To boost electromagnetics' flavor, we accompanied many problems with short Matlab code acting as *a calculator and result illustrator*. We completely ignored the descriptions of algorithms behind the codes because they are often quite complicated and require ample, very sophisticated, and abstract mathematical specifics to understand the physical picture. Such an approach lets us shift the focus from the often emasculated and practically fruitless problems primarily based on math transformations to more complicated but close to practical tasks. We hope to visualize typically invisible EM fields and stimulate in-depth analysis and discuss the fundamental principles. Projecting images onto a big screen, the lectures may organize whole-class conversation making the audience significantly engaged. These scripts are for people who have never programmed in Matlab or CST before.
We cheer our readers to look through Matlab scripts and CST models to discover and sophisticate the algorithm embedded in them. We encourage you to use the student edition of MATLAB and CST STUDIO SUITE® to get enhanced problem understanding.

Attention. Regrettably, copy and paste into Matlab Command Window saves appropriate Matlab format just in Chrome Web Browser. You have to restart https://emfieldbook.com/ in https://www.google.com/ if your browser is different.

Problem 1. Introduction to Rectangular Waveguide (WR). Dominant Mode TE_{10}. The cross-sectional dimensions of the waveguide are a x b ($a > b$). Please refresh Sections 6.1.3, 6.4.3, and 6.6.4 about a rectangular waveguide. Recall, the WRs do not support TEM-mode propagation; the frequency dispersion is mandatory, and the WRs are relatively narrow-banded. The *single-mode regime,* when the total EM energy caries by only one *dominant* wave mode TE_{10}, takes place if $\lambda_{c2} < \lambda < \lambda_{c1}$ or $\lambda/2 < a < \lambda$. Go to https://1drv.ms/f/s!AjtsKS-uvNP1avsbUFY9UsxLVVE, click subsequently on the icon Document and Waveguides. Mark, copy and download WaveduideRect.m file to a newly created directory named Waveguides, for example. Then open the WaveduideRect.m file in Matlab and run the animation. Figure 1 depicts several screenshots you can watch during the simulation.

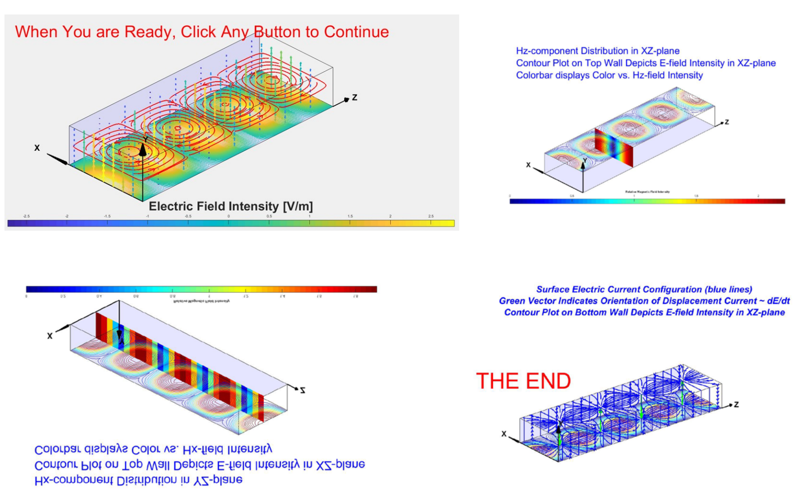

Figure 1. Screenshots of EM-fields and Currents.

Problem 2. **Power Handling**. Please refresh Sections 6.1.4, 6.4.3, and 6.6.4 about a rectangular waveguide. Recall, the power handling means the maximum RF *peak or average* power delivered by a feed line without interruption or internal damage like electrical breakdown, line element deformation, or overheating. Go to https://1drv.ms/f/s!AjtsKS-uvNP1avsbUFY9UsxLVVE, click subsequently on the icon Document and WGBreakdown. Mark, copy and download all pictures and morph1.m file to a newly created directory named WGBreakdown, for example. Then open the morph1.m file in Matlab and run the animation consisting of two parts. The fully developed discharge (last frame) in Figure. 1 depicts a very complicated structure containing multiple discharge sports and channels occurring in the early lightning stages. On the left picture, the strength of discharge is displayed by white intensity, while on the right, by the color variations.

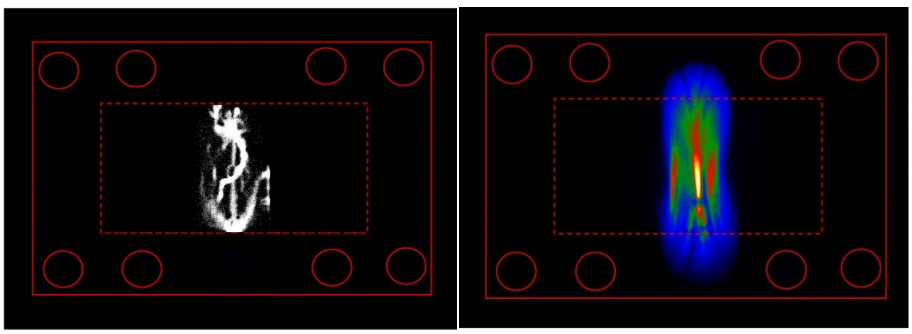

Figure. 1 Fully development discharge images.

The first animation is based on images published in the paper[1]. The more colorful second animation includes the images from the thesis[2]. Both breakdown experiments or, in fact, surface flashover developments were provided at 2.85 GHz utilizing the rectangular waveguide (WR284 of 2.84" x 1.34" or 72.136mm x 34.036mm) at a deep vacuum[1] typical for geostationary satellites and air pressure[2] corresponding to altitudes around 50,000 feet (~15km) above the sea level typical for civil and military aircraft. The surface flashover effect on the dielectric windows is one of the primary factors limiting the microwave power radiating by satellites and aircraft antennas. We refer the reader for more details to the originals[3]. Figure 2 illustrates the multiplication principle diagram leading to the so-called Townsend Avalanche (gas ionization process where free electrons are accelerated by an electric field, collide with gas molecules, and consequently free additional electrons, and so on). Figure 3 displays schematically the three stages of discharge development[4]: (a) E-field force lines close to avalanche experience a focusing effect and develop secondary avalanches; (b) a thin plasma filament/streamer is formed; (c) when the streamer reaches the electrodes, a spark happens through the channel opened in this way.

In 1889, F. Paschen experimentally demonstrated that at higher pressures (above a few torrs), the dielectric strength of a gas is a function (generally not linear) of the gas pressure and the gap length,

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[1] A. N., James Dickens, D. Hemmert, H. Krompholz, L. L. Hatfield, and M. Kristiansen, Window Breakdown Caused by High-Power Microwaves, IEEE Transactions on Plasma Science, Vol. 26, No. 3, June 1998, https://ieeexplore.ieee.org/document/700757

[2] G. F. Edmiston, High Power Microwave Window Flashover at Atmospheric Pressure, Thesis, Texas Tech University, 2005

[3] https://etd.auburn.edu/bitstream/handle/10415/5207/Chen_Thesis%205.13.2016.pdf?sequence=2

[4] https://catalogimages.wiley.com/images/db/pdf/9783527340767.excerpt.pdf

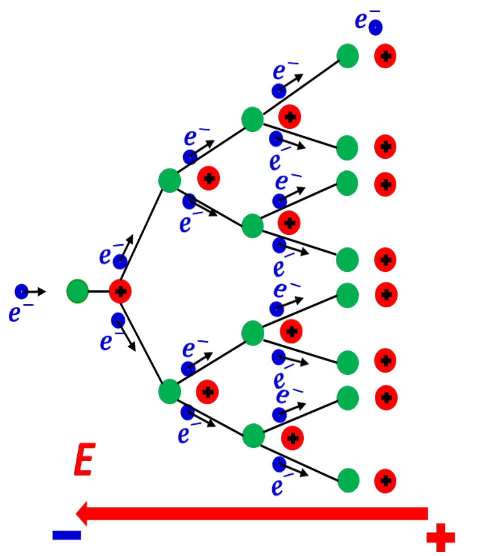


Figure 2. Diagram of multiplication principle

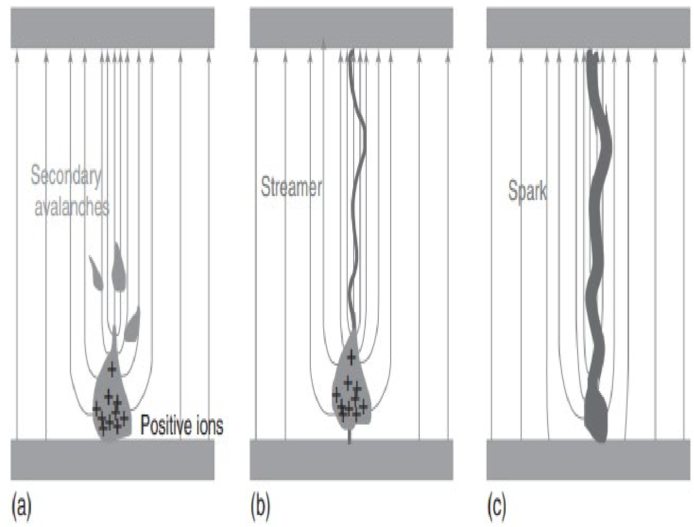


Figure 3. Three stages of discharge

as Figure 4 depicts[5]. Gases are used as electrical insulators in high voltage applications, e.g., transformers, circuit breakers, high voltage switchgear, radar waveguides, etc. Notice, The build-up of moisture can degrade the dielectric strength of the gas.

Go to https://1drv.ms/f/s!AjtsKS-uvNP1avsbUFY9UsxLVVE, click subsequently on the icon Document and WGBreakdown to copy and paste the file GasBreakdown.pdf containing Table of Relative Dielectric Strength of several insulating gases at ambient.

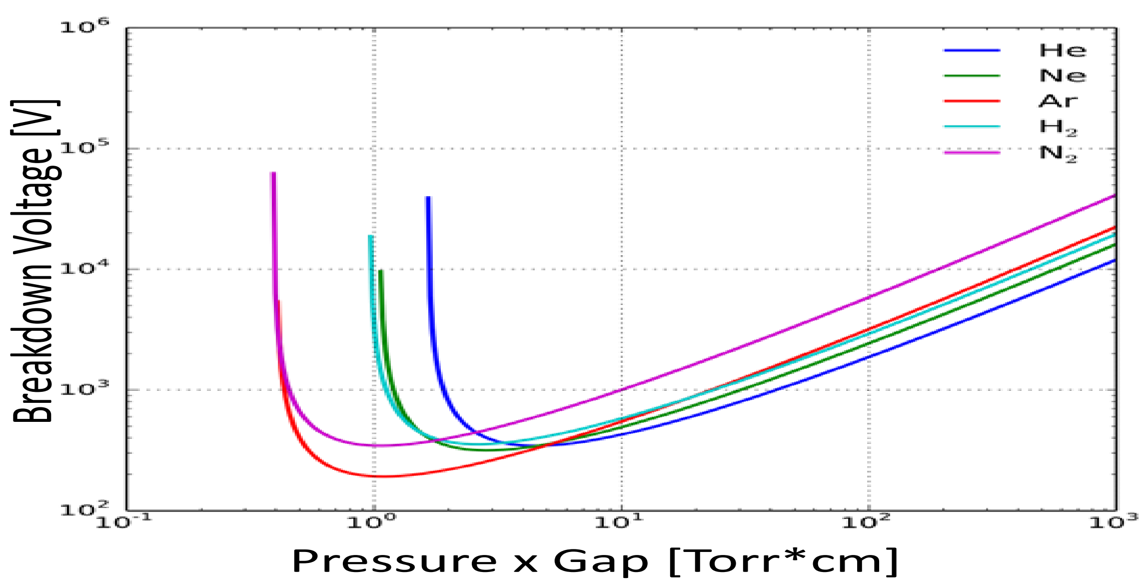


Figure 4. Paschen curves

[5] https://en.wikipedia.org/wiki/Paschen%27s_law

Problem 3. Introduction to Circular Waveguide (WC). The radius of the waveguide is a while its length is equal to waveguide wavelength. Please refresh Sections 6.1.3, 6.4.4, and 6.6.5 about circular waveguide. Recall, the WCs do not support TEM-mode propagation; the frequency dispersion is mandatory, and the WCs are relatively narrow-banded. The *single-mode regime,* when the total EM energy caries by only one *dominant* wave mode TE_{11}, takes place if $\lambda_{c2} < \lambda < \lambda_{c1}$ or $2.06\lambda < a < 3.41\lambda$. Go to https://1drv.ms/f/s!AjtsKS-uvNP1avsbUFY9UsxLVVE, click subsequently on the icon Document and Waveguides. Mark, copy and download WaveduideCircle.m file to a newly created directory named Waveguides, for example. Then open the WaveduideCircle.m file in Matlab and run the animation. Figure 1 depicts several screenshots you can watch during the simulation.

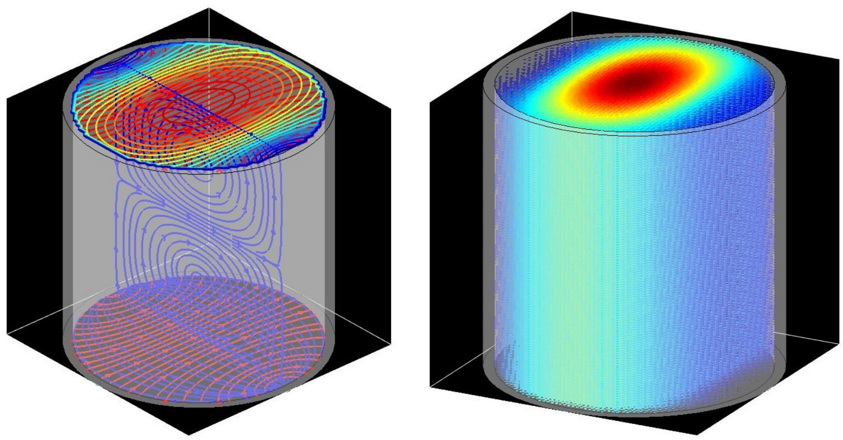
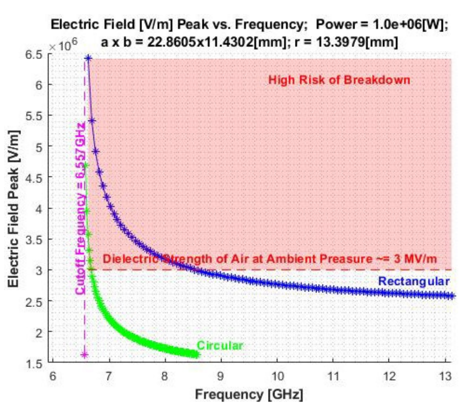


Figure 1. Screenshots of EM-fields and Power Flux for TE_{11}-mode

Problem 4. Rectangular (WR) and Circular (WC) Waveguide Comparison.



Go to https://1drv.ms/f/s!AjtsKS-uvNP1avsbUFY9UsxLVVE, click subsequently on the icon Document and Waveguides. Mark, copy and download RectCircleWGcompare.m file to a newly created directory named Waveguides, for example. Then open the RectCircleWGcompare.m file in Matlab and run the animation. Figure 1 depicts several screenshots for TE_{11} – mode you can watch during the simulation. In the same Waveguide directory, you can find the text file Standard WG.pdf containing the Table of Standard Waveguides. Load and open this file as a reference for your simulation.

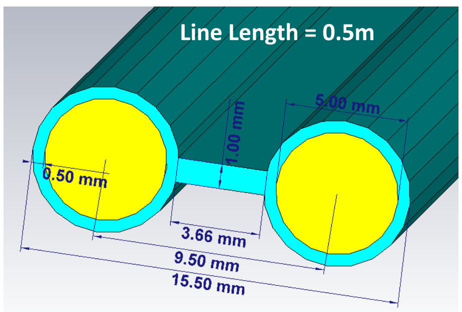
This analysis's main purpose is to compare WR and WC critical characteristics like power handling, attenuation, and dispersion. Simultaneously, both waveguides carry equal power by the dominant modes TE_{10} and TE_{11}, respectfully, and have identical cutoff frequencies.

The WR cutoff frequency of dominant TE_{10} -mode and the same WC parameter of dominant TE_{11}-mode are

$$f_c^{WR} = c/2a\,, \qquad f_c^{WC} = 1.8412c/2\pi r$$

Here c is the speed of light, a is the WR wide wall, and r is the WC radius. Therefore, $f_c^{WR} = f_c^{WC}$ if $r = (1.8412/\pi)a = 0.586a$, or $D = 2r = 1.172a \cong a$. The cross-section area of each waveguide is $A^{WC} = \pi r^2 = (1.8412^2/\pi)a^2 = 1.0791a^2$ and $A^{WR} = a^2/2$ as $b = a/2$. It means $A^{WC} = 2.1582A^{WR}$ and the cross-section perimeters $p^{WC} = 1.227p^{WR}$. Based on this result, explain the outcome of numerical simulation and answer why the rectangular waveguide applications are much broader than a circular ones. Nonetheless, the WC has lower dissipation and higher power handling at the same frequencies.

Problem 5. Two-wire Ribbon-type Line. Please review Introduction and Sections 6.1.1 – 6.1.5, 6.2.1, 6.6.1 – 6.6.2 in Chapter 6. The current project is built on the CST STUDIO SUITE model of the line shown on the left. The copper wires of diameter d = 5mm are colored in yellow while the polyethylene ($\varepsilon_r = 2.25, \sigma = 10^{-15}[\mathrm{S/m}]$) ribbon covering the wires and filling the D = 9.5mm gap between them is depicted in light blue. You can change any dimension and dielectric properties if you wish. To get the required CST files, go to https://1drv.ms/f/s!AjtsKS-uvNP1avsbUFY9UsxLVVE. Open the file directory *Two-wire Ribbon-type Line*, click the right/secondary button on the mouse while the cursor hovers over the icon TwoWireLine.cst and choose Download. Save this file somewhere on your computer and run the CST project. If you do not want to run CST or do not have access to it, merely observe the pictures beneath.



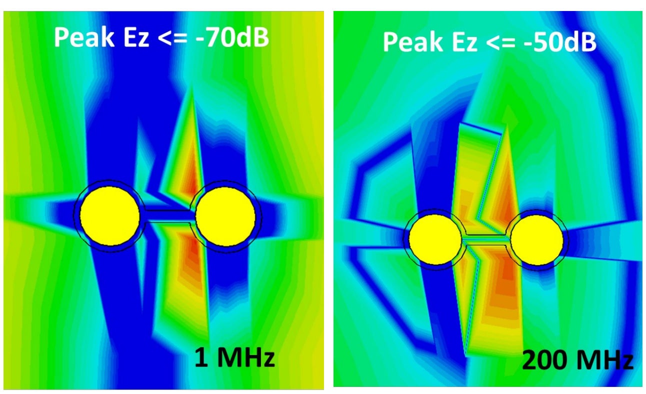


Figure 1. Ez-component distribution in XY-plane

According to Sections 6.1.1 and 6.2.2, TEM mode should carry the energy along the line. However, the presence of dielectric ribbons converts such a pure transverse mode into the quasi-TEM mode with $E_z \to 0, H_z \to 0$. Eventually, the frequency lowering makes quasi-TEM mode more and more similar to TEM mode. Figure 1 demonstrates the Ez-component distribution in the transverse XY-plane. The rigorous solution of Maxwell's equations reveals another important fact[6]. Since the line is the *finite length and lossy* (explain why both are important), energy dissipation connected to the line's

[6] Not follow from the classical circuit analysis and equivalent infinite lumped circuit model pictured in Section 6.1.2

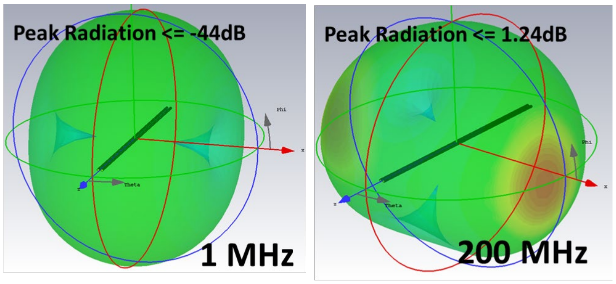


Figure 2. Two-wire Line Radiation Patterns

radiation appears especially at higher frequencies. Look at Figure 2, depicting the simulated line's radiation pattern at 1 MHz and 200 MHz. Notice the wavelength at 200 MHz is 1.5m that much exceeds the line cross-section dimensions. The radiation peak at 1 MHz occurs along the x-axis, while the same peak switches to the y-direction at 200 MHz. *Could you explain this? Does the lossless line of finite length radiate?*

The next line parameter is an attenuation defined mostly by the surface electric current. Figure 3 shows such current distribution at 1 MHz and 100 MHz. The impact of line loss is visible at 100 MHz, where the current magnitude drops to the end of the line. *Explain the nonuniform distribution of the current over the circumference of each wire.*

Figure 4 illustrates the power loss density in the dielectric ribbon. *Explain why the loss peak occurs in the gap between wires.*

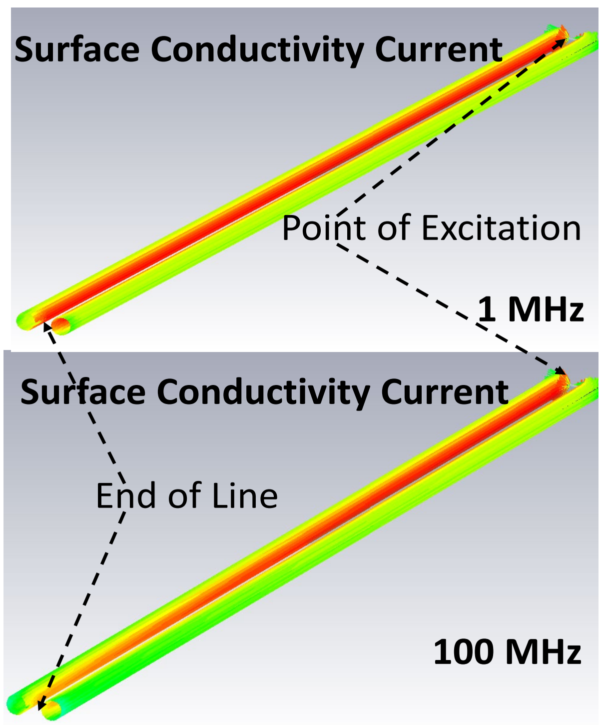


Figure 3. Surface Current Density

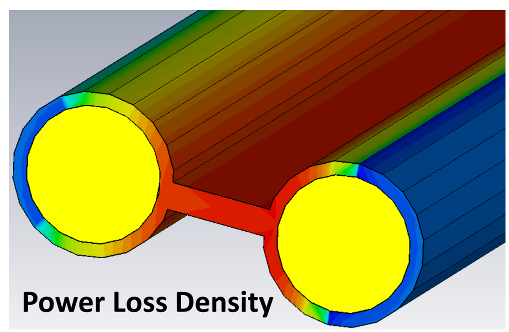


Figure 4. Power Loss Density

The total attenuation in the line of 0.5m length represents in Figure 5.

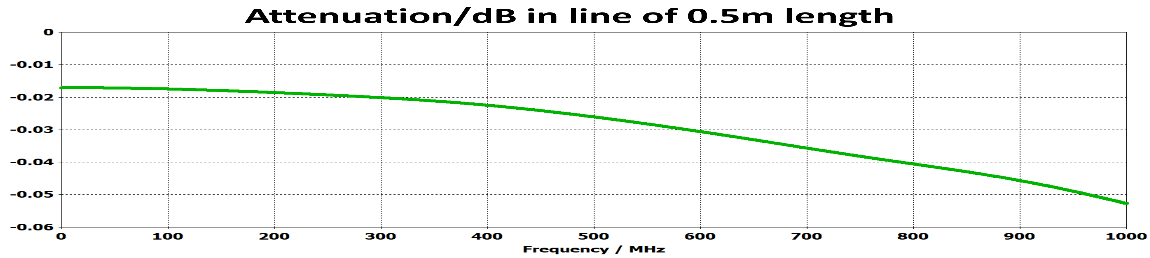


Figure 5. Attenuation in line

Figure 6 displays the structure of E- and H-fields of the quasi-TEM mode propagating along the line.

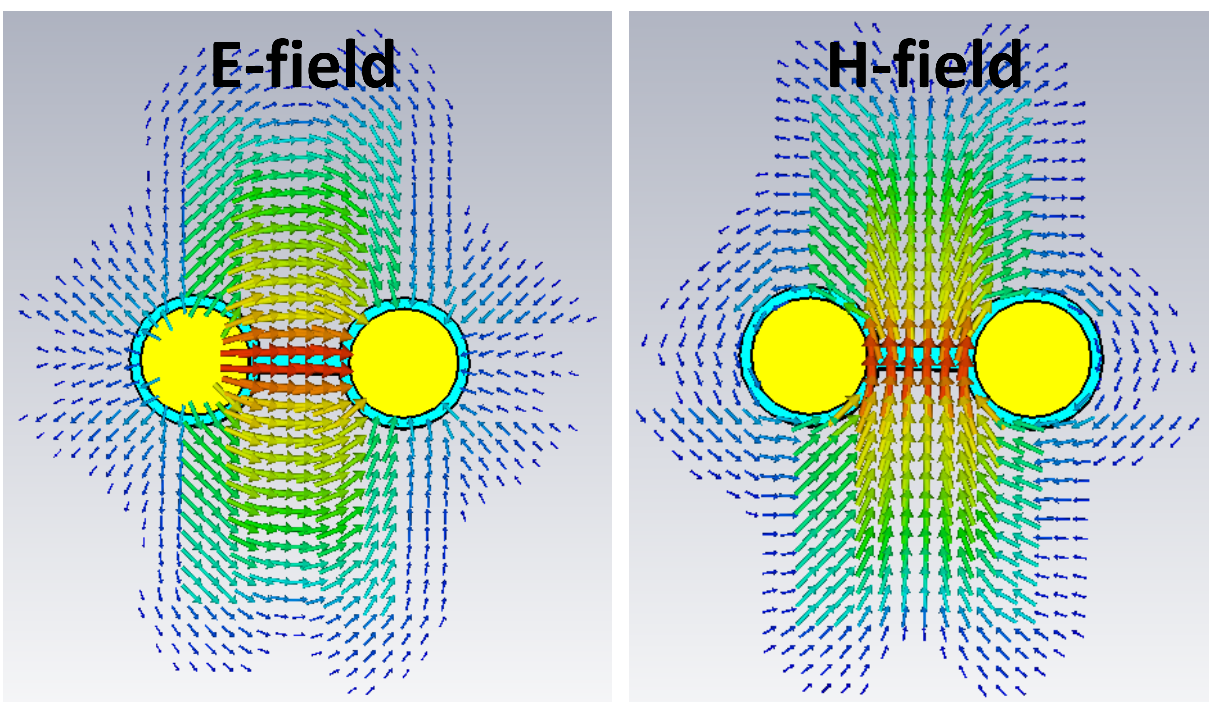


Figure 6. Structure of E- and H-fields of the quasi-TEM mode

It is expected the TEM mode propagates along the line with the speed of light. But both the dielectric presence and loss slows it down. *Explain why?* The CST simulation found that the energy carries along the line with $v/c = 0.9028$. If so, we can define the electric and magnetic energy stored-per-unit length W'_{em} as (see equation (6.8) in Chapter 6) $W'_{em} = P/v = (1/3 \cdot 10^8)/0.9028 = 3.692 \cdot 10^{-9}[\text{J/m}]$, where $P = 1[\text{W}]$ is the power delivered by a generator of $U_e = 10\text{V}$. You can take all these data from the CST simulation results. Therefore, the distributed capacitance-per-unit length is (check equation (6.6) in Chapter 6) $C' =$

$2W_e'/U_e^2 = 2(W_{em}'/2)/U_e^2 = 3.692 \cdot 10^{-11}$[F/m] and $\mathcal{L}' = 1/(v^2 C') = 3.917 \cdot 10^{-7}$[H/m] while the line impedance is $Z_c = \sqrt{\mathcal{L}'/C'} = 103$[Ohms]. A classical circuit theory tells us that the same parameters (no ribbon) should be equal[7] to $\mathcal{L}' = (\mu_0/\pi)\mathrm{acosh}\,(D/d) = 5.03 \cdot 10^{-7}$[H/m], $C' = \pi\varepsilon_0/\mathrm{acosh}\,(D/d) = 2.21 \cdot 10^{-11}$[F/m], and (with ribbon) $Z_c = 100.6$ [Ohms]. *Explain the differences inspecting* 1MHz *plots in Figures 3 and 6.*

[7] https://electronics.stackexchange.com/questions/256927/how-to-calculate-total-impedance-of-two-parallel-conductors