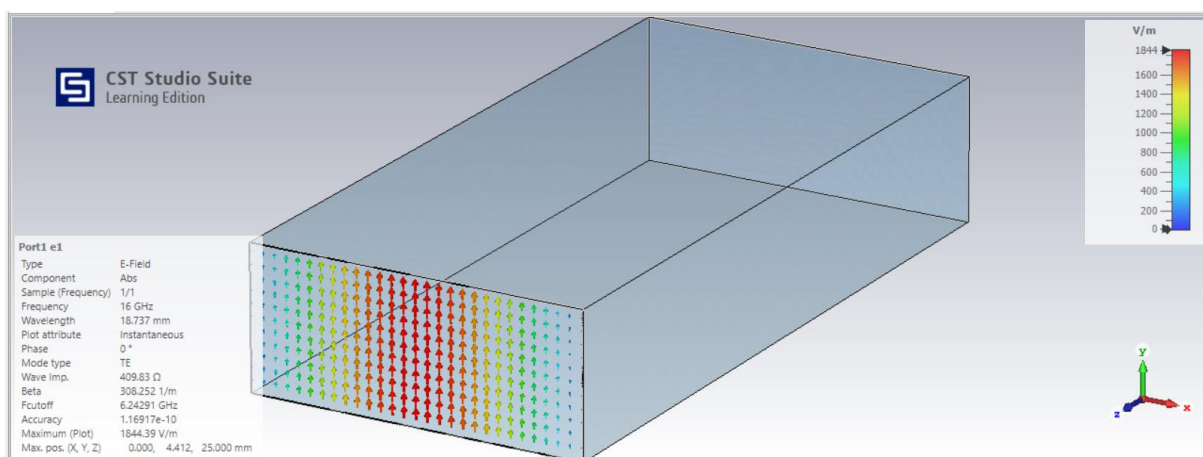


Figure 1: E-field magnitude distribution at Port 1 for the TE₁₀ dominant mode (vacuum waveguide, 16 GHz). A single half-wave sinusoidal lobe is visible along the width $a = 24$ mm, polarised in the y-direction. The field peaks at the waveguide centre. Simulated cutoff frequency: 6.243 GHz;

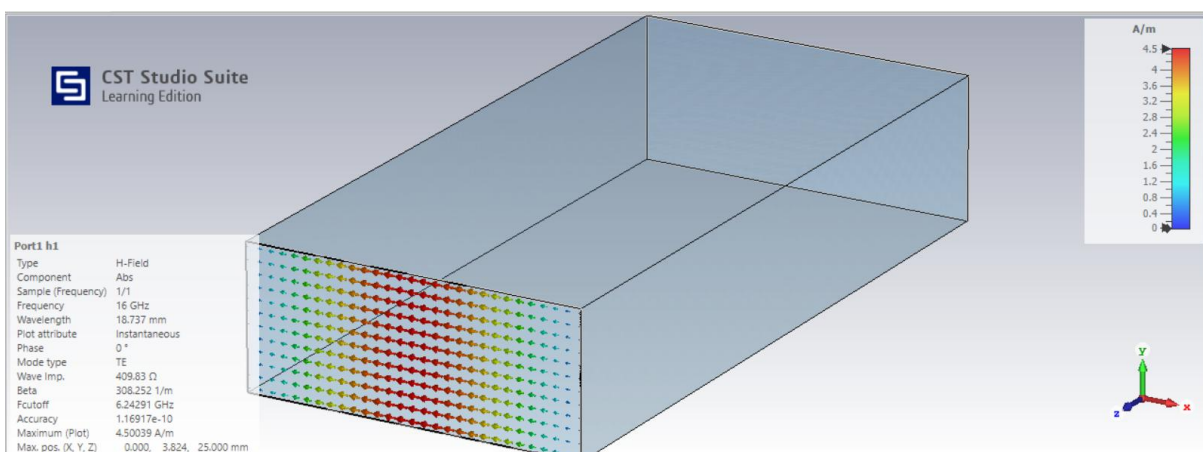


Figure 2: H-field magnitude distribution at Port 1 for the TE₁₀ dominant mode (vacuum waveguide, 16 GHz).

Mode 2

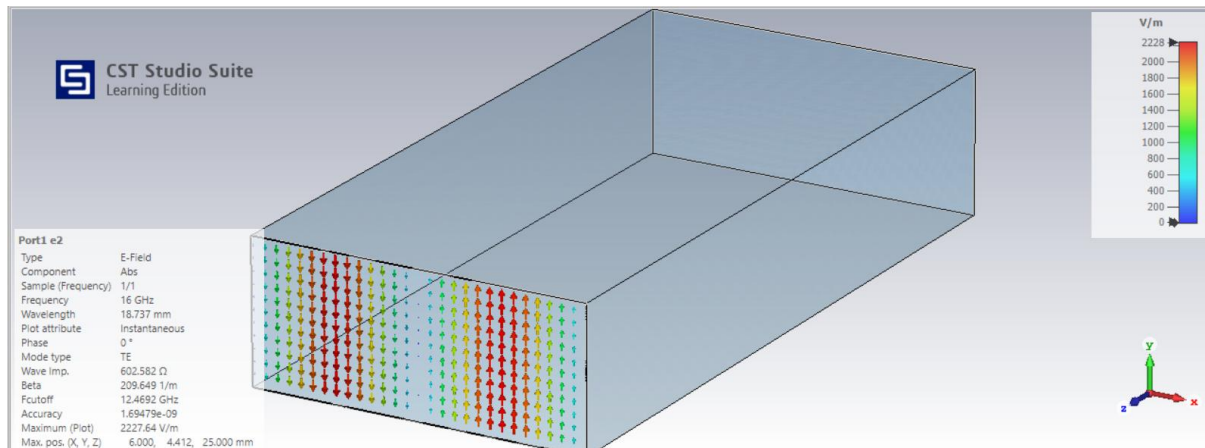


Figure 3: E-field magnitude distribution at Port 1 for the TE₂₀ mode (vacuum waveguide, 16 GHz). Two half-wave lobes of electric field intensity are visible along the width, separated by a null plane at $x = a/2 = 12$ mm.). Simulated cutoff frequency: 12.469 GHz;

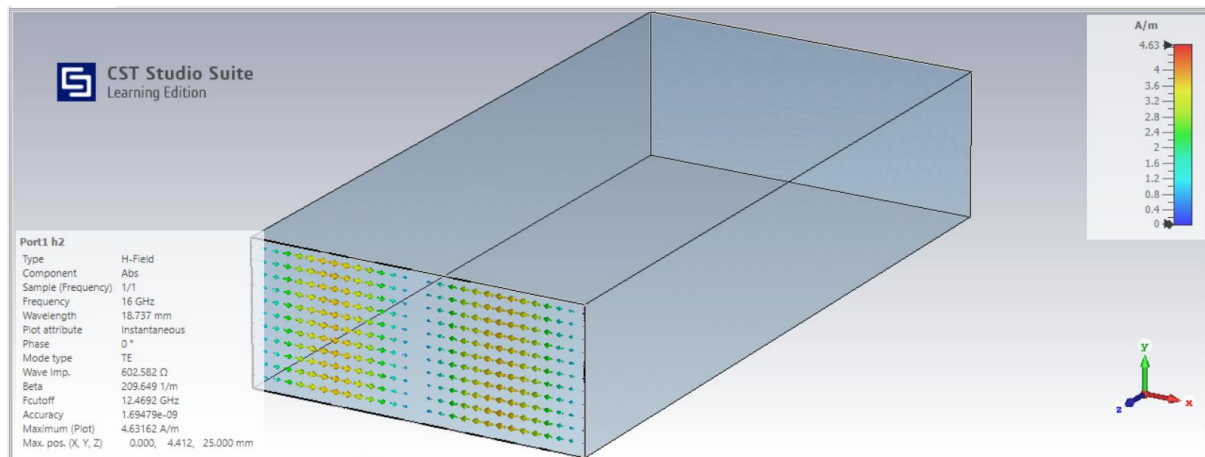


Figure 4: H-field magnitude distribution at Port 1 for the TE₂₀ mode (vacuum waveguide, 16 GHz). Two magnetic field lobes mirror the dual E-field variation

Mode 3

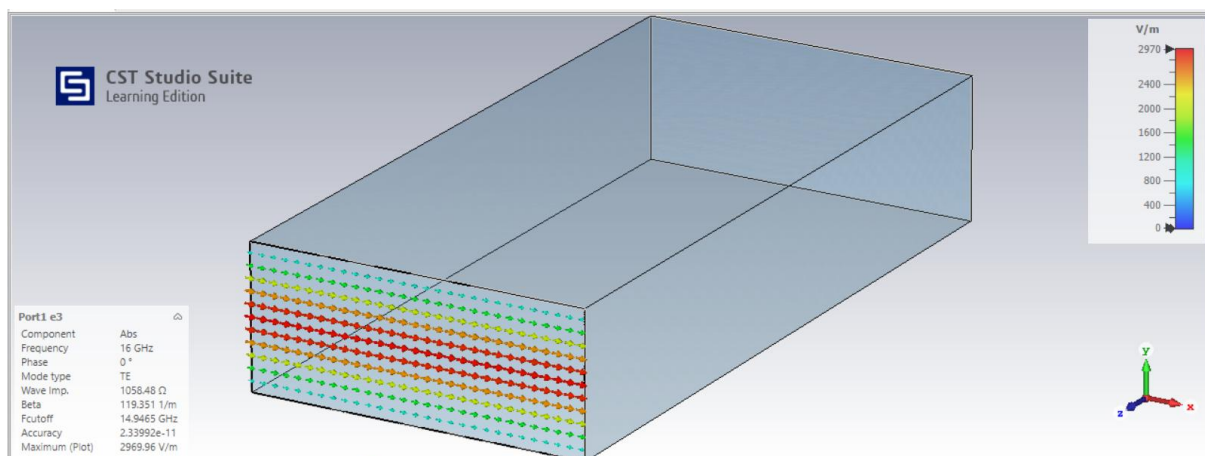


Figure 5: E-field magnitude distribution at Port 1 for the TE₀₁ mode (vacuum waveguide, 16 GHz). A single half-wave lobe is visible along the height $b = 10$ mm. Simulated cutoff frequency: 14.947 GHz

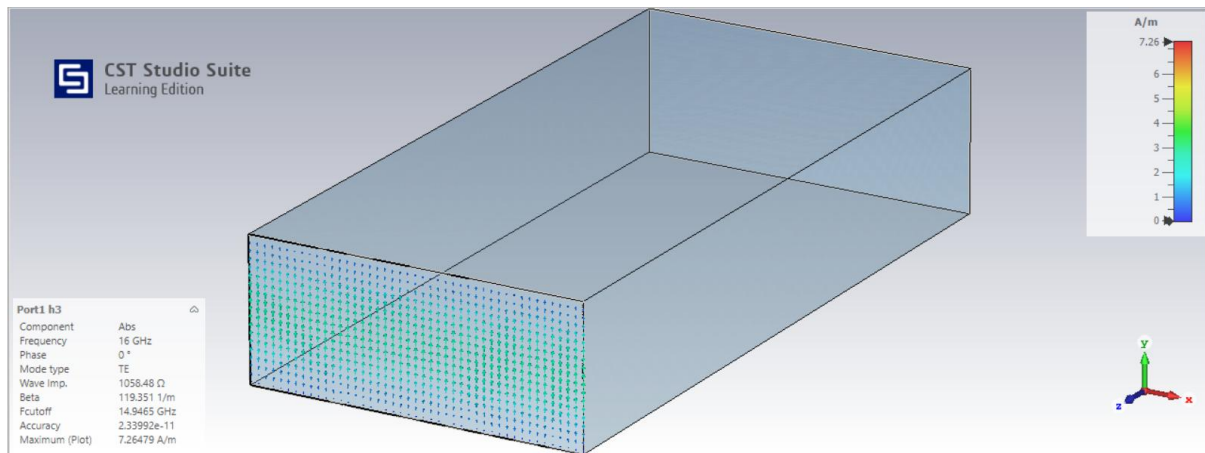


Figure 6: H-field magnitude distribution at Port 1 for the TE_{01} mode (vacuum waveguide, 16 GHz).

Port 2

Mode 1

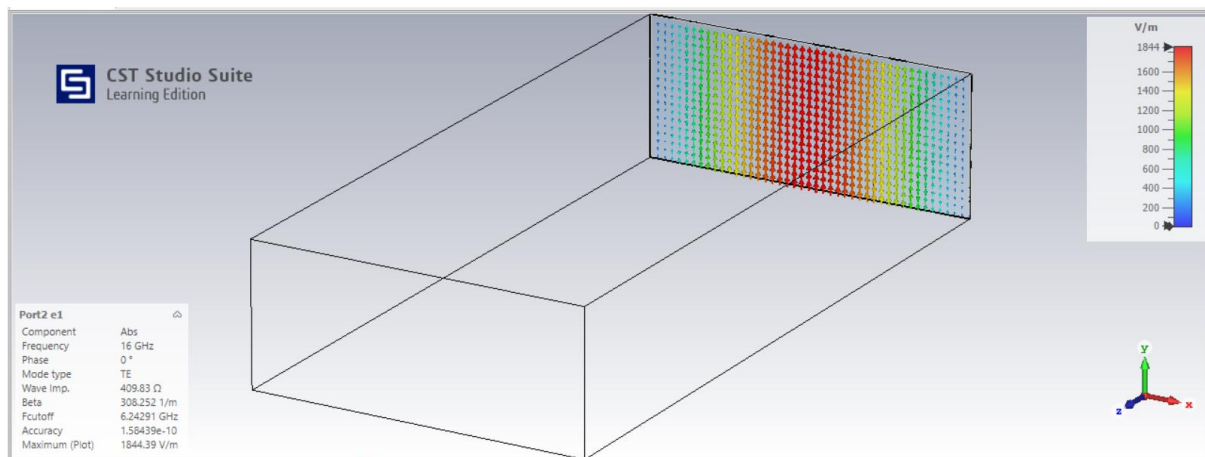


Figure 7: E-field magnitude distribution at Port 2 for the TE_{10} dominant mode (vacuum waveguide, 16 GHz). The single-lobe field pattern is identical in form to Port 1, confirming that the dominant mode

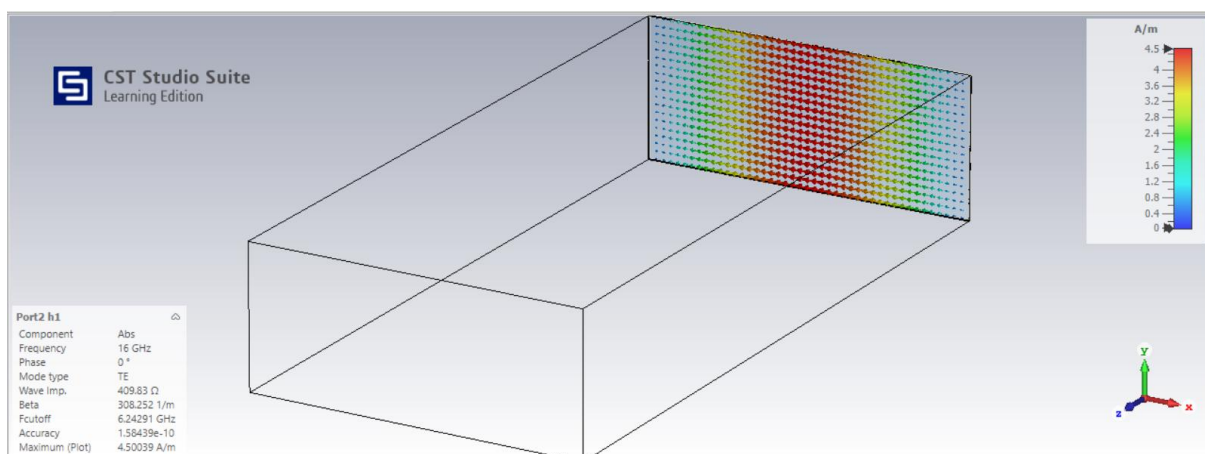


Figure 8: H-field magnitude distribution at Port 2 for the TE_{10} dominant mode (vacuum waveguide, 16 GHz).

Mode 2

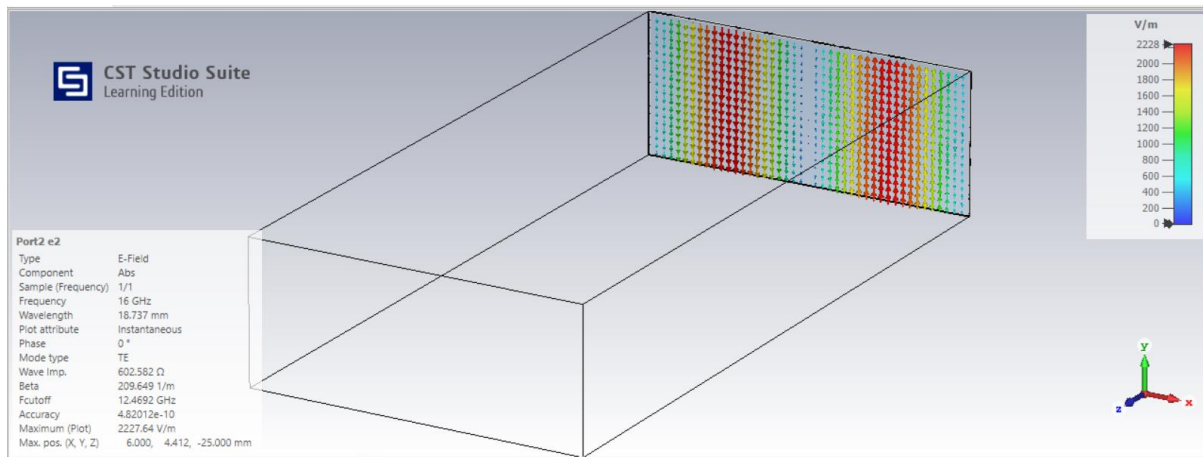


Figure 9: E-field magnitude distribution at Port 2 for the TE_{20} mode (vacuum waveguide, 16 GHz). The two-lobe pattern with a central null at $x = 12$ mm reproduces the Port 1 field,

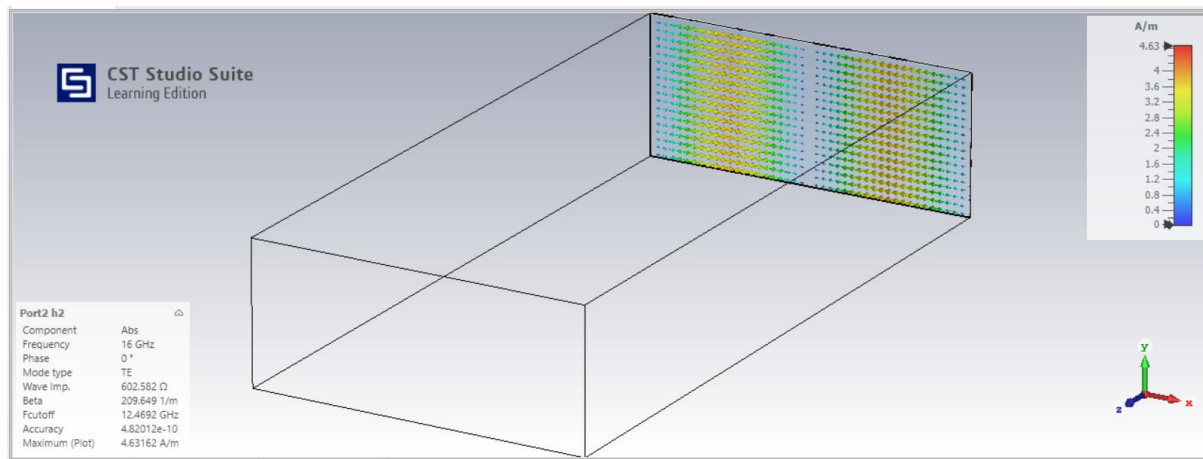


Figure 10: H-field magnitude distribution at Port 2 for the TE_{20} mode (vacuum waveguide, 16 GHz).

Mode 3

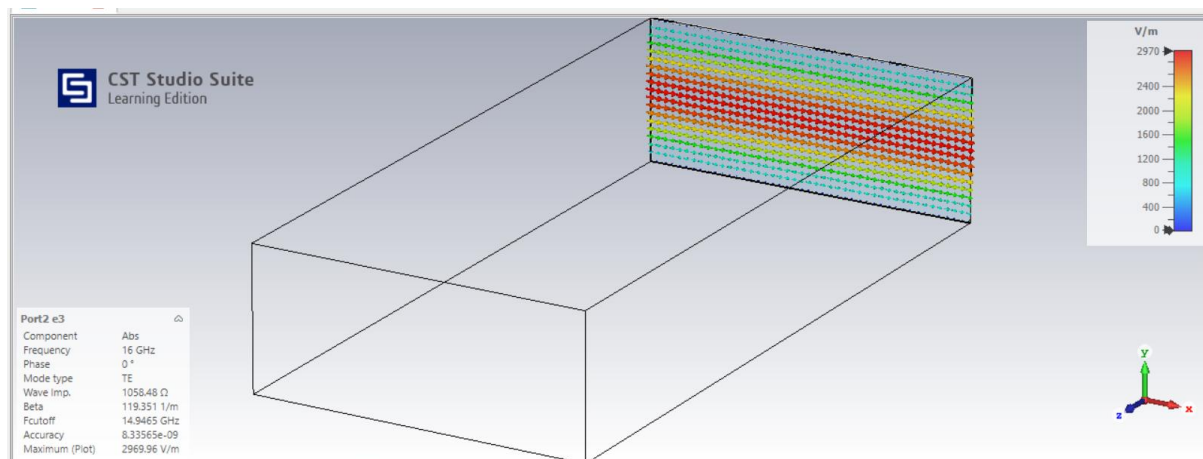


Figure 11: E-field magnitude distribution at Port 2 for the TE_{01} mode (vacuum waveguide, 16 GHz). Cutoff: 14.947 GHz.

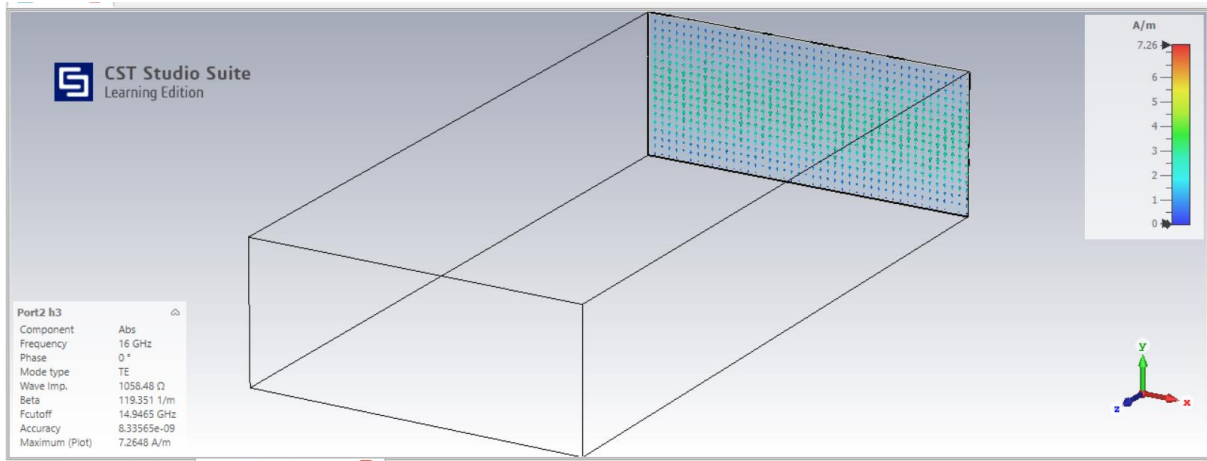


Figure 12: H-field magnitude distribution at Port 2 for the TE₀₁ mode (vacuum waveguide, 16 GHz).

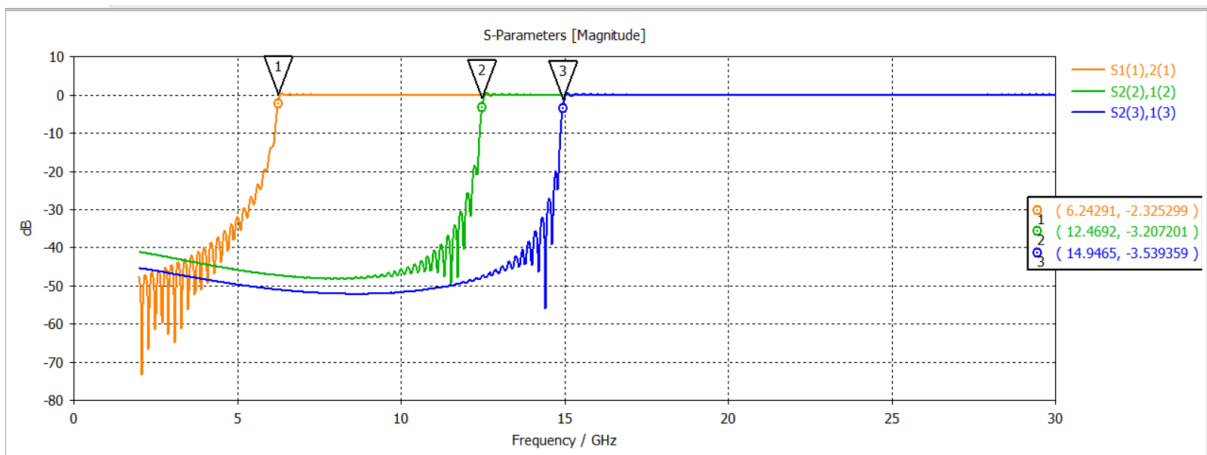


Figure 13: S-parameter magnitude plot (2–30 GHz) for the vacuum-filled PEC rectangular waveguide showing three propagating modes. Marker 1 at 6.243 GHz identifies the TE₁₀ cutoff (dominant mode); Marker 2 at 12.469 GHz identifies TE₂₀; Marker 3 at 14.947 GHz identifies TE₀₁. S₂₁ (transmission) rises sharply at each cutoff as the corresponding mode begins to carry power.

Cutoff Frequency Calculations

$$f_c = \frac{c}{2} \cdot \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \quad [11]$$

Where

- c - Speed of light (approximately 3×10^8 vacuum)
- a - Width of the waveguide
- b - Height of the waveguide
- m - Number of half-wavelength variations of the field along the a dimension
- n - Number of half-wavelength variations of the field along the b dimension
- f_c - The cutoff frequency

Mode 1

$$\frac{3 \cdot 10^8}{2} \cdot \sqrt{\left(\frac{1}{0.024}\right)^2 + \left(\frac{0}{0.010}\right)^2} = 6250000000 \text{ Hz} / 6.25 \text{ GHz}$$

Mode 2

$$\frac{3 \cdot 10^8}{2} \cdot \sqrt{\left(\frac{2}{0.024}\right)^2 + \left(\frac{0}{0.010}\right)^2} = 12500000000 \text{ Hz} / 12.5 \text{ GHz}$$

Mode 3

$$\frac{3 \cdot 10^8}{2} \cdot \sqrt{\left(\frac{0}{0.024}\right)^2 + \left(\frac{1}{0.010}\right)^2} = 15000000000 \text{ Hz} / 15 \text{ GHz}$$

There is slight variation between the calculated and simulated modes:

- For Mode 1 there is a difference of 0.11% , with the simulated cutoff frequency being 6.24291GHz.
- For Mode 2 there is a difference of 0.22%, with the simulated cutoff frequency being 12.4693GHz
- For Mode 3 there is a difference of 0.36%, with the simulated cut-off frequency being 14.9465Ghz

As show by the graph and calculations the dominant mode is Mode 1 due to it having the lowest cutoff frequency

Task 1b - PTFE Wave Guide

Port 1

Mode 1

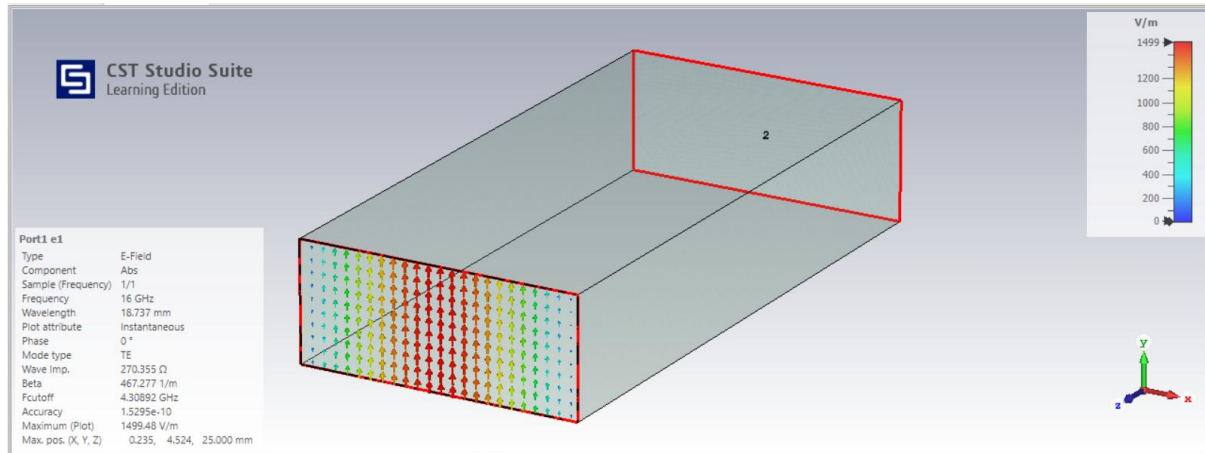


Figure 14: E-field magnitude distribution at Port 1 for the TE_{10} dominant mode of the PTFE-filled waveguide (16 GHz). The single half-wave lobe along $a = 24$ mm is retained; however, the cutoff frequency is reduced to 4.309 GHz (vs 6.243 GHz in vacuum) due to the lower phase velocity in PTFE ($\epsilon_r = 2.1$)

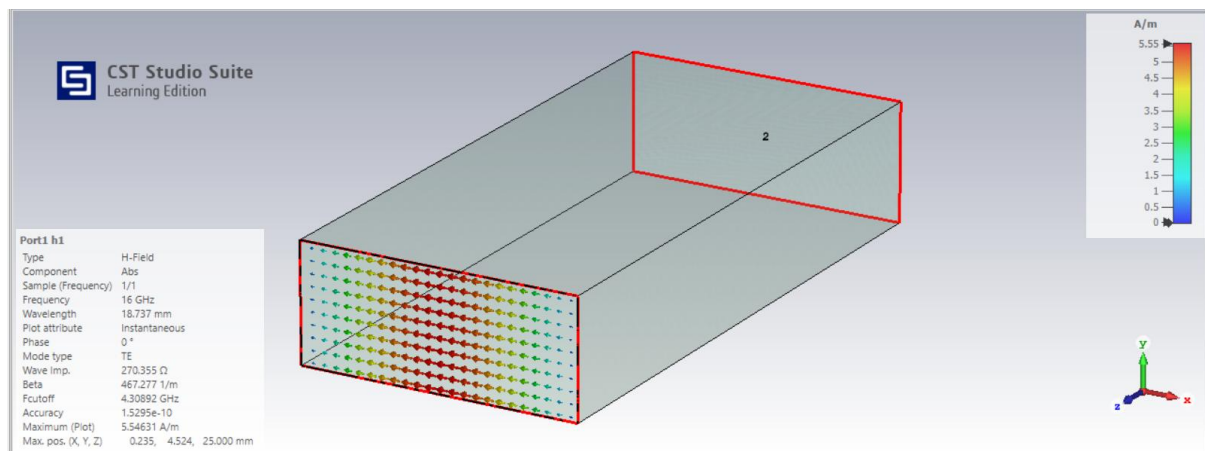


Figure 15: H-field magnitude distribution at Port 1 for the TE_{10} dominant mode of the PTFE-filled waveguide (16 GHz). The loop topology is identical to the vacuum case

Mode 2

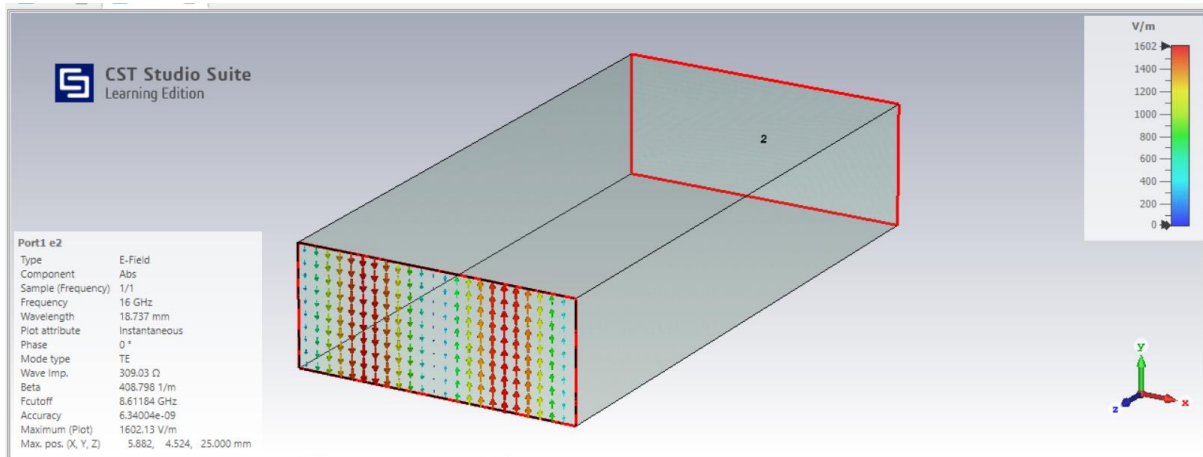


Figure 16: E-field magnitude distribution at Port 1 for the TE_{20} mode of the PTFE-filled waveguide (16 GHz). The two-lobe pattern with a central null at $x = 12$ mm is preserved from the vacuum case. Simulated cutoff frequency: 8.612 GHz

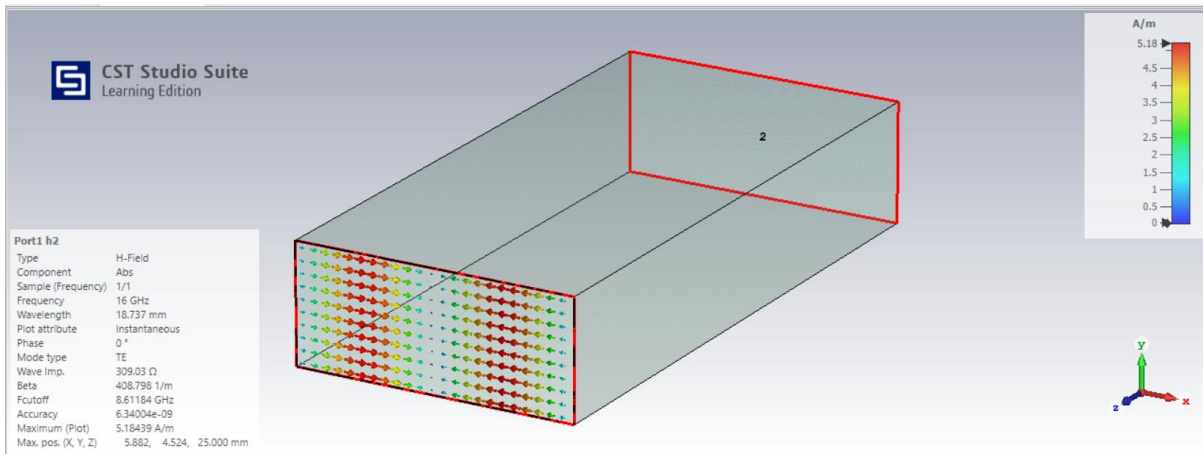


Figure 17: H-field magnitude distribution at Port 1 for the TE_{20} mode of the PTFE-filled waveguide (16 GHz).

Mode 3

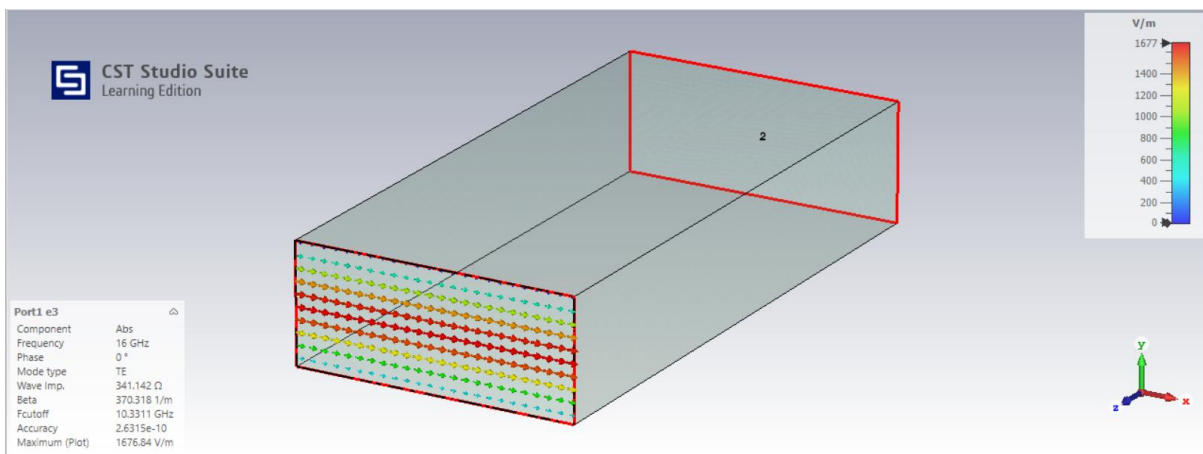


Figure 18: E-field magnitude distribution at Port 1 for the TE_{01} mode of the PTFE-filled waveguide (16 GHz). The single height-direction lobe is retained. Simulated cutoff: 10.331 GHz

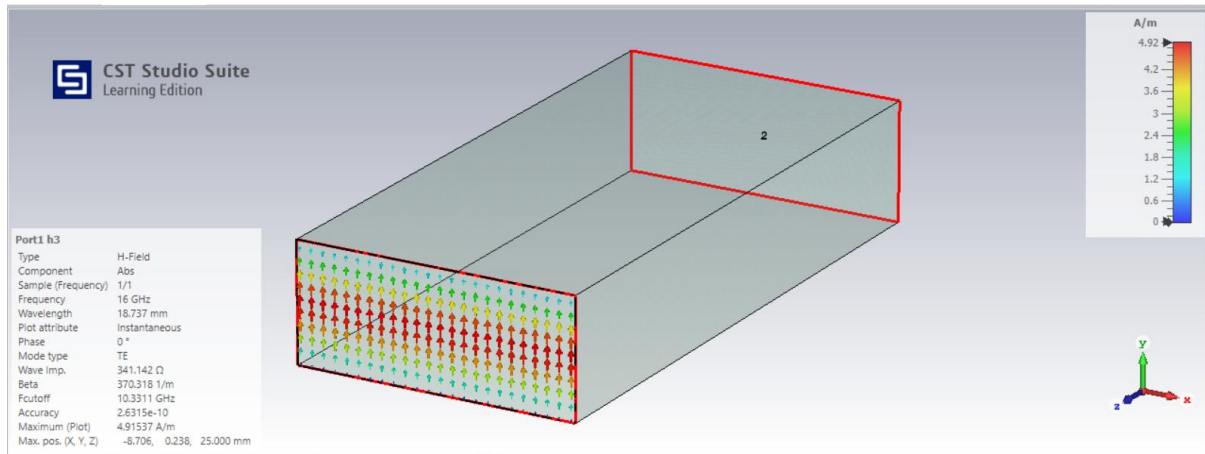


Figure 19: H-field magnitude distribution at Port 1 for the TE_{01} mode of the PTFE-filled waveguide (16 GHz). Maximum H-field at the top and bottom walls is consistent with TE_{01} theory

Port 2

Mode 1

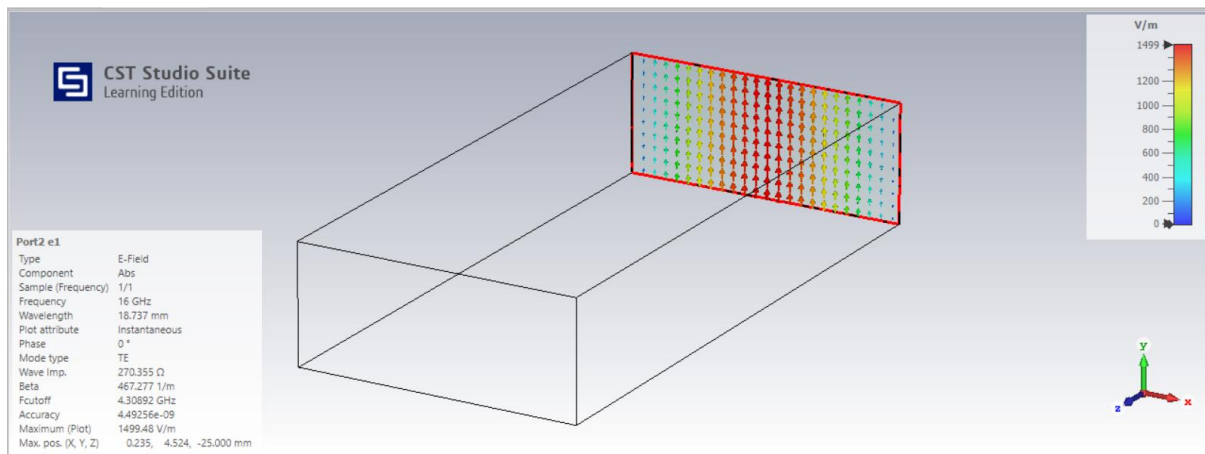


Figure 20: E-field magnitude distribution at Port 2 for the TE_{10} dominant mode of the PTFE-filled waveguide

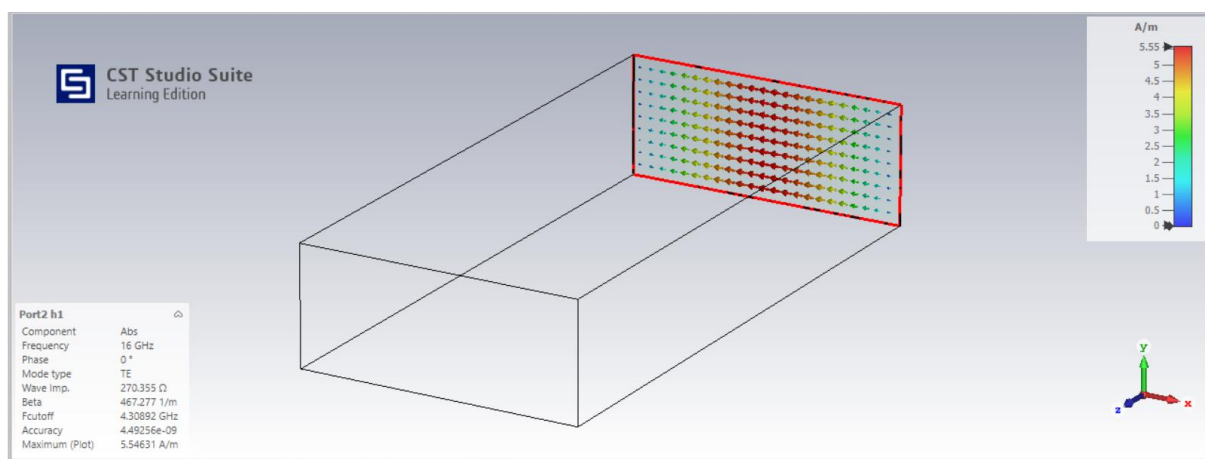


Figure 21: H-field magnitude distribution at Port 2 for the TE_{10} dominant mode of the PTFE-filled waveguide (16 GHz). Output H-field pattern matches Port 1

Mode 2

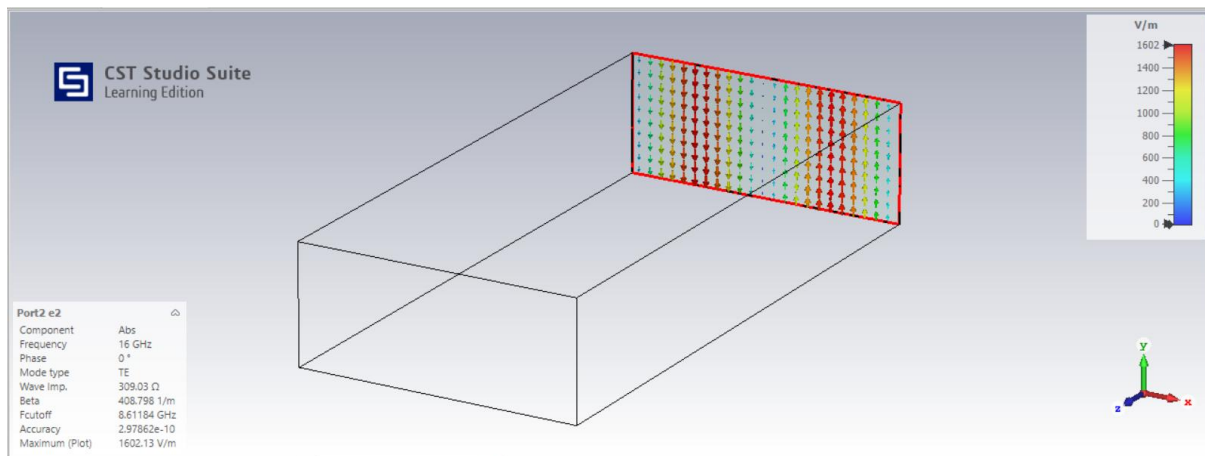


Figure 22: E-field magnitude distribution at Port 2 for the TE_{20} mode of the PTFE-filled waveguide (16 GHz).

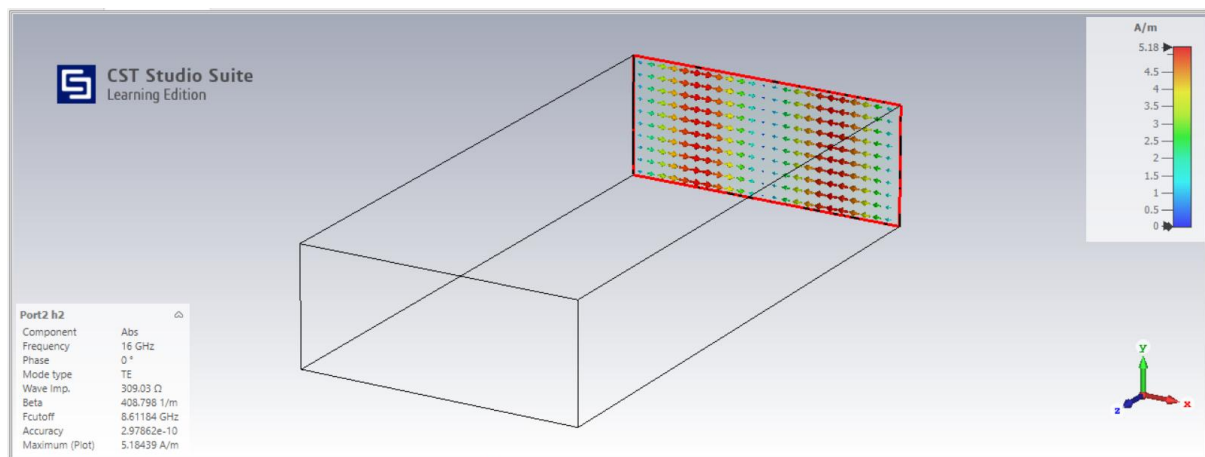


Figure 23: H-field magnitude distribution at Port 2 for the TE_{20} mode of the PTFE-filled waveguide (16 GHz)

Mode 3

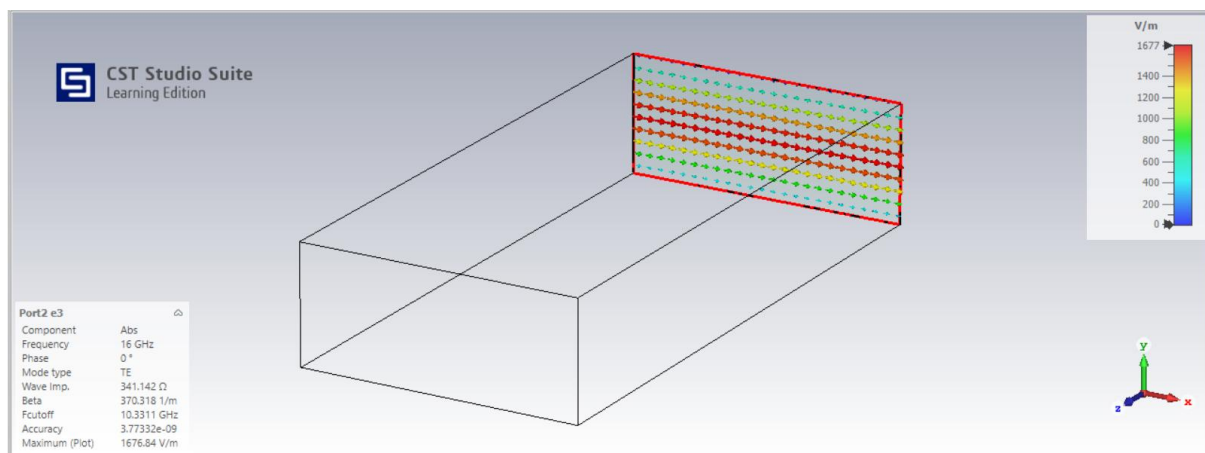


Figure 24: E-field magnitude distribution at Port 2 for the TE_{01} mode of the PTFE-filled waveguide (16 GHz).

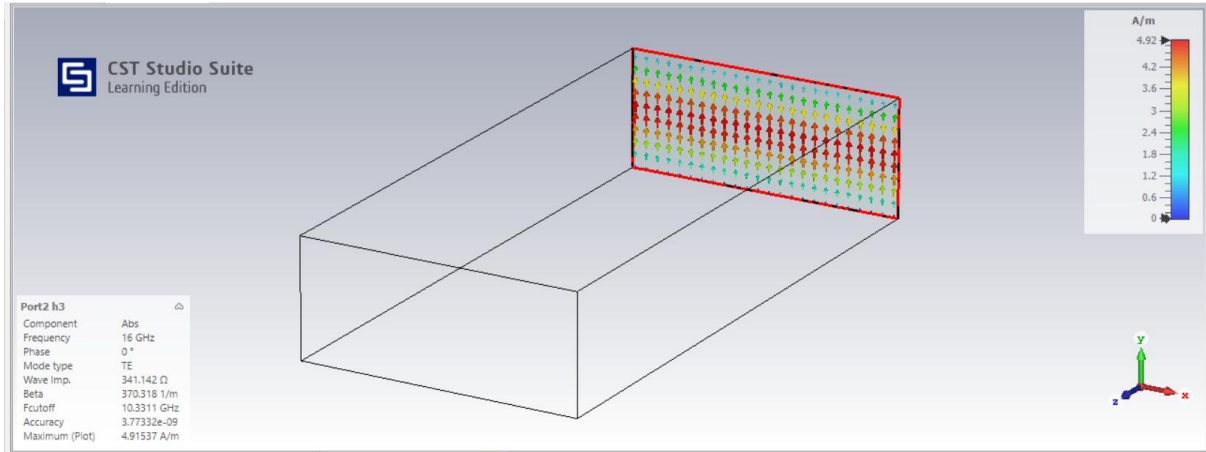


Figure 25: H-field magnitude distribution at Port 2 for the TE₀₁ mode of the PTFE-filled waveguide (16 GHz).

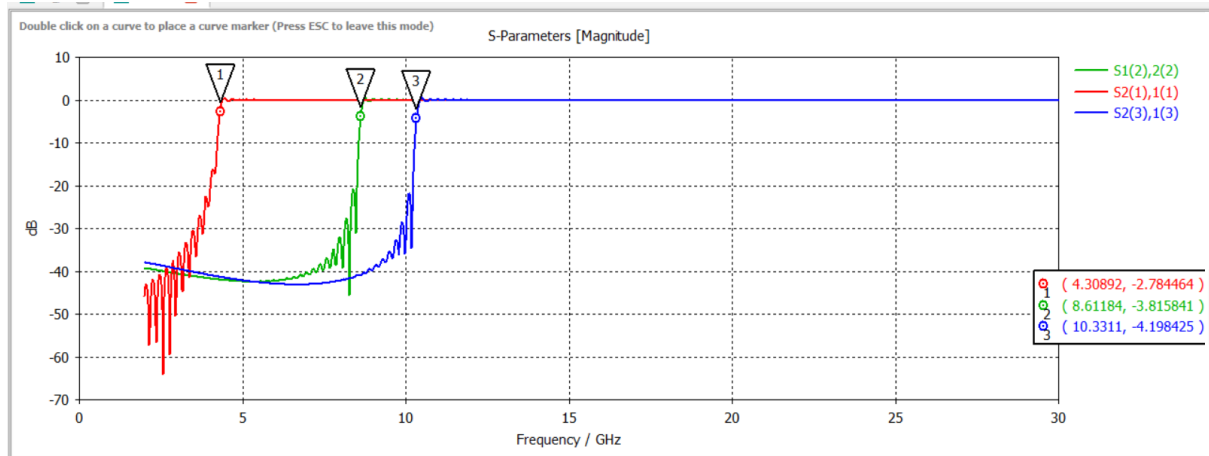


Figure 13: S-parameter magnitude plot (2–30 GHz) for the vacuum-filled PEC rectangular waveguide showing three propagating modes. Marker 1 at 4.309 GHz identifies the TE₁₀ cutoff (dominant mode); Marker 2 at 8.612GHz identifies TE₂₀; Marker 3 at 10.331 GHz identifies TE₀₁. S₂₁ (transmission) rises sharply at each cutoff as the corresponding mode begins to carry power.

Cutoff Frequency Calculations

When calculating cut-off frequency for a dielectric filled waveguide a different formula is used:

Where v is:

$$v = \frac{1}{\sqrt{\epsilon\mu}} \quad [11]$$

Where:

- v – Phase velocity
- ε – Permittivity of the medium
- μ – Permeability of the medium

Therefore:

$$v = \frac{c}{\sqrt{2.1 \cdot 1}} = 207019667.8027 \text{ m/s}$$

Mode 1

$$\frac{207019667.8027}{2} \cdot \sqrt{\left(\frac{1}{0.024}\right)^2 + \left(\frac{0}{0.010}\right)^2} = 312909745.89 \text{ Hz} / 4.3 \text{ GHz}$$

Mode 2

$$\frac{207019667.8027}{2} \cdot \sqrt{\left(\frac{2}{0.024}\right)^2 + \left(\frac{0}{0.010}\right)^2} = 862581949.779167 / 8.63 \text{ GHz}$$

Mode 3

$$\frac{207019667.8027}{2} \cdot \sqrt{\left(\frac{0}{0.024}\right)^2 + \left(\frac{1}{0.010}\right)^2} = 10.350983390.135 \text{ Hz} / 10.35 \text{ GHz}$$

Again there is slight variation between the calculated and simulated modes:

- For Mode 1 there is a difference of 0.093% , with the simulated cutoff frequency being 4.30892 GHz.
- For Mode 2 there is a difference of 0.16%, with the simulated cutoff frequency being 8.61184 GHz
- For Mode 3 there is a difference of 0.19%, with the simulated cut-off frequency being 10.3311 GHz

As show by the graph and calculations the dominant mode is Mode 1 due to it having the lowest cutoff frequency of 4.3GHz

Task 1 Analysis

In the vacuum-filled (PEC) waveguide, electromagnetic waves propagate at the speed of light in free space. The cutoff frequency of any mode is controlled by this velocity and the physical dimensions of the waveguide. When the interior is filled with Teflon (PTFE, $\epsilon_r = 2.1$, $\mu_r = 1$), the wave's velocity is reduced. Because cutoff frequency is directly proportional to wave velocity every mode's cutoff frequency is scaled down by the same factor of 0.690. This is why all three modes shift: TE_{10} drops from 6.25 GHz to 4.31 GHz, TE_{20} from 12.5 GHz to 8.63 GHz, and TE_{01} from 15.0 GHz to 10.35 GHz. This is because the dielectric slows the wave effectively increasing the electrical path length of the wave without changing the waveguides dimensions. This results in the Teflon-filled waveguide acting like a physically larger waveguide. This shows the clear practical applications of using Teflon over a vacuum filled waveguide. However, as the dielectric material will inherently take energy passing through it and expend it as heat there are implications for when one is designing waveguides that operate at very high power or very high frequency, in that signal loss or disruption may become an issue

Safety Standards for RF Energy

RF exposure safety is governed by a layered framework of international recommendations, regional regulations, and sector-specific standards.

Key RF Exposure Quantities

- **Specific Absorption Rate** — Measures how much RF energy the body absorbs (W/kg). Used mainly **below ~6 GHz**, where energy penetrates deeper and heating of internal tissue is the main concern.
- **Power Density** — Measures RF power incident on a surface (W/m²). Used **above 6 GHz**, where energy is absorbed mostly at the skin surface.
- **Maximum Permissible Exposure** — Defines safe exposure limits using SAR, electric/magnetic field strength, or power density depending on frequency.

According to the ICNIRP 2020 guidelines, exposure above 6 GHz is averaged over a 6-minute period and over a defined skin surface area of 4 cm². The allowable exposure level is frequency dependent rather than a single constant value. [12]

ICNIRP distinguishes between occupational exposure and general public exposure. Occupational limits apply to trained individuals working under controlled conditions who are aware of potential RF exposure and can take appropriate precautions. General public limits include larger safety margins to account for individuals of varying ages, health conditions, and levels of awareness. As summarized in the GSMA guidance document, occupational

reference levels are commonly several times higher than the corresponding general public limits [12].

How to Ensure RF Safety Compliance

Because a waveguide is a fully enclosed metal tube, virtually all RF energy is confined within it. Below the cutoff frequency of the lowest-order mode, fields decay exponentially evanescent attenuation [3], providing natural suppression of leakage. This is fundamentally different from open transmission lines or antennas, which radiate by design. This, however, does not mean that waveguides are safe from leakage; as such waveguides have many rules to be compliant with standards.

The primary leakage path in any waveguide system is at mating flanges [13]. Standard choke flanges (IEC 60154) use a quarter-wave cavity around the joint that presents a very high impedance to the waveguide wall current, minimising leakage even when a small physical gap exists. Regular torque verification and gasket inspection are required under maintenance programmes to sustain compliance [14]. The MPE distance or the range at which power density drops below the limit defines a physical exclusion zone enforced by interlocks, barriers, and warning signage — all required under UK/EU Directive 2013/35/EU for workplace RF safety.

Any waveguide port not connected to an active component must be terminated in a matched load. Waveguide terminations use wedge-shaped microwave absorber (carbon-loaded ceramic or foam) inside a metal housing, converting RF power to heat safely. This prevents reflected power from reaching personnel or sensitive components [15].

Task 2 – Dipole Antenna

The second task involved creating a half-wave dipole antenna with a radius of 1mm to operate at a wavelength of 242mm. The full values of the antenna were calculated as follows:

$$f = \frac{c}{\lambda} \text{ [16]}$$

$$f = \frac{3 \times 10^8}{0.242}$$

$$f = 1238812000 \text{ Hz}$$

$$f = 1.2388 \text{ GHz}$$

Where:

- f – Frequency
- c – The speed of light
- λ – Wavelength (in metres)

$$L = \frac{\lambda}{2} \quad [16]$$

$$L = \frac{0.242}{2}$$

$$L = 0.121$$

Where :

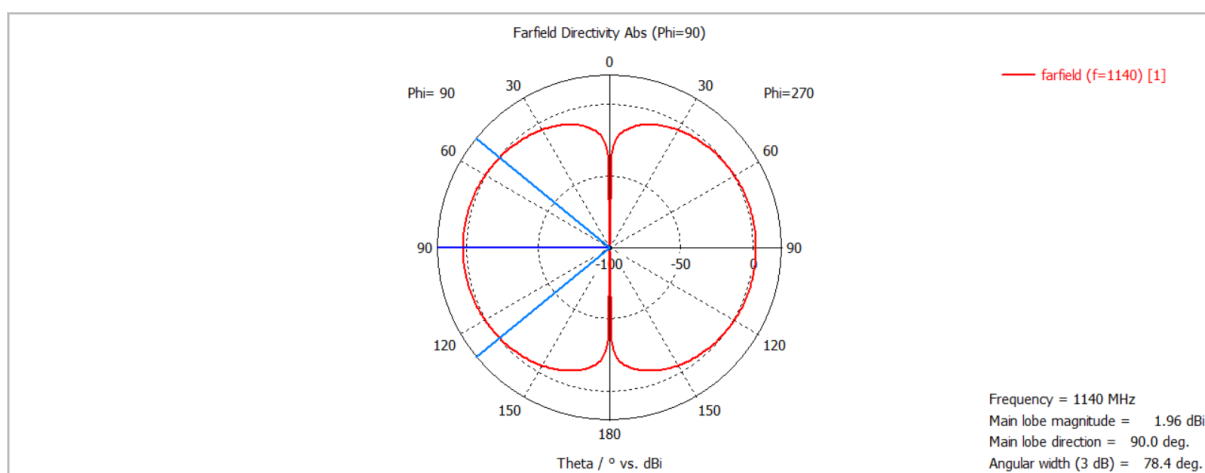
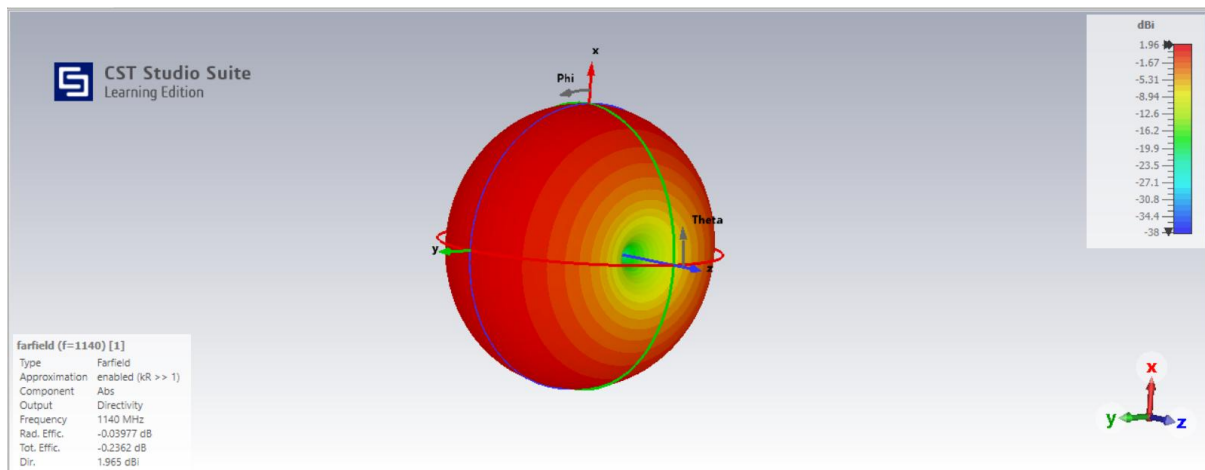
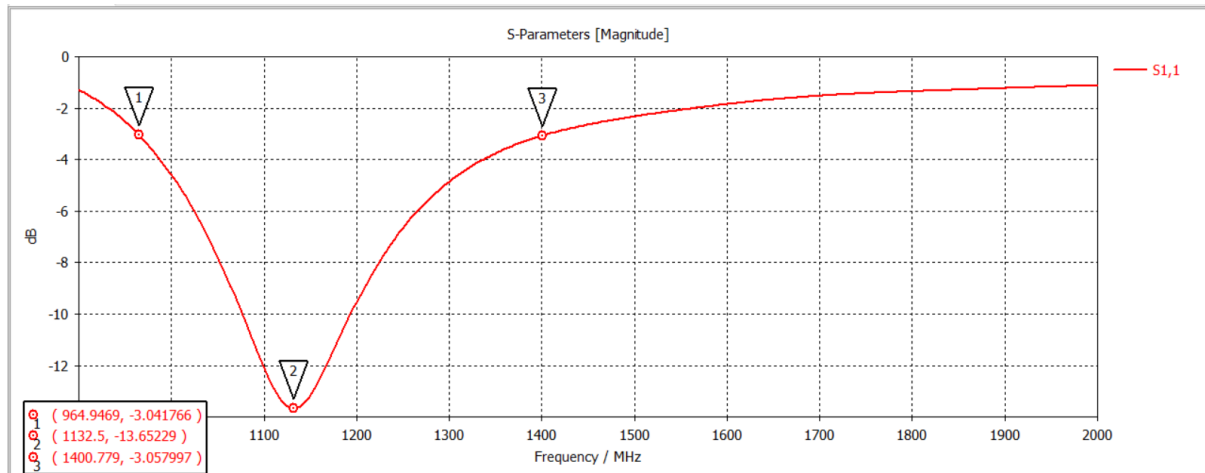
- L – Length of a pole in the dipole (in metres)
- λ – Wavelength (in metres)

Antenna Design

The antenna was created in CST Studio Suite with the specifications outlined above. First a cylinder with a length of 243mm and a radius of 1mm was created, this was made slightly larger to accommodate the lumped port that would be required in between the two poles. Using a Boolean subtraction operation found in the software another cylinder with a radius of 1mm and a length of 1mm was removed from the centre of the first cylinder. This created two equal, equidistant poles for the lumped port to be placed between. Once this had been placed, its port set and the impedance set to 50Ω a vacuum was created with the size of full wavelength on the XY axis and two full wavelength on the Z axis.

Simulation Results

The dipole was simulated, a gain plot and S11 graph shows the dipoles performance.



Simulation Analysis

Above are the outputs of the dipole antenna simulation. The half-wave dipole was designed to operate at a wavelength of 242mm, this wavelength has the theoretical resonant frequency of 1.2388GHz. The simulation results show the antennas attenuation at 1.1325GHz this slight variation. This discrepancy is most likely due to difference in theory and practicality, in theory the antenna is infinitely thin and the gap between the poles and the lump port is theoretically zero. This can be achieved in simulation however provides no real use as this cannot be repeated in the real-world defeating the point of the simulation.

The radiation pattern produced exhibits the characteristic shape of a half-wave dipole with a maximum gain of 1.96 dBi.

Task 3

Unmanned aerial vehicles (UAVs) are becoming more and more prevalent in across all sectors both private and public. Drones used for personal videography can easily be misused by bad actors for surveillance, espionage and even terror attacks. This raises significant security and engineering challenges and advance long range detection and identification measures are more important than ever to protect the public [19].

The most common forms of drone and UAV detection methods are: RF, RADAR, Electro-Optical/Infrared and Acoustic [17], [18].

Radio Frequency: Relies on the principle that drone and pilot operate through a WiFi or GSM link. These specific electromagnetic signals can be detected however the main drawback of this method that it cannot direction-find a UAV quickly, further, signal interference can greatly diminish its effectiveness in real-world scenarios [17].

RADAR: The leading detection method for both locating and tracking UAV's using reflecting signals to detect a drone location and speed. RADAR faces similar challenges to RF detection as interference from other signals and environmental clutter can reduce accuracy. Positioning the RADAR system at a high elevation can reduce the total clutter by still will suffer problems form signal interference or possible jamming [9],[17].

Electro-Optical/Infrared: These systems rely on camera based computer vision to detect drones in the air. Integrated with AI these systems can differentiate between birds and drones alike in the sky where a human may be unable to make an accurate identification. The problem with these systems are obvious being that they can only detect in the area which the camera is pointing. And, whilst the systems are able to differentiate between what is and what isn't a drone, false positives and negatives do occur especially the UAV has not been included in the training data set [17], [19].

Acoustic: Acoustic detection utilises the unique sound that a drone makes when in the air. Popular methods use a microphone array to exploit the change in phase of a waveform due to the Doppler Shift effect and the direction of arrival estimation to give a estimate of the target [19].

Whilst these methods can all detect UAVs a holistic approach combining methods generally give the most accurate outcomes across scenarios [17], [19].

Societal and Ethical Implications

The transition drones and UAVs have had over the years from solely military to civilian applications and tools present large scale implications for public safety, privacy, and regulations [20]. Drone detection systems rely on technologies like acoustic sensors, optical cameras and RF scanners to identify and target UAVs, and whilst they are designed to identify drones, they are also more than capable to monitor and collect information about the public's private life. Mass aerial and RF monitoring can create tension between the public's right to a private life and the state's responsibility to protect people and businesses. A roll out on mass without complete transparency could cause less freedom to protest and live a public life. This felt risk of government overreach could effect a government's ability to roll out systems that would have a genuine, positive, effect on public safety. As seen in 2018 drone operators were able to shut down Gatwick Airport for an extended period of time causing the airport's largest disruption since the 2010 volcano eruption in Iceland [21]. Drone identification systems therefore have a role in public safety and cannot be simply ignored, regulation and transparency is a must when deploying these very much needed systems.

Environmental Implications

As stated before drone detection systems make use of the electromagnetic spectrum and as such may interfere with Wi-Fi signals, emergency communications, consumer electronics and wildlife. High power radar installations used to detect and jam frequencies may also inadvertently jam or disrupt critical infrastructure. Another impact of placing high power RF towers across a country is its effect on wildlife. A study of house sparrows in Spain found a negative correlation between increased field strength (1MHz to 3GHz) and sparrow population densities [22]. Evidence also points to EMF effecting the abundance and diversity of pollinators, however due to already declining populations this causation cannot yet be established [23].

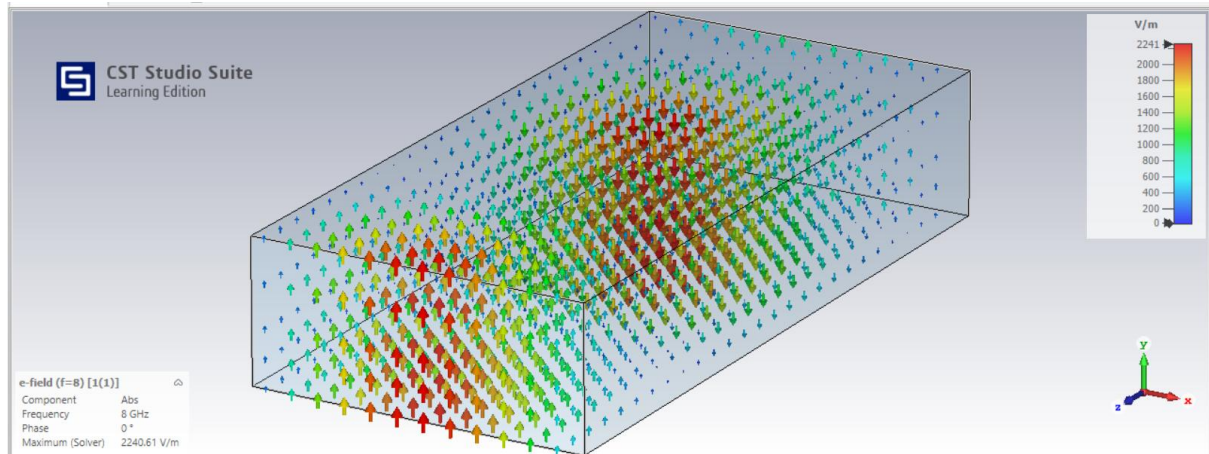
Appendix

PEC Waveguide Magnitudes and Vectors

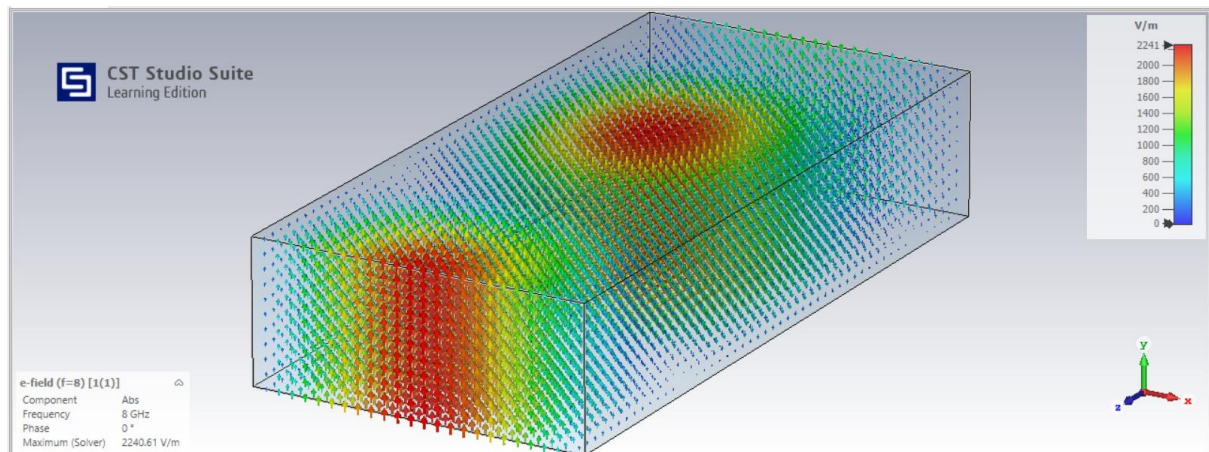
Port 1 Mode 1

E-Field

Vector

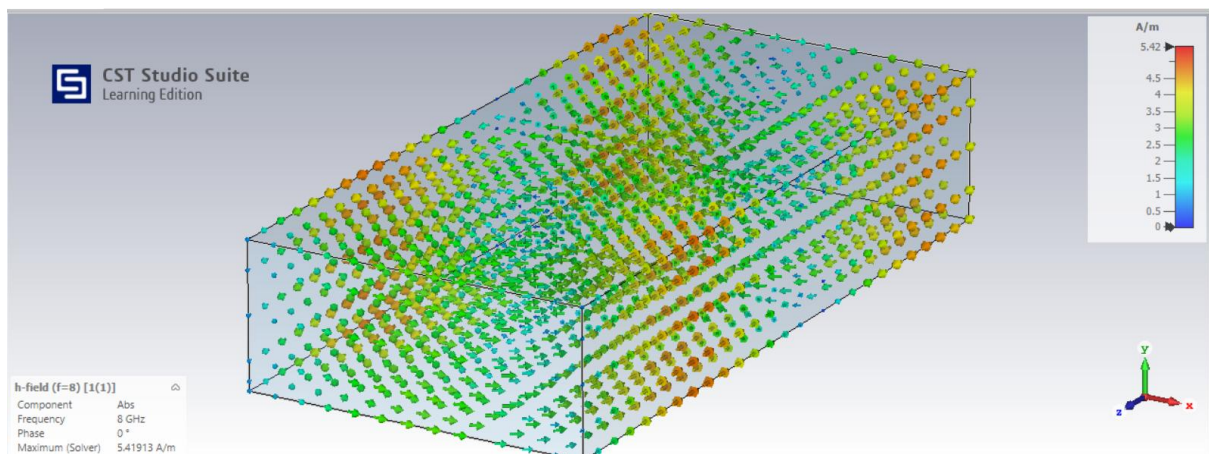


Magnitude

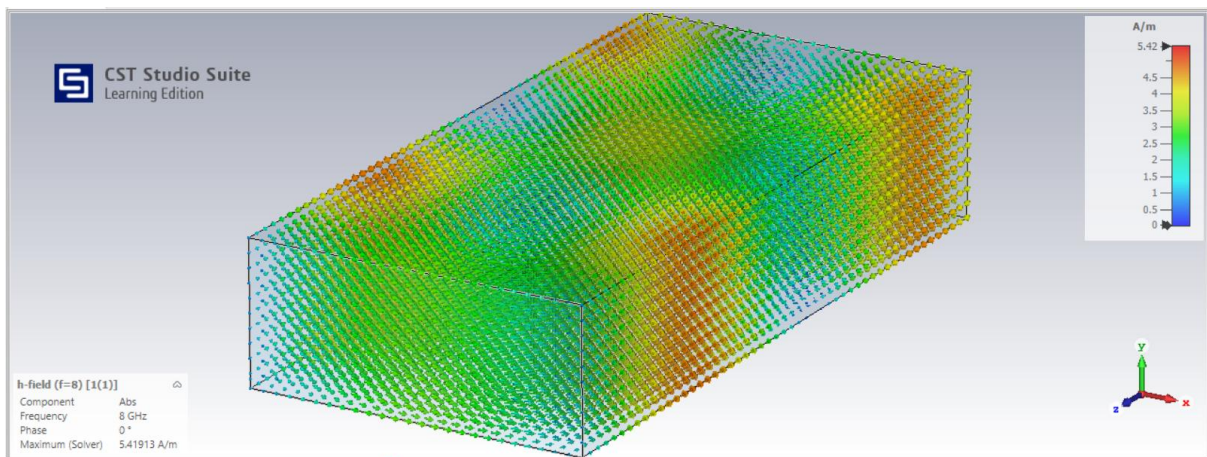


H-Field

Vector



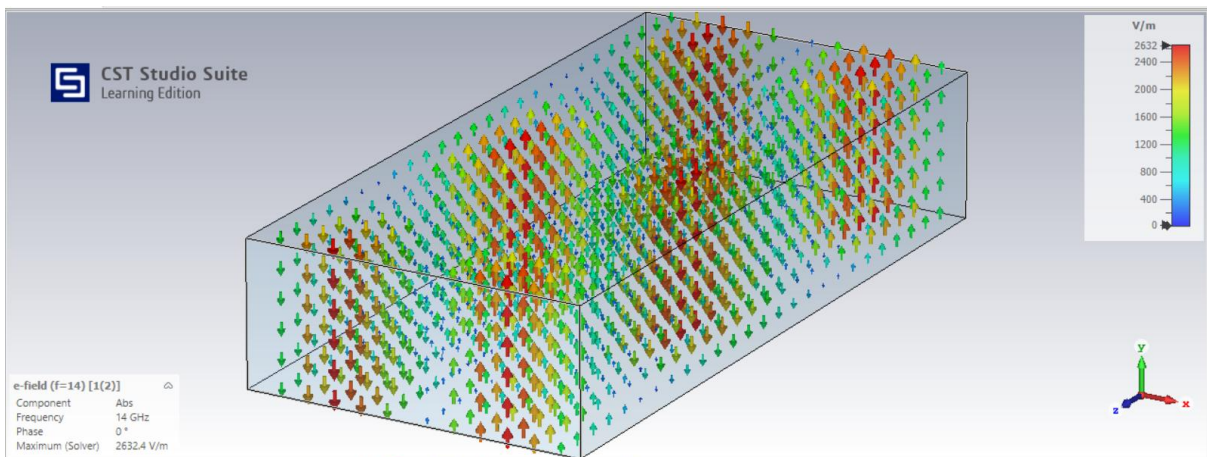
Magnitude



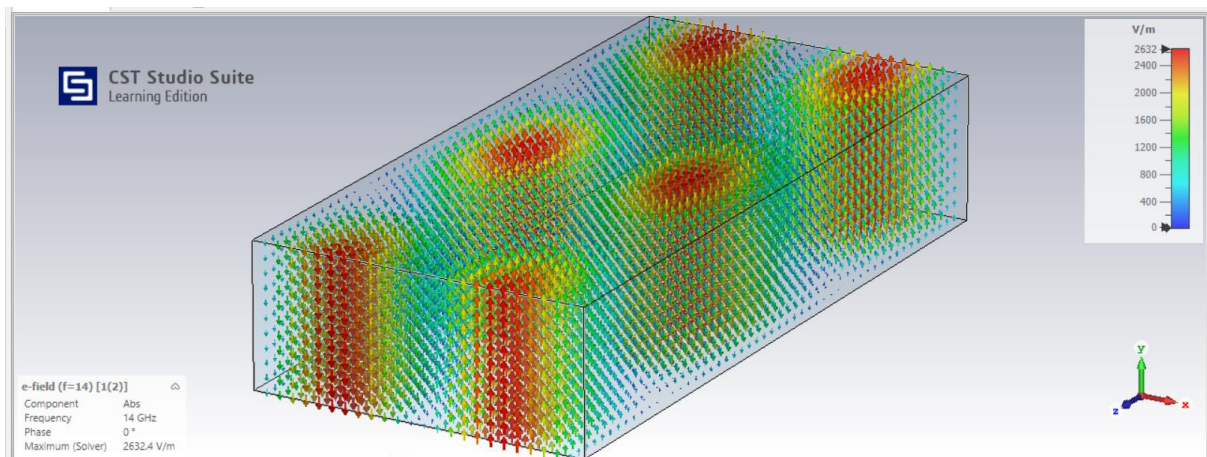
Port 1 Mode 2

E-Field

Vector

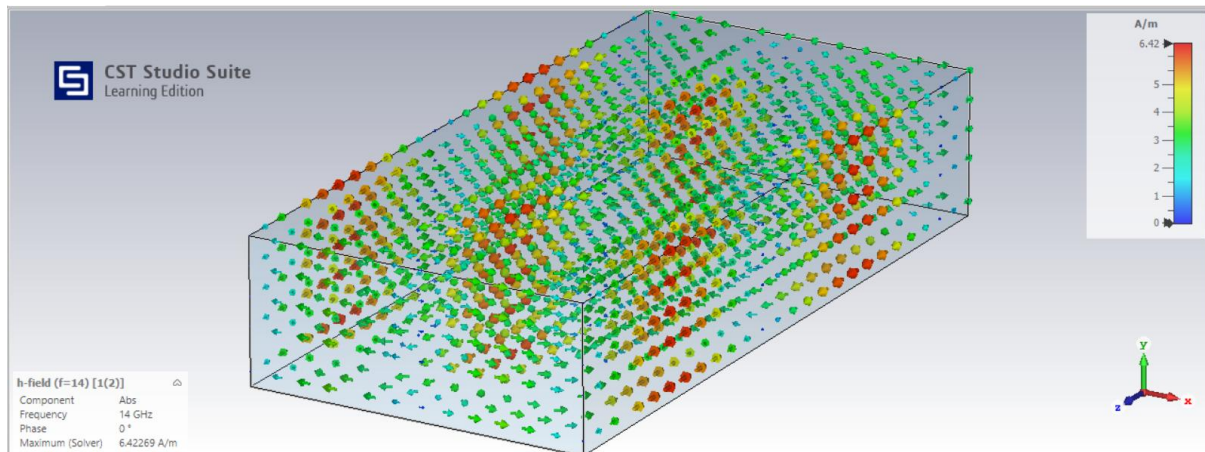


Magnitude

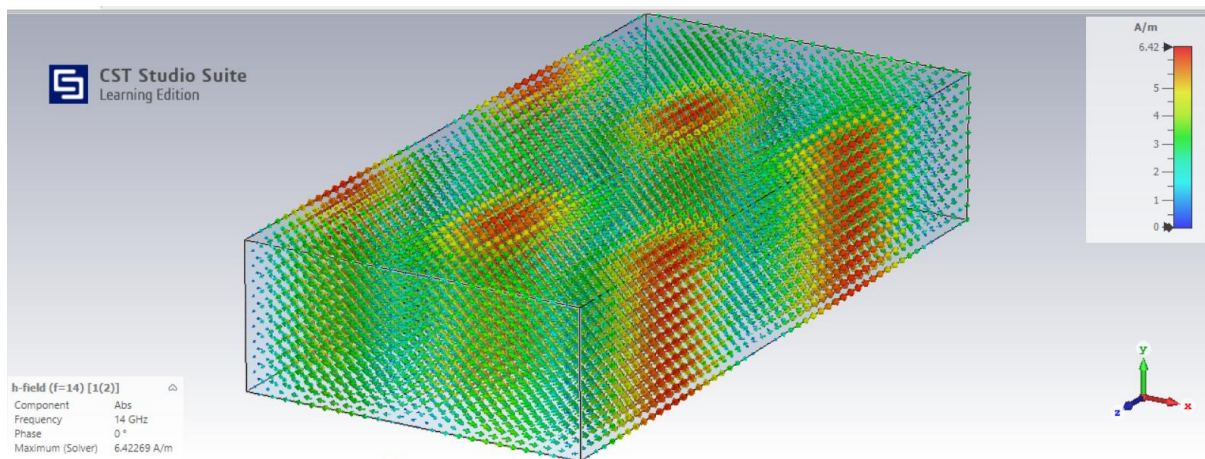


H-Field

Vector



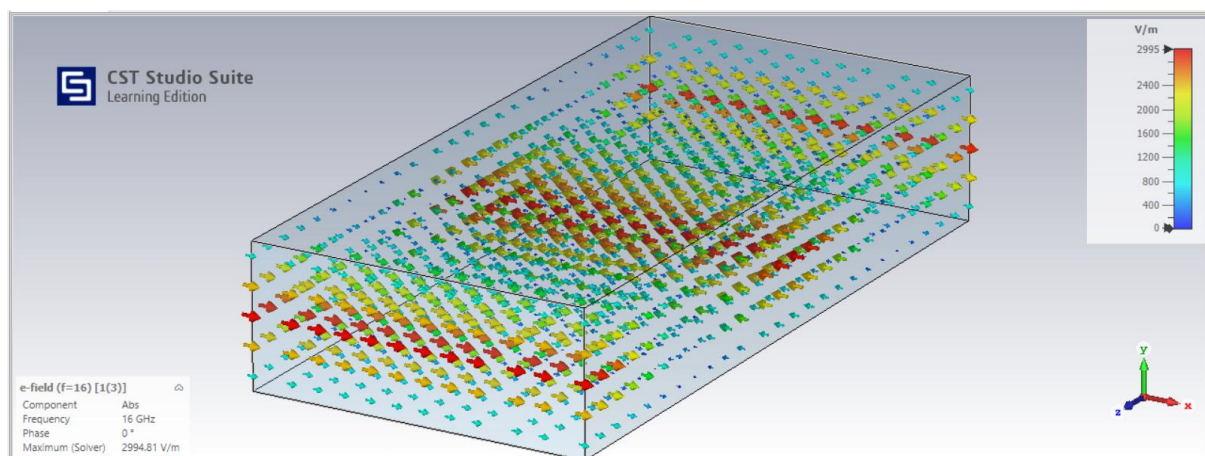
Magnitude



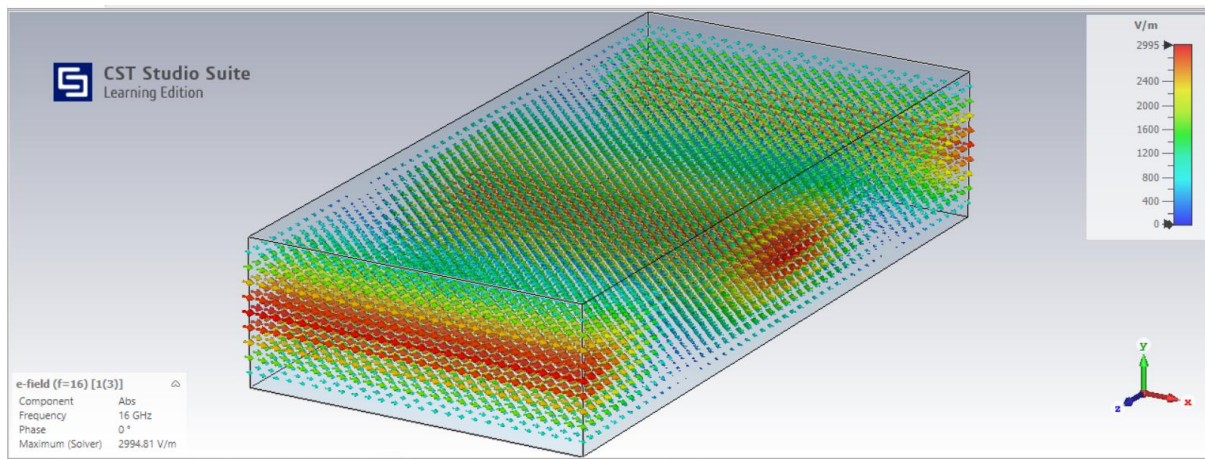
Port 1 Mode 3

E-Field

Vector

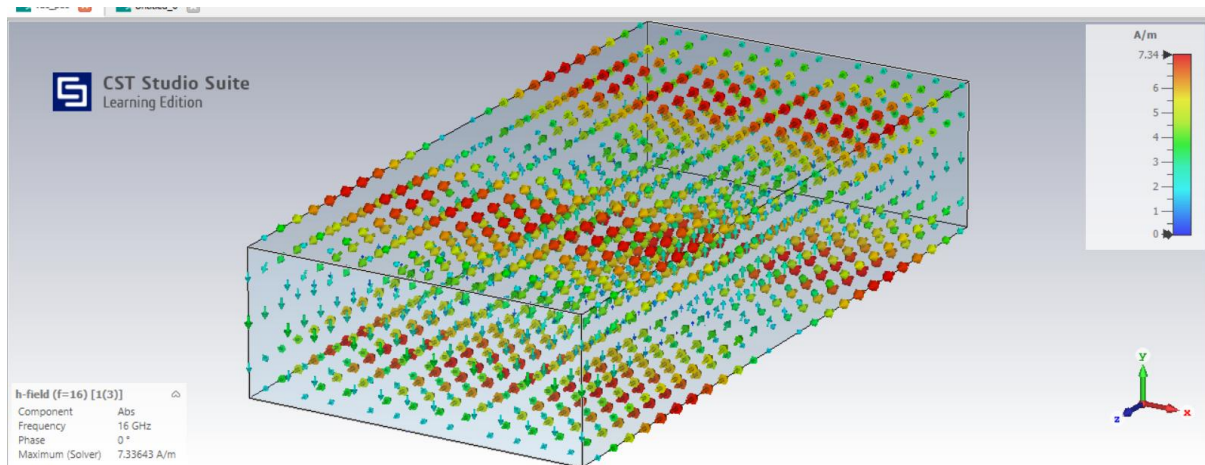


Magnitude

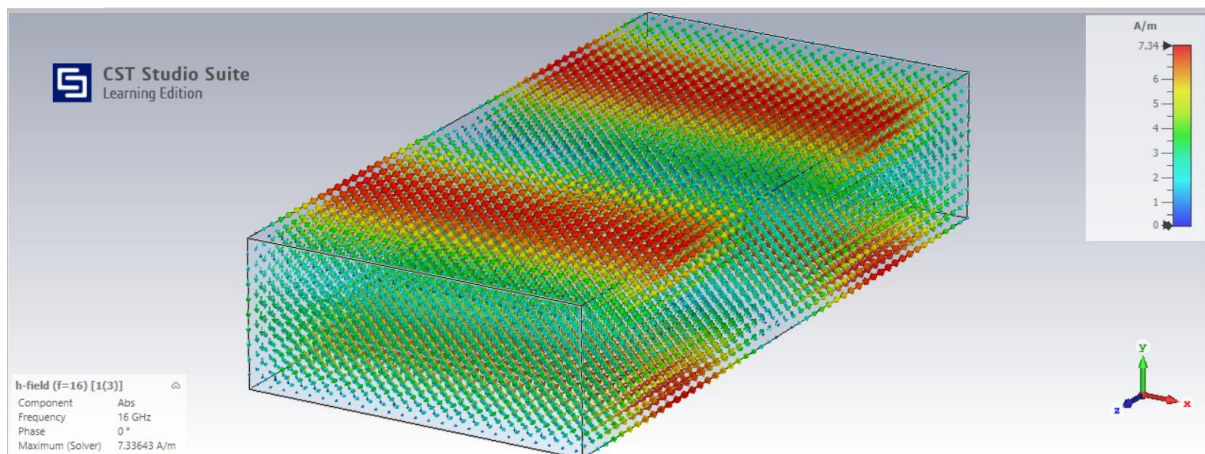


H-Field

Vector



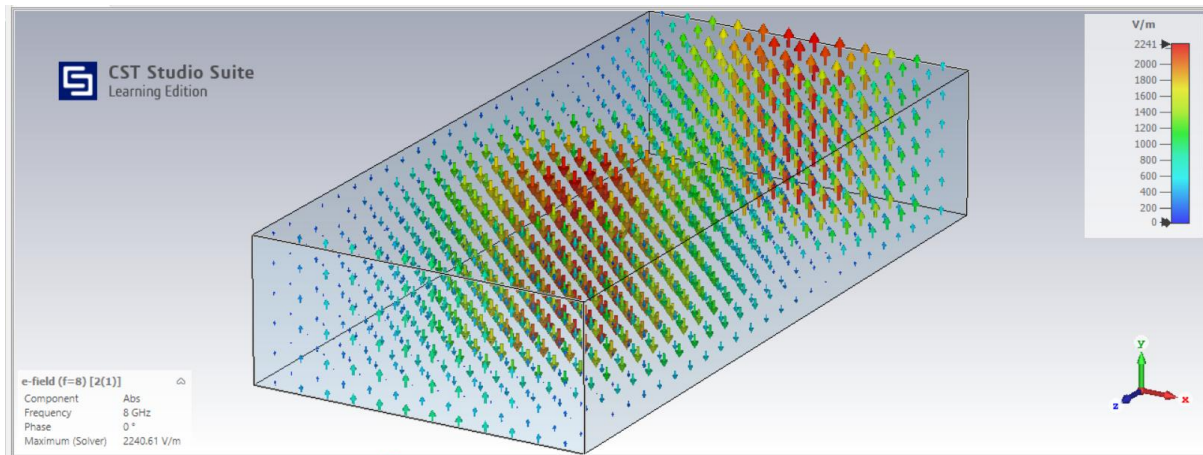
Magnitude



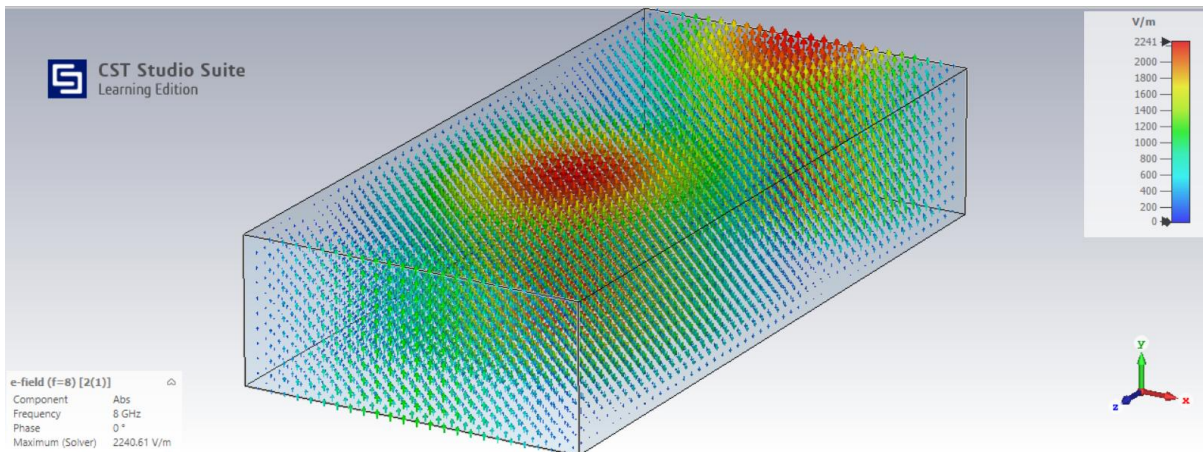
Port 2 Mode 1

E-Field

Vector

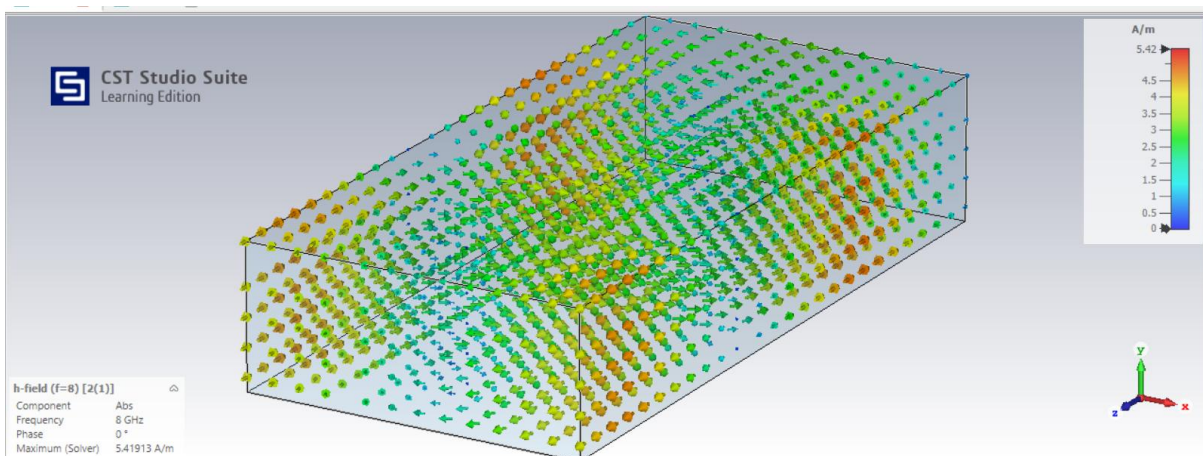


Magnitude

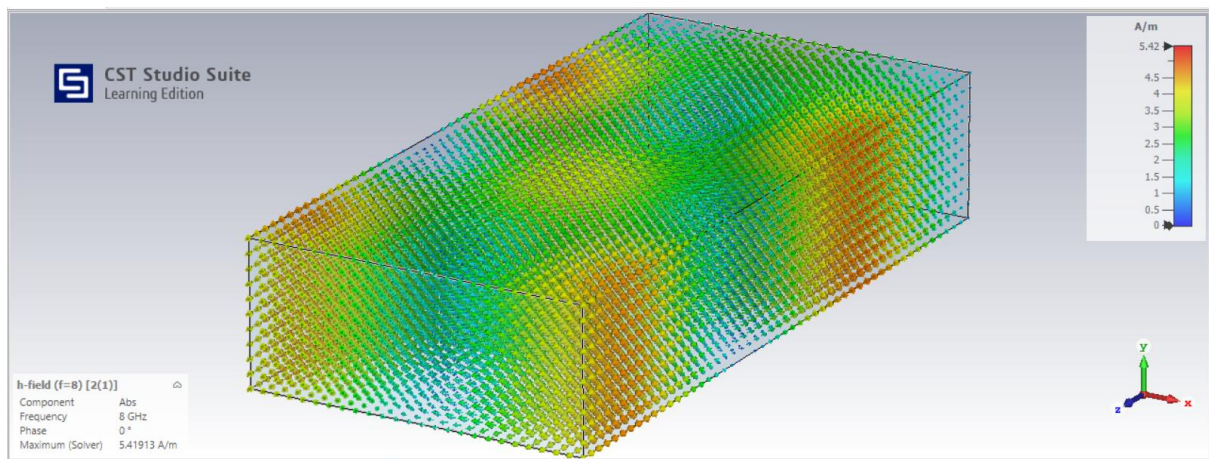


H-Field

Vector



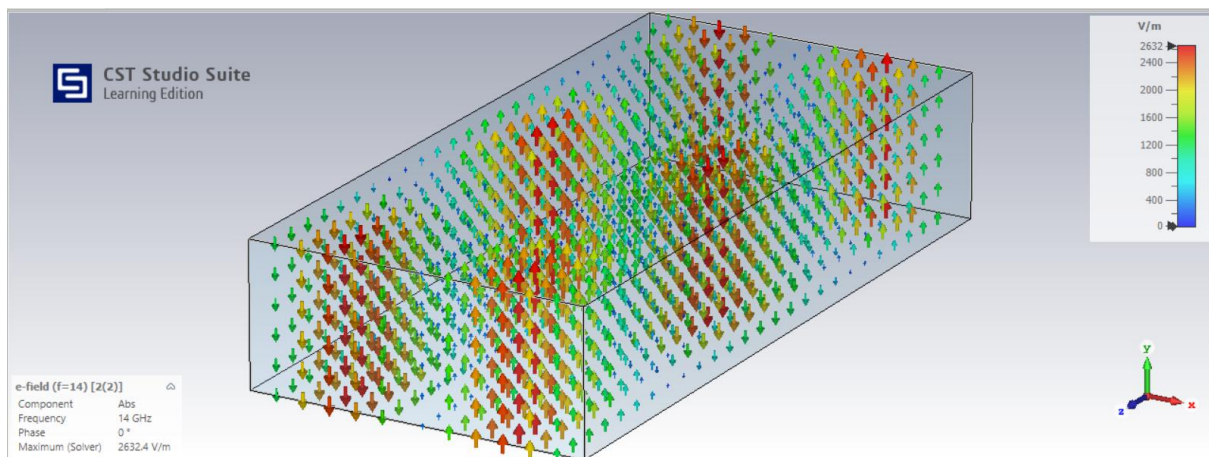
Magnitude



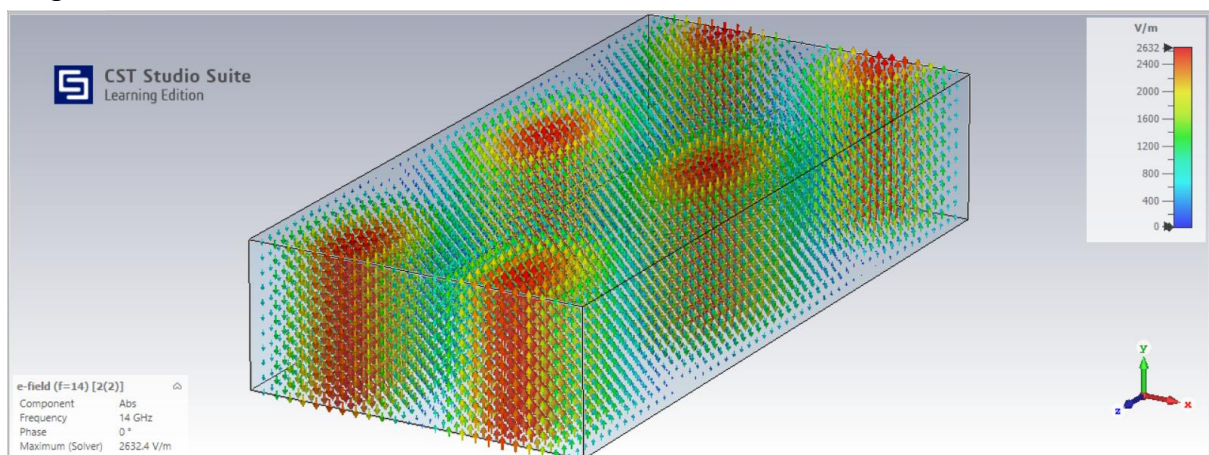
Port 2 Mode 2

E-Field

Vector

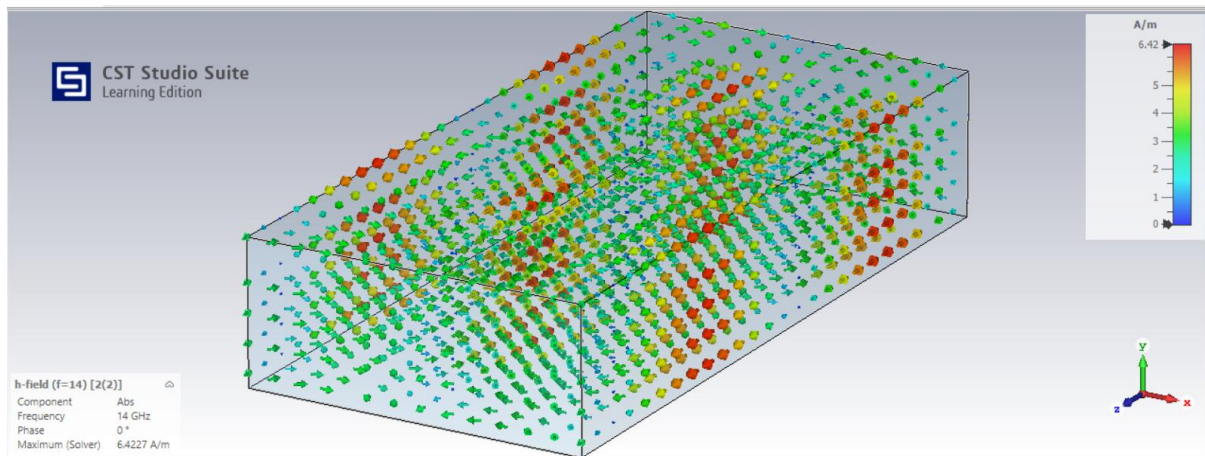


Magnitude

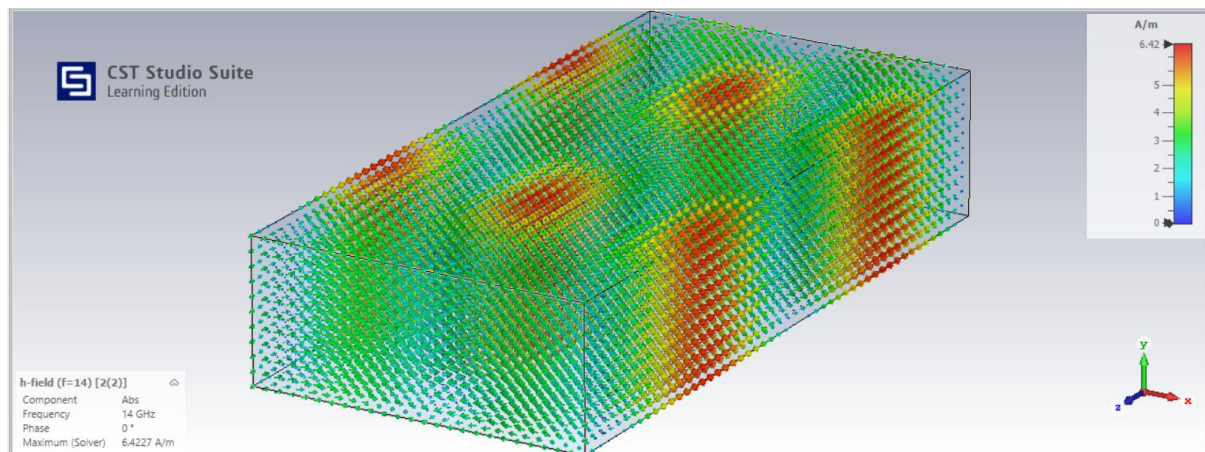


H-Field

Vector



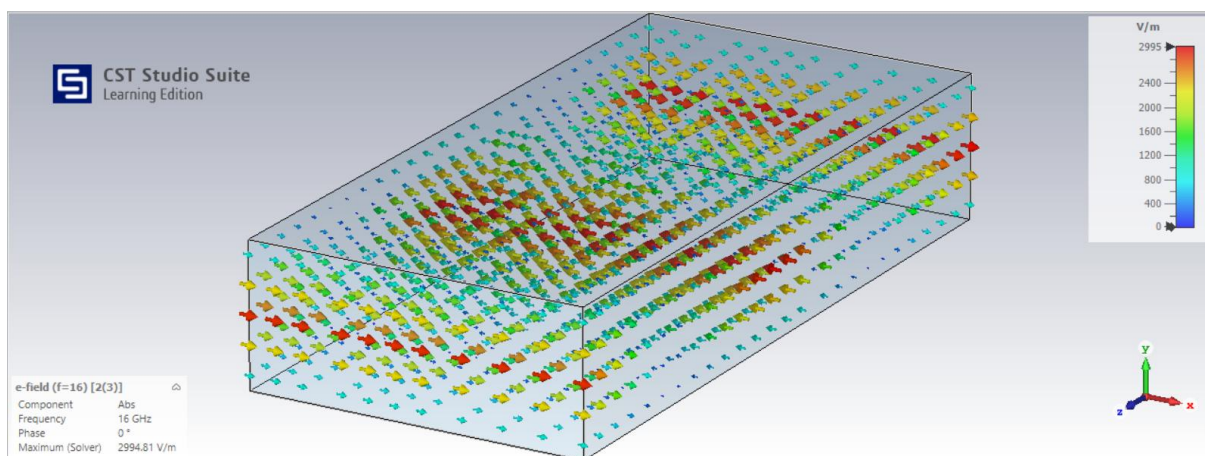
Magnitude



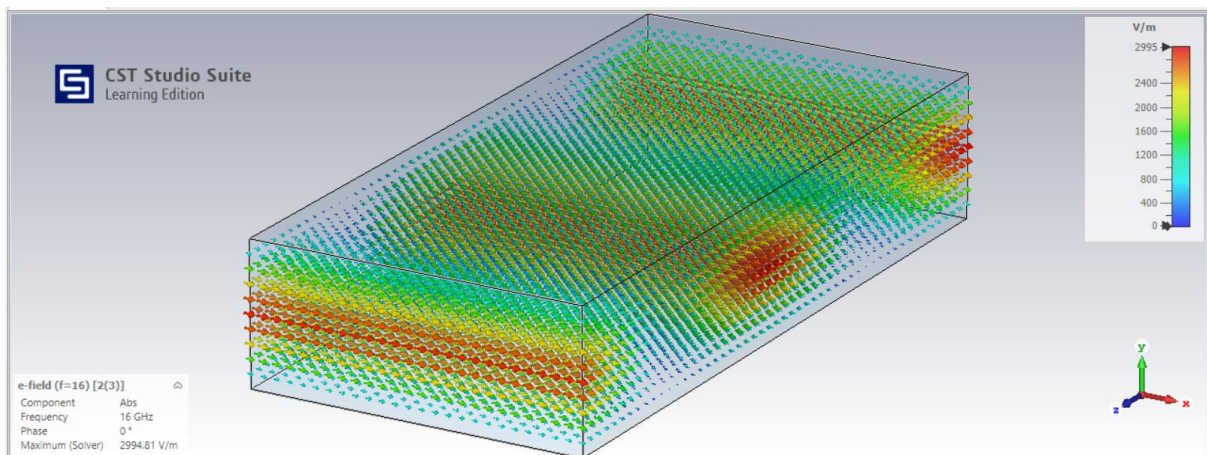
Port 2 Mode 3

E-Field

Vector

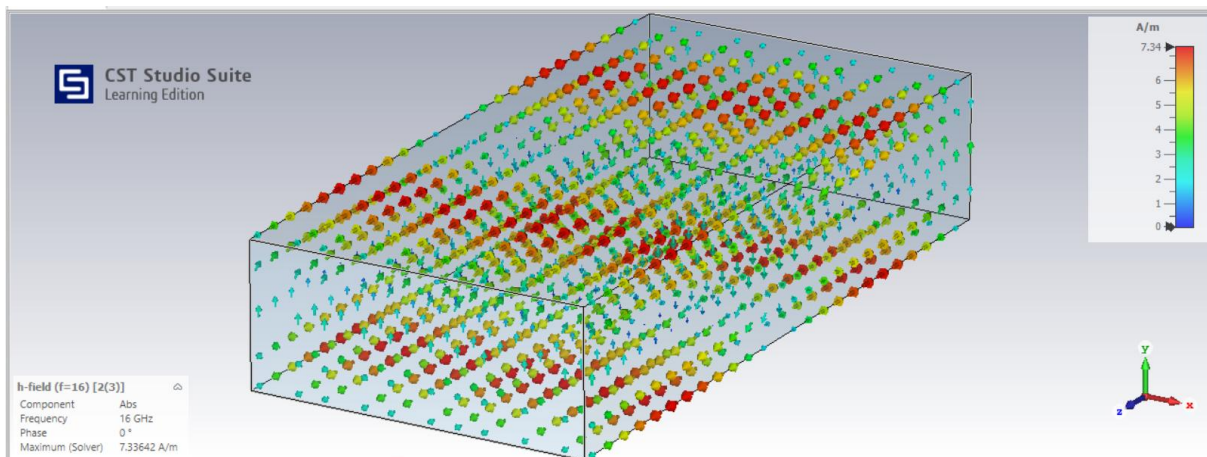


Magnitude

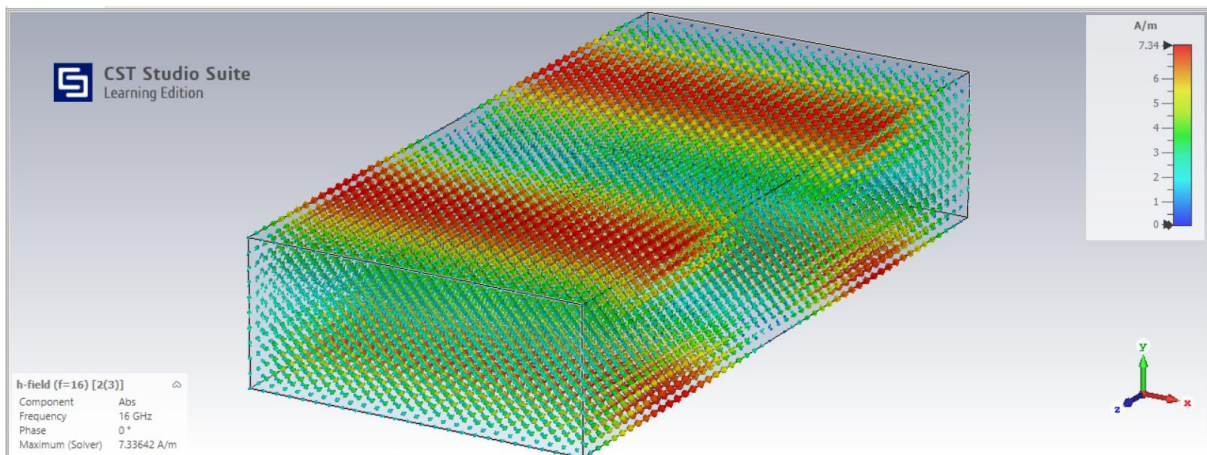


H-Field

Vector



Magnitude

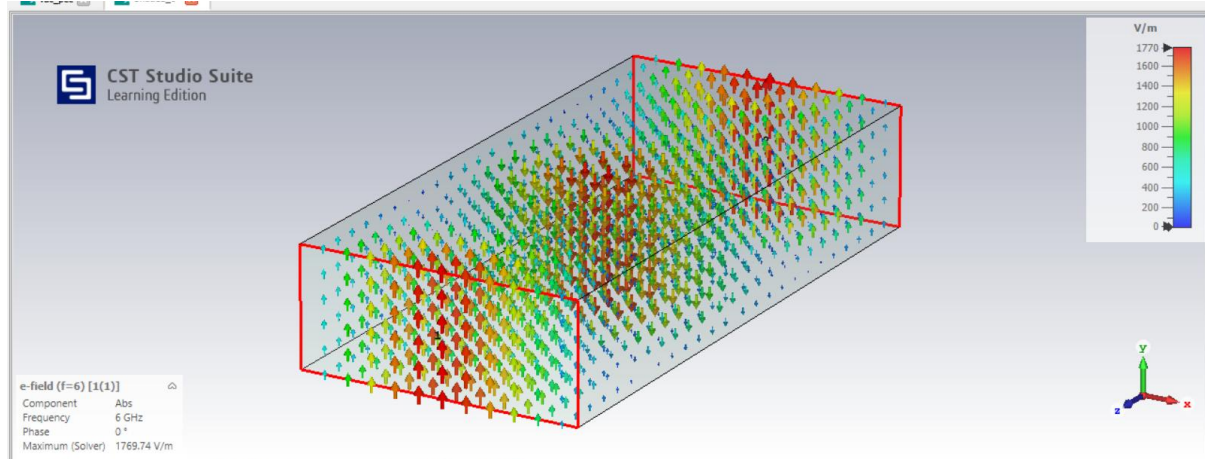


PTFE Waveguide Magnitudes and Vectors

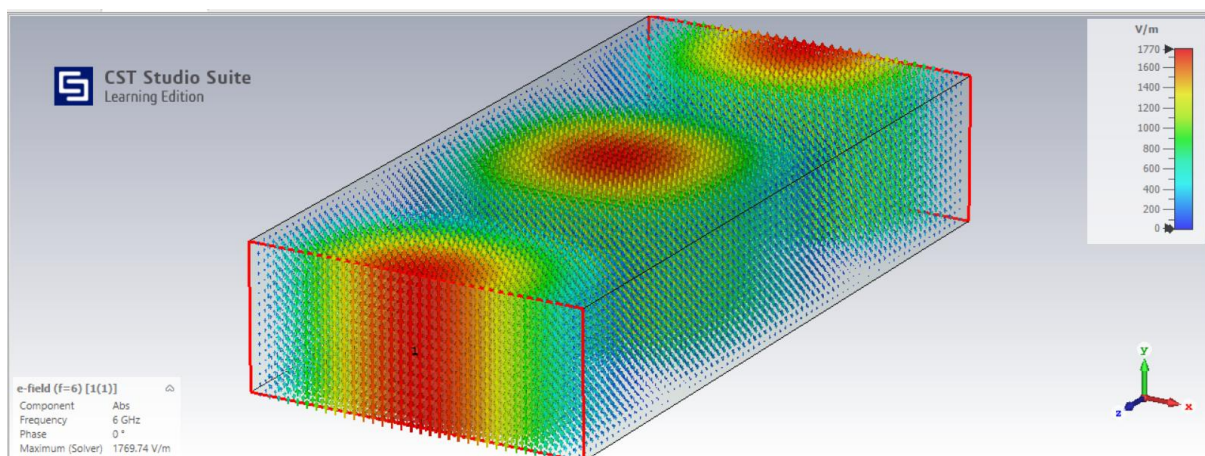
Port 1 Mode 1

E-Field

Vector

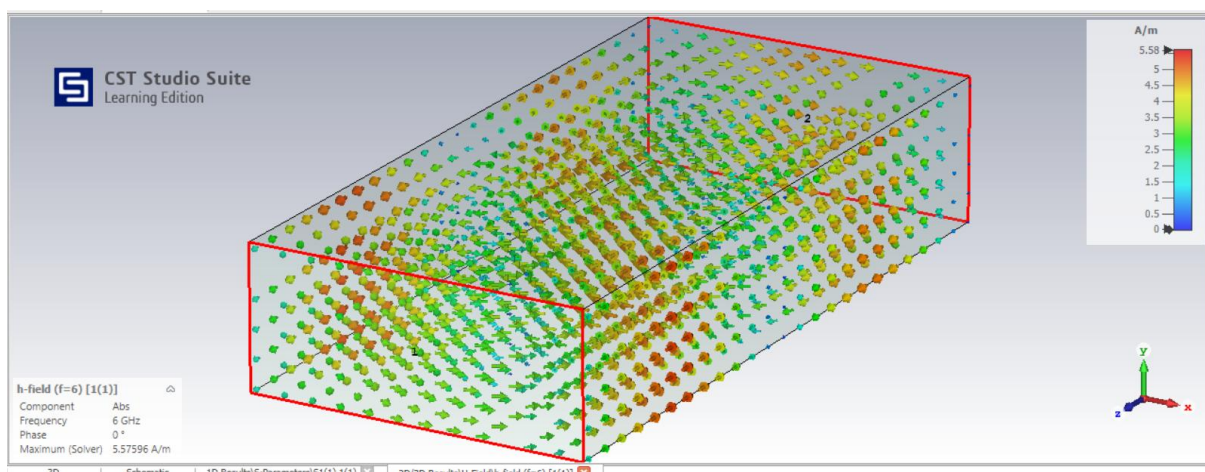


Magnitude

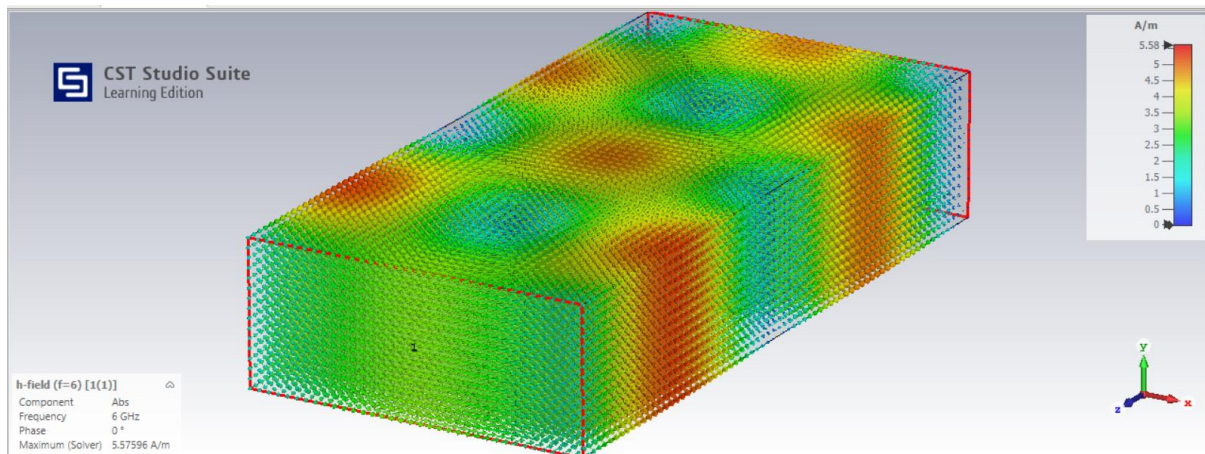


H-Field

Vector



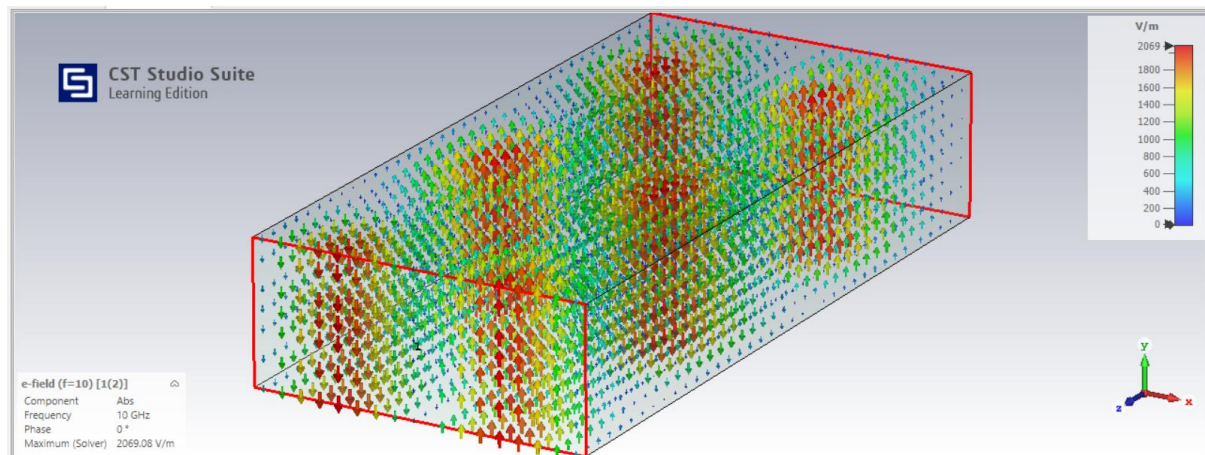
Magnitude



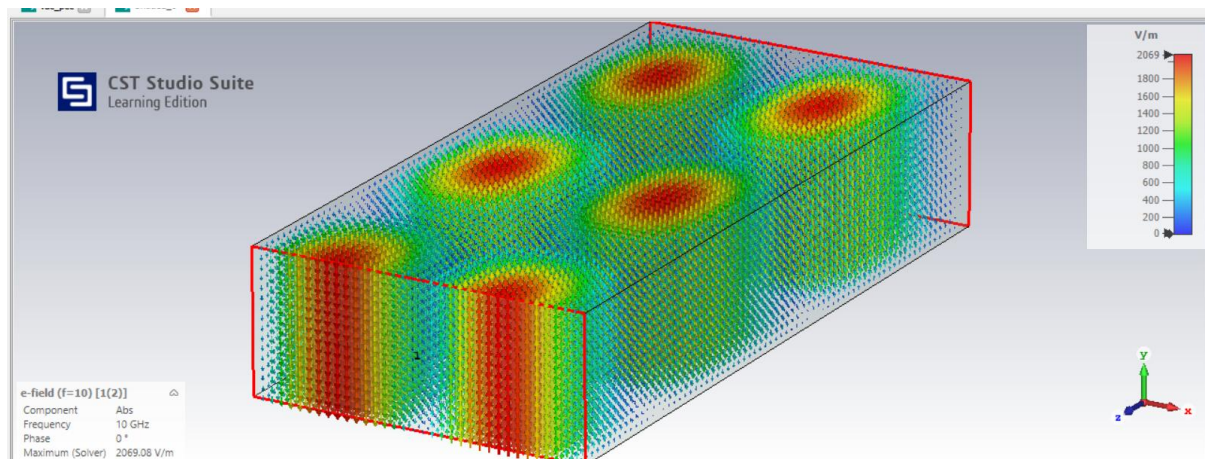
Port 1 Mode 2

E-Field

Vector

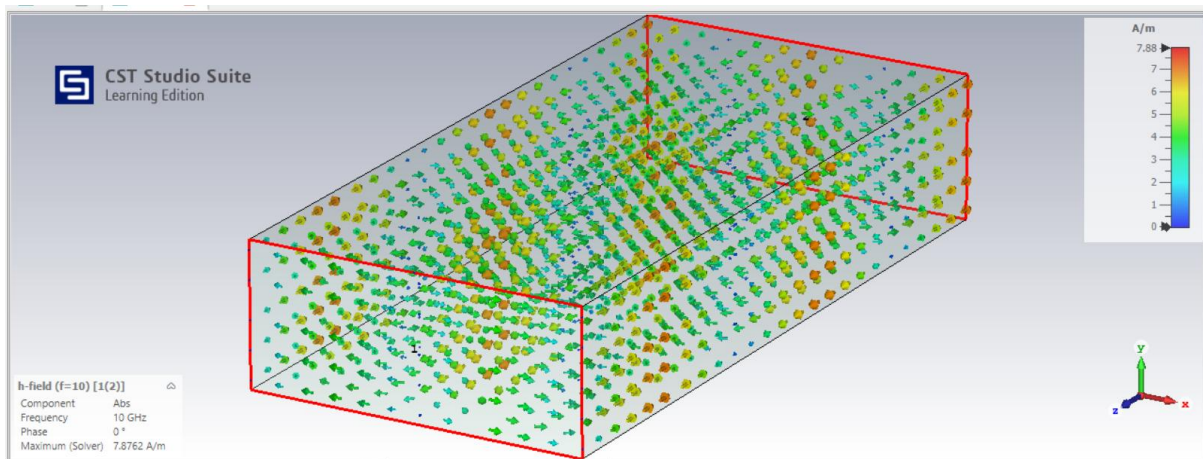


Magnitude

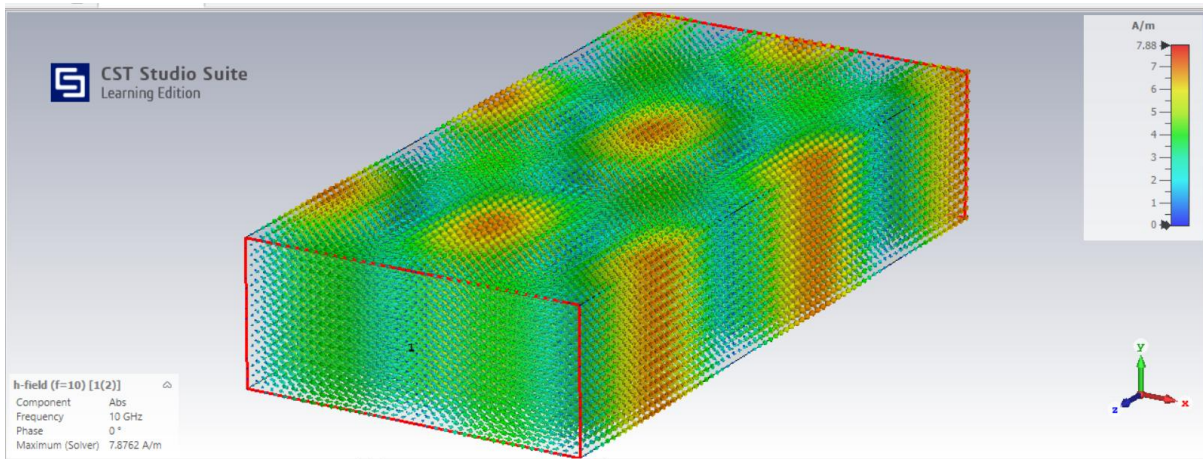


H-Field

Vector



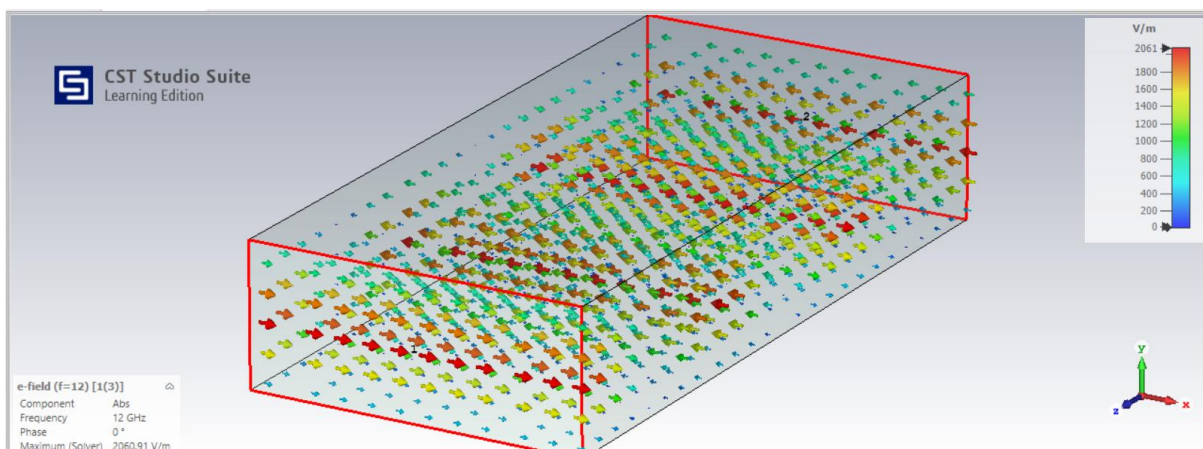
Magnitude



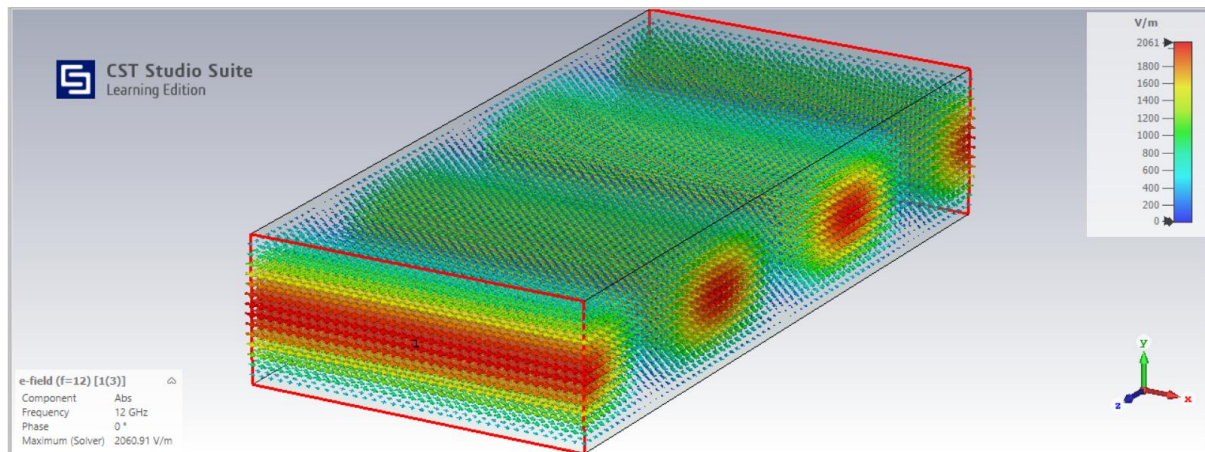
Port 1 Mode 3

E-Field

Vector

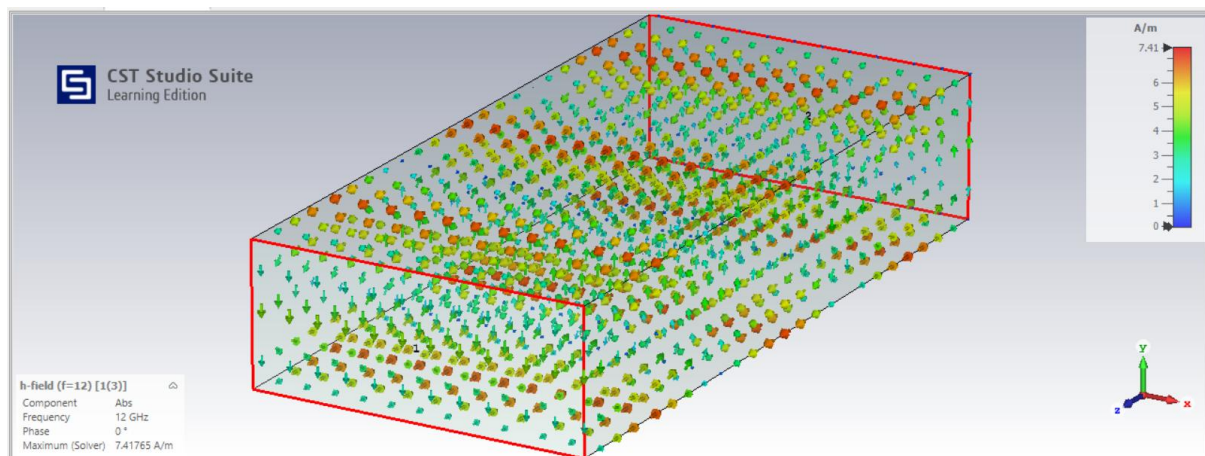


Magnitude



H-Field

Vector

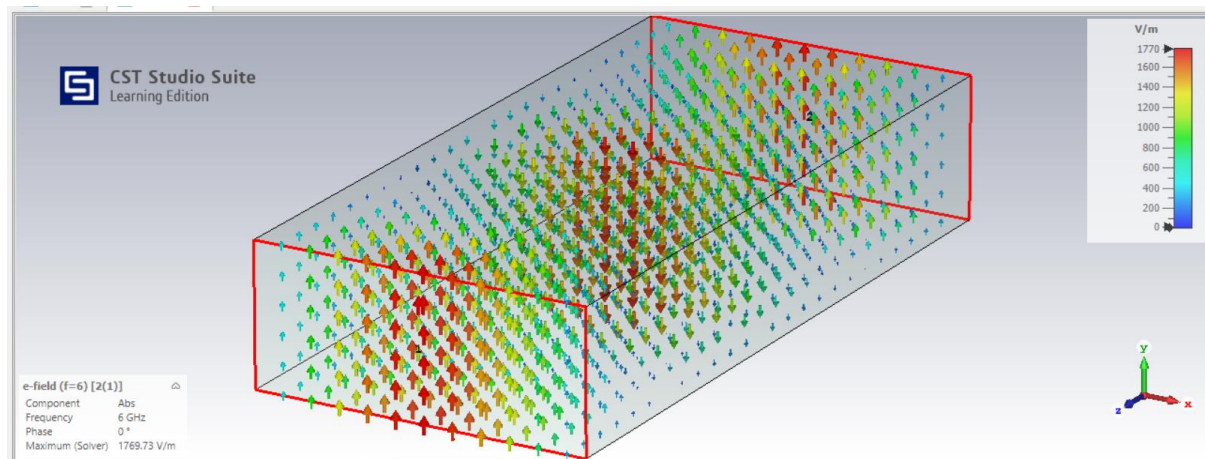


Magnitude

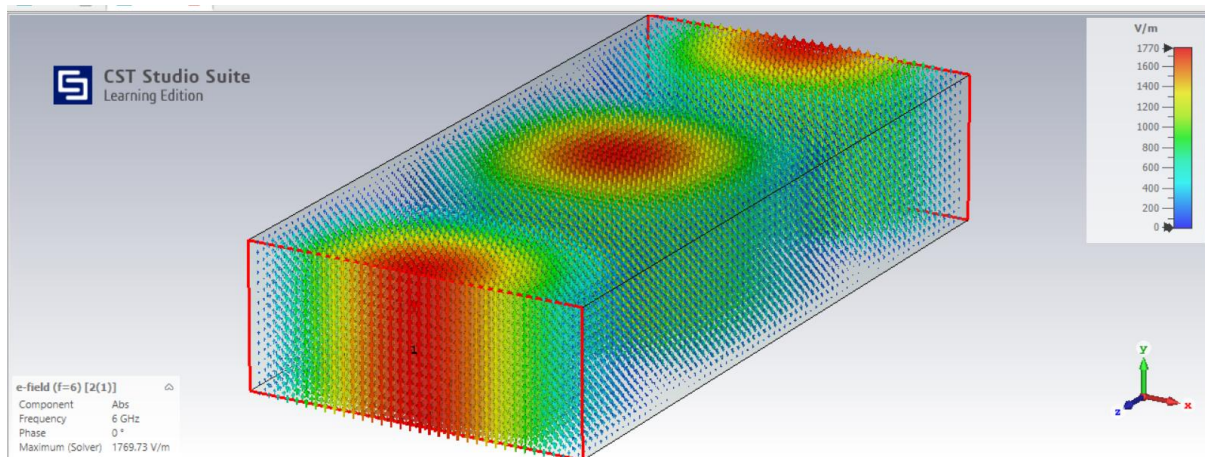
Port 2 Mode 1

E-Field

Vector

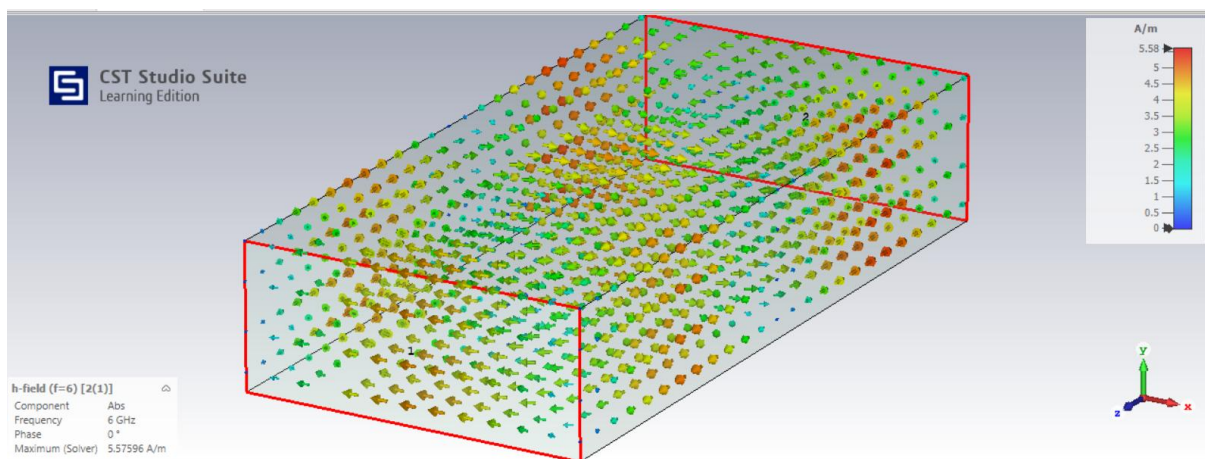


Magnitude

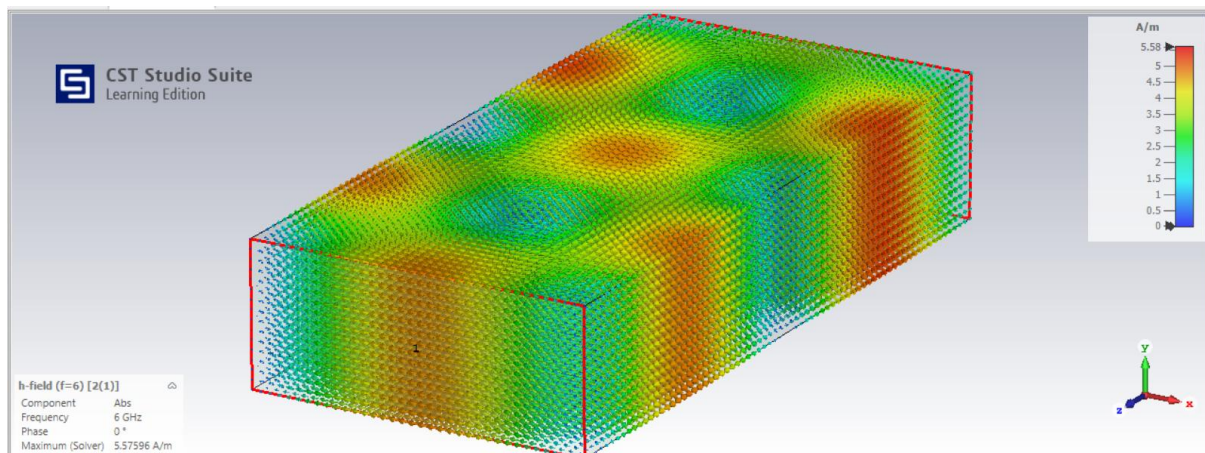


H-Field

Vector



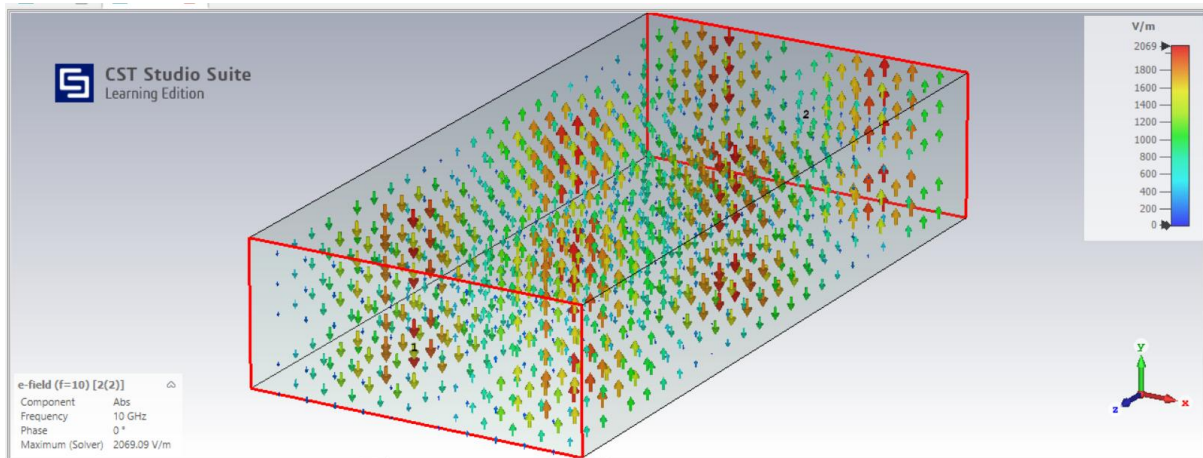
Magnitude



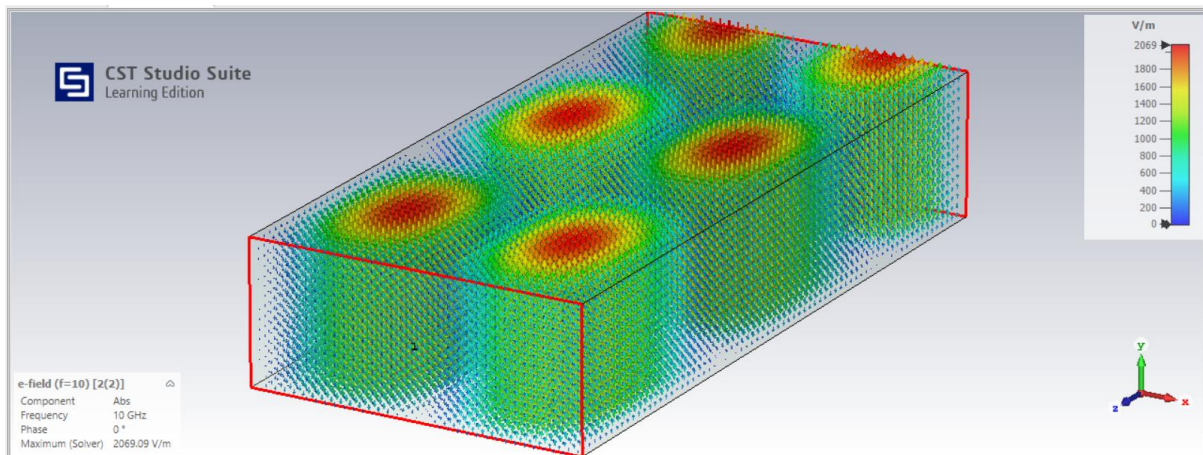
Port 2 Mode 2

E-Field

Vector

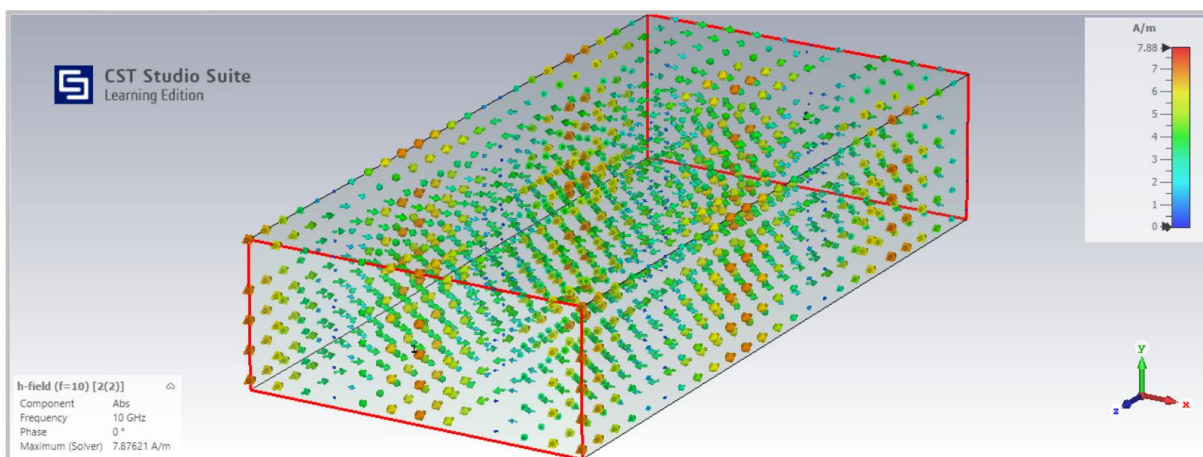


Magnitude

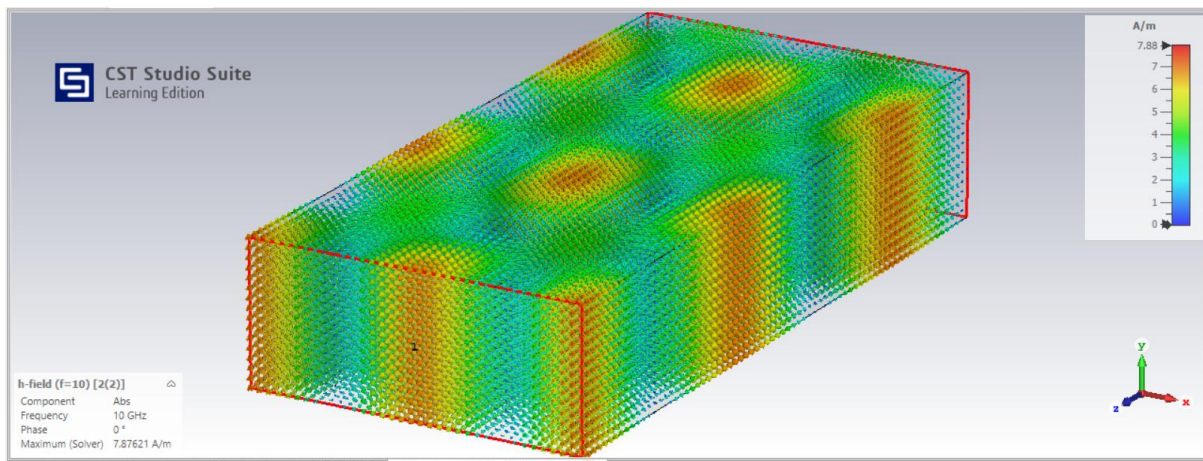


H-Field

Vector



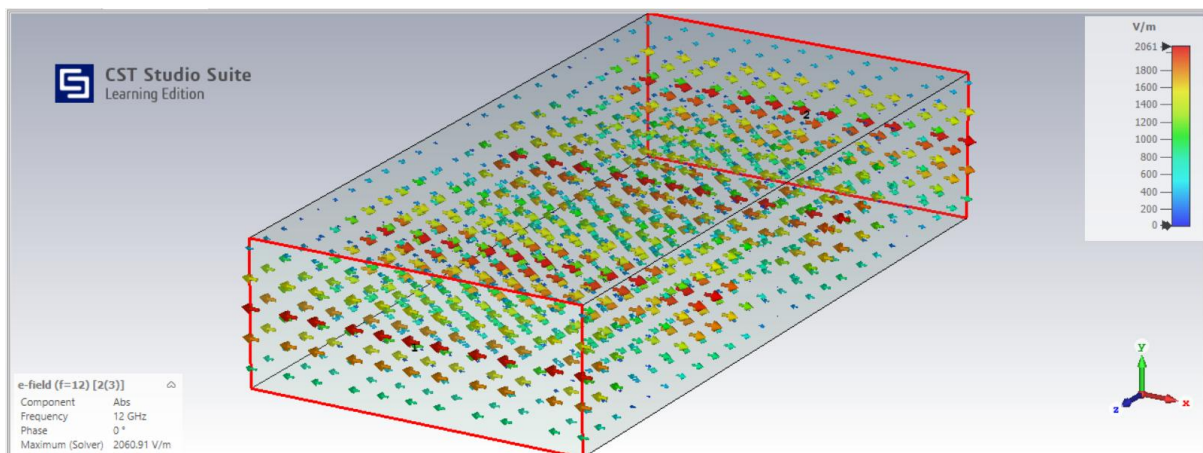
Magnitude



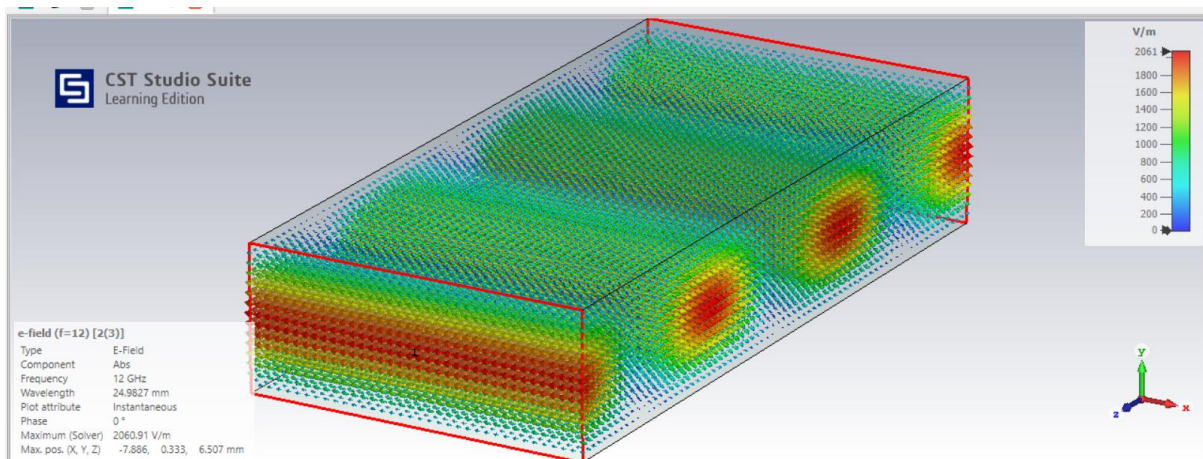
Port 2 Mode 3

E-Field

Vector

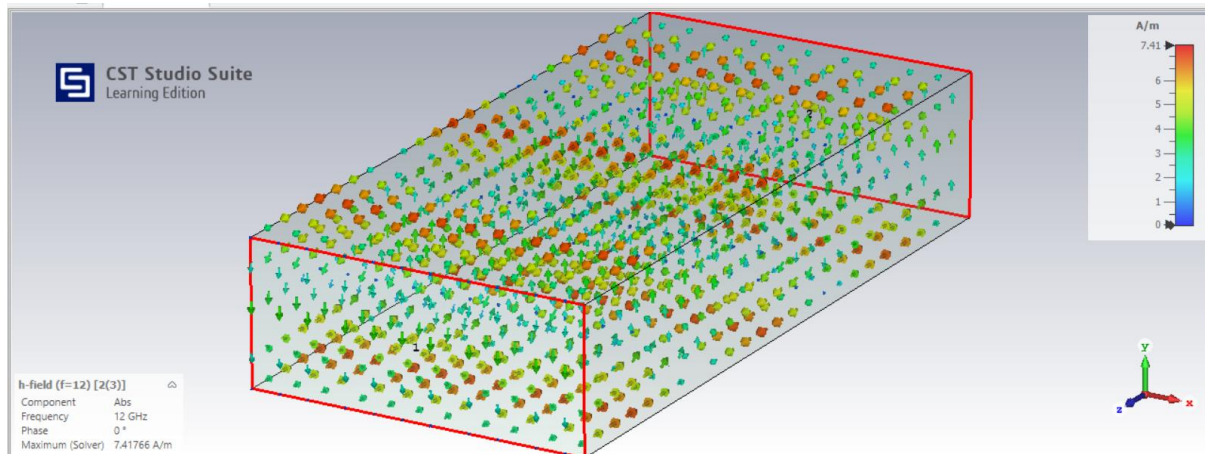


Magnitude

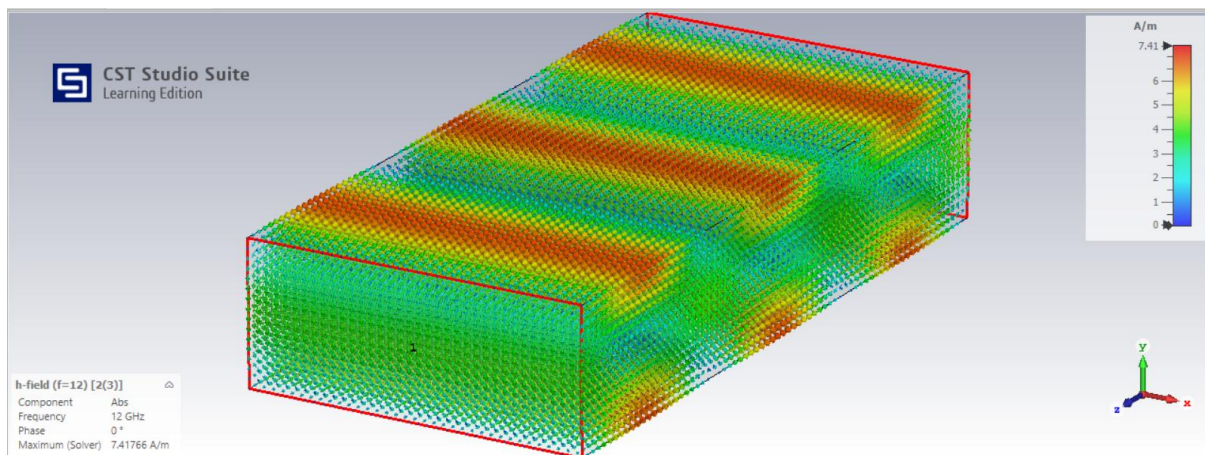


H-Field

Vector



Magnitude



References

- [1] J. Radatz, *The IEEE Standard Dictionary of Electrical and Electronics Terms*. Institute of Electrical & Electronics Engineers(IEEE), 1997.
- [2] R. E. Collin, *Foundations for microwave engineering / [Hauptw.]*, 2. ed. New York: Macgraw-Hill, 1992, p. 214.
- [3] "Waveguide (radio frequency)," *Wikipedia*, May 19, 2021.
[https://en.wikipedia.org/wiki/Waveguide_\(radio_frequency\)](https://en.wikipedia.org/wiki/Waveguide_(radio_frequency))
- [4] "Feed Systems and Waveguide Basics for Ground Stations," *Satellitegroundstation.com*, 2026.
<https://satellitegroundstation.com/resources/feed-systems-and-waveguide-basics-for-ground-stations/>
(accessed May 22, 2026).

- [5] “Parallel-Plate Waveguide for Volume Radio Frequency Transmission in MRI,” *Nih.gov*, 2024. <https://pmc.ncbi.nlm.nih.gov/articles/PMC4499329/> (accessed May 22, 2026).
- [6] “Penetration panel,” *Questions and Answers in MRI*. <https://mriquestions.com/wirestubes-thru-wall.html>
- [7] “Top 7 applications of waveguide assemblies in radar technology,” *DOLPH MICROWAVE*, Aug. 21, 2025. <https://www.dolphmicrowave.com/default/top-7-applications-of-waveguide-assemblies-in-radar-technology/> (accessed May 22, 2026).
- [8] Wikipedia Contributors, “Beam waveguide antenna,” *Wikipedia*, Oct. 12, 2023. https://en.wikipedia.org/wiki/Beam_waveguide_antenna
- [9] Y. Pan, D. Xie, Y. Zhao, X. Wang, and Z. Huang, “Overview of Radar Jamming Waveform Design,” *Remote Sensing*, vol. 17, no. 7, p. 1218, Mar. 2025, doi: <https://doi.org/10.3390/rs17071218>.
- [10] H. Khalil, M. M. Ahmed, and U. Rafique, “Nose-Cone Conformal Substrate-Integrated Waveguide Slot Array Antenna for X-Band Radar Applications,” *International Journal of Antennas and Propagation*, vol. 2019, pp. 1–11, Dec. 2019, doi: <https://doi.org/10.1155/2019/6262574>.
- [11] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: Wiley, 2011.
- [12] “EMF Exposure Guidelines Explaining the 2020 guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP),” 2020. Available: <https://www.gsma.com/solutions-and-impact/connectivity-for-good/public-policy/wp-content/uploads/2020/10/GSMA-EMF-Exposure-Guidelines-Oct20.pdf>
- [13] Electronics Notes, “Waveguide Flange» Electronics Notes,” *Electronics-notes.com*, 2026. <https://www.electronics-notes.com/articles/antennas-propagation/rf-feeders-transmission-lines/waveguide-flanges.php> (accessed May 22, 2026).
- [14] RF Essentials, “Waveguide Terminations: Engineering the End of the Signal Chain,” *Rfessentials.com*, Apr. 13, 2026. <https://rfessentials.com/industry-news/component-spotlight/waveguide-terminations-engineering-signal-chain/> (accessed May 22, 2026).
- [15] “Why Do Waveguide Chokes Minimize Leakage,” *DOLPH MICROWAVE*, Apr. 15, 2025. <https://www.dolphmicrowave.com/default/why-do-waveguide-chokes-minimize-leakage/> (accessed May 22, 2026).
- [16] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ, USA: John Wiley & Sons, 2016.
- [17] V. Semenyuk, I. Kurmashev, A. Lupidi, D. Alyoshin, L. Kurmasheva, and A. Cantelli-Forti, “Advances in UAV detection: integrating multi-sensor systems and AI for enhanced accuracy and efficiency,” *International Journal of Critical Infrastructure Protection*, vol. 49, p. 100744, Feb. 2025, doi: <https://doi.org/10.1016/j.ijcip.2025.100744>.
- [18] “An Introduction to Drone Detection Methods,” *Aerodefense.tech*, 2025. <https://blog.aerodefense.tech/drone-detection-methods>
- [19] S. Ding, X. Guo, T. Peng, X. Huang, and X. Hong, “Drone Detection and Tracking System Based on Fused Acoustical and Optical Approaches,” *Advanced intelligent systems*, vol. 5, no. 10, Jul. 2023, doi: <https://doi.org/10.1002/aisy.202300251>.

[20] George, “The Societal Impact of the Drone Revolution,” *Partners Universal Innovative Research Publication*, vol. 3, no. 1, pp. 9–16, 2025, doi: <https://doi.org/10.5281/zenodo.14907512>.

[21] Wikipedia Contributors, “Gatwick Airport drone incident,” *Wikipedia*, Sep. 06, 2019. https://en.wikipedia.org/wiki/Gatwick_Airport_drone_incident

[22] A. Balmori and Ö. Hallberg, “The Urban Decline of the House Sparrow (*Passer domesticus*): A Possible Link with Electromagnetic Radiation,” *Electromagnetic Biology and Medicine*, vol. 26, no. 2, pp. 141–151, Jan. 2007, doi: <https://doi.org/10.1080/15368370701410558>.

[23] Blanka Pophof, Bernd Henschenmacher, D. R. Kattnig, J. Kuhne, A. Vian, and Gunde Ziegelberger, “Biological Effects of Radiofrequency Electromagnetic Fields above 100 MHz on Fauna and Flora: Workshop Report,” *Health Physics*, vol. 124, no. 1, pp. 31–38, Nov. 2022, doi: <https://doi.org/10.1097/hp.0000000000001625>.