Course Project
“Transmission Line Parameters”

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Introduction

In Electronics and communication engineering a **transmission line** is a cable, a waveguide or another structure composed from conductors and dielectrics designed to conduct alternative currents of radio frequency. That means that the frequency is high enough that their wave nature should be taken into account.

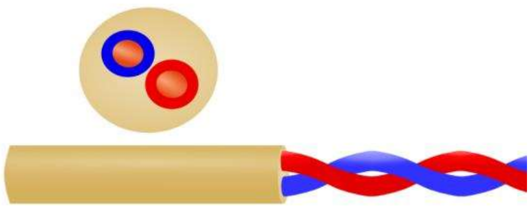
Ordinary low frequency wires and cable cannot be used for transmitting high frequency currents because the electromagnetic energy tends to radiate into surrounding space, adversely effecting on nearest circuits and devices.

Transmission lines often used for connecting radio transmitters and receivers with their antennas, distribution video signals over cables, and for high-speed computer data buses.

Unlike true **waveguides**, which are used with even higher frequencies and enclosed all amount of electromagnetic field inside it, **transmission line** a not strictly closed for electromagnetic field. Designers usually try to control the electromagnetic field pattern to avoid the undesirable effect of the transmission line on neighboring lines and devices.

The most common transmission line has two conductors: outward conductor and return conductor. Depending of conductor's geometry transmission lines can be **balanced** (symmetric) and **unbalanced**. The former has the outward and return conductors of the same shape, and they both are located similarly with respect to grounding plane.

Examples of balanced lines are: twisted pair, twin-lead pair when it locates parallel to grounding plane.

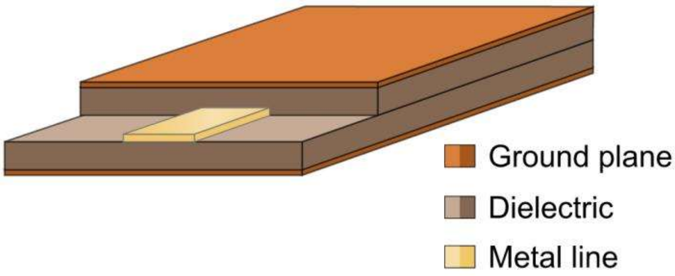


Twisted pair

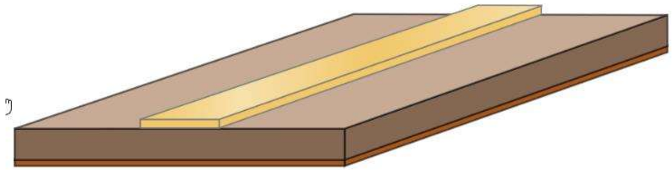
Twin-lead cable (actually a ladder line)

Unbalanced lines has outward and return conductor of different shape. Often the grounding plane plays a role of return conductor. Examples of unbalanced lines include coaxial cable, planar transmission lines. The latest are convinient for placing on printed circuit boards (PCB).

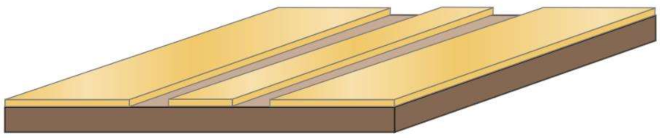
Planar transmission lines:



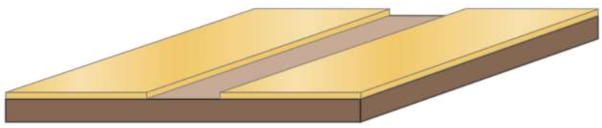
Stripline: The thin flat signal (outward) conductor is sandwiched in a dielectric betwee to ground planes, that former the return conductor. The upper an dlower dielectric layers can be the same or different



Microstrip line differs from a stripline in that It contains only one grounding plane

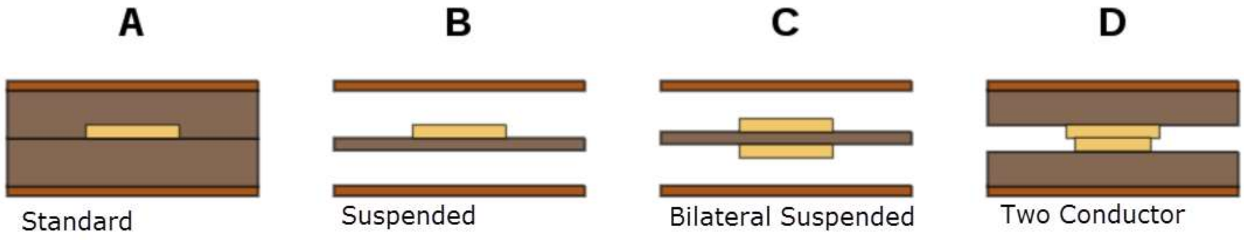


In **Coplanar waveguides (CPW)** contains a single conducting track on a dielectric substrate surrounded by two return conductors located (theoretically infinite) in the same plane.
Another variant is so called conductor-backed coplanar waveguide (CBCPW), contains also third infinite ground plane of the back side of the substrate

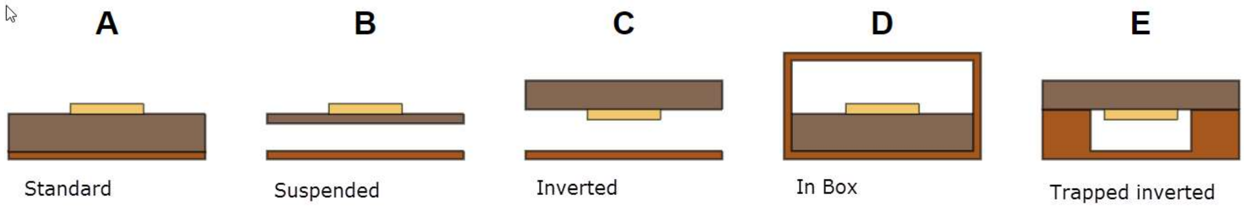


Slotline is a gap betwwen two similar big (infinite) conducting planes, one of them acts as a outward conductor and other is a returning conductor.

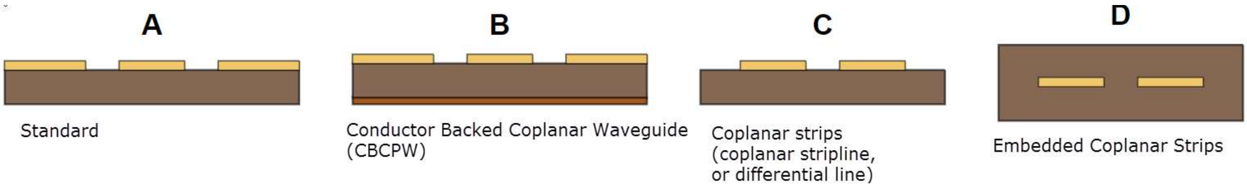
Variants of Strpline



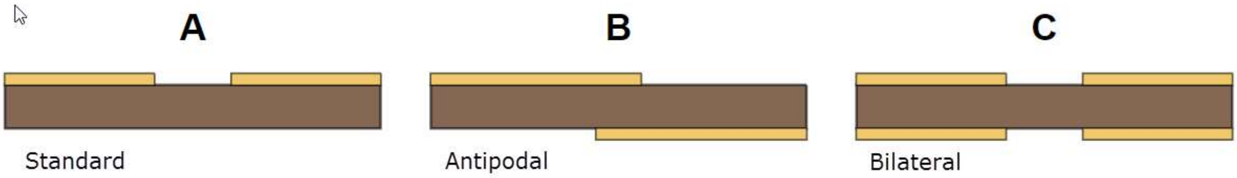
Variants of Microstrip lines



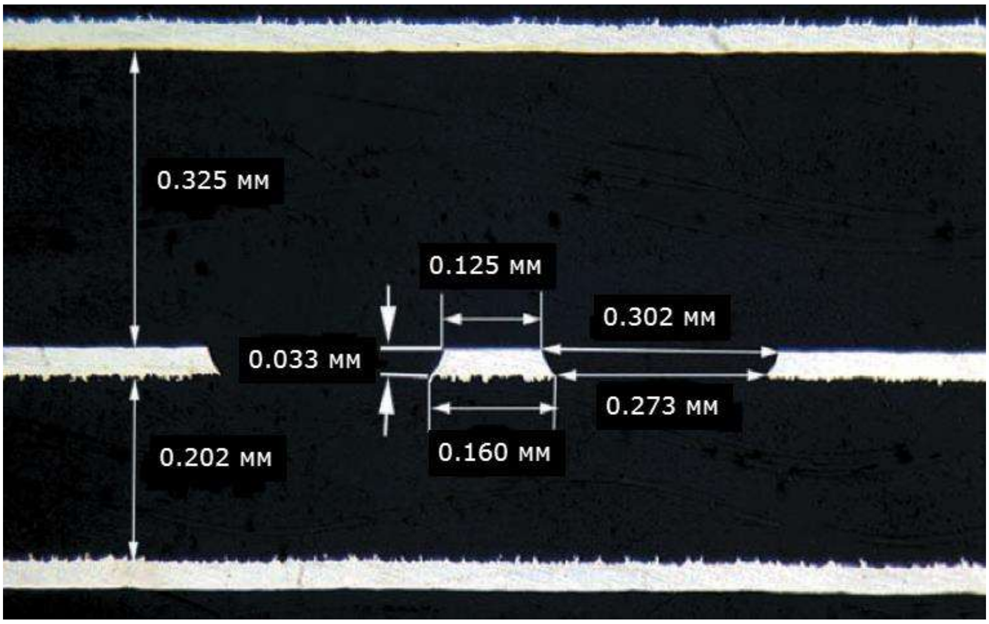
Variants of Coplanar Waveguides



Variants of slotlines



Another type of planar lines



A coplanar waveguide buried into internal layers of printed circuit board (PCB). On the picture is a photograph of a multi-layer PCB. Only 3 of 8 layers are shown. The real shape of the conductors is not rectangular due to etching technique.

Transmission line parameters

The most interesting parameters are: characteristic impedance Z_0 and the velocity of propagation v_p. Both parameters are defined in terms of inductance per unit length L and capacitance per unit length C:

$$Z_0 = \sqrt{\frac{L}{C}} \tag{1}$$

$$v_p = \frac{1}{\sqrt{LC}} \tag{2}$$

The above equations do not take into account the energy loss and skin-effect.

At first glance, we have to solve two field problems: one electric problem to find the capacitance C and the second magnetic problem to find the inductance L. However, in case of the phase velocity is a priory known, we only need an electrostatic model.

When no dielectric nor magnetic is used, the phase velocity of wave propagation is equal to the light speed in vacuum: $v_p = c = 2.990 \cdot 10^8$ m/s.

Substituting the ideal velocity $v_p = c$ to (2) we get:

$$c = \frac{1}{\sqrt{LC_0}} \qquad (3),$$

where C_0 – is the line capacitance per unit length when all dielectrics are removed.

Resolving (3) for the inductance L we substitute it back to (1) and (2). Now we get:

$$Z_0 = \frac{1}{c\sqrt{CC_0}} \quad (4)$$

$$v_p = c\sqrt{\frac{C_0}{C}} \quad (5)$$

Now we can solve for impedance only two electrostatic problems: one with dielectrics and the second with all dielectrics replaced by air. Note that we solve the static problem (with frequency $f=0$). For pure transverse electromagnetic field (TEM) a static analysis is accurate enough for the first order mode of electromagnetic frequency. A microstrip is not pure TEM, but a quasi-TEM structure, and its impedance is actually frequency dependent. The static analysis is adequate enough until the substrate is thin enough and the strip conductor is very narrow comparing to the wavelength.

Sometimes it is very useful to employ the symmetry of problem geometry, including into the model only a half or a quarter of the complete cross-section. The impact of cut part is modelled by appropriate boundary condition. Using symmetry we able to model odd or even mode (same or opposite potential of two conductors in balanced lines).

Project working program

Each student receives his/her own individual input data, containing the kind of planar transmission line with geometric dimensions.

The goal of modelling is obtaining the **line impedance** Z_0 and velocity of wave propagation v_p depending on the input parameter. The result should be presented on a XY-plot and in a table.

There a three kind of geometric dimensions in a model:

1. **Fixed dimensions** are the constant given by the teacher
2. Dimension of **theoretically infinite** planes. The student expected to make a reasoned decision of such dimension in such a way that it does not affect on the accuracy.
3. **Variable dimensions and parameters** are given in form of a range. The given range should be divided into reasonable number of steps in order to get a good dependency of output parameters in input parameters.

Each student is expected to reason the decisions he/she has made concerning bounding theoretically infinite planes as well as chosen mesh density.

Part 1: Line Impedance Calculation

The goal is calculation of characteristic impedance Z_0 and the velocity of propagation v_p

The theory is given above (see “Transmission line parameters”).

Working program:

1. *Create the new QuickField problem* with the ***electrostatics*** problem formulation, ***plane-parallel*** model class and appropriate length units.
2. *Create a geometry model* including all conductors and dielectric given in the individual project data. When creating the model the student should estimate a reasonable value of potentially infinite dimensions and later prove his/her decision.
3. *Apply boundary conditions*: known potential or charges as well as the artificial "infinitely far" boundaries.
4. *Solve the problem*, review the field picture, identify and fix possible mistakes
5. *Calculate the line capacitance C* with given dielectric permittivity, and C_0 with all dielectric replaced with free space.
6. *Calculate impedance Z_0* and propagation velocity v_p / c using (4) and (5).
7. *Repeate steps 2-6 with varying position of infinite far artificial boundary until the results Z_0 and v_p converges*
8. Repeat calculation varying the given parameter in given range with reasonable step. Use found position of the "infinite" boundary. Provide the plot of Z_0 and v_p versus varying parameter.

Part 2: Line inductance and conductor loss calculation

The goal is to calculate the inductance L_{AC} and resistance R_{AC} of the transmission line for the alternative current with the given frequency f. We also wish to compare AC inductance L_{AC} and resistance R_{AC} with DC ones: L_{DC} and R_{DC}. It is expected that the $R_{AC} > R_{DC}$, and $L_{AC} < L_{DC}$. Please think why it is so.

To calculate the AC inductance and solving the AC magnetic problem taking into account eddy currents with given frequency. The easiest way for calculating DC inductance and resistance is solving the same AC magnetics problem again with a very low frequency, for example $f_0 = 1\ Hz$.

1. *Create the new QuickField problem* with the ***AC-magnetics*** problem formulation, ***plane-parallel*** model class, appropriate length units and given frequency. Copy your geometry, created for electrostatic part for this problem. Note, that unlike the electrostatic problem, now we have to include both signal and grounding conductors to the model, i.e. build a finite element mesh. Use the nominal sizes given in youк individual project data with no variation.
2. *Modify a copied geometry model* in order to include the signal and grounding conductors into the model
3. *Control the mesh density* inside conductors taking into account the penetration depth of the electromagnetic field inside the conductor. It is recommended to provide at least 4-5 layers of triangles (finite elements) per penetration depth δ, which can be estimated as

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}},$$

where σ is the electric conductivity, μ - magnetic permeability, and ω – the cyclic frequency.

4. *Give the permeability and conductivity* for each block in the model. Also give the field source (the total current) for signal and grounding conductor.
5. *Provide necessary boundary conditions*. On artificial infinite edges, it is a condition of vanishing magnetic field. For our case the zero Dirichlet condition A=0 is quite suitable.

6. *Put the field source* data for signal conductor (total current I=1 A) and grounding plane (total current = -1 A)
7. *Solve the problem* and use the impedance wizard for calculation the inductance L_{AC} and the resistance R_{AC}.
8. Set the very low frequency, say f=1 Hz, and repeat the step 6 again, for calculation of direct current inductance L_{DC} and the resistance R_{DC}

Creating the project report

Each student has to present provide the project report in both printed and electronic form, accompanied with QuickField model files ready for viewing and solving. The report file name (Word document or PDF) should include:

1. Student group number with no slash
2. Student's given and family name
3. Code name of the individual project

Example: *332151_Ivan_Petrov_MS1.docx*

The content of the project report should provide:

1. The given project data,
2. The short theoretical description. There is no need to copy all information from this document to the report. You would better include some minimal amount of facts that you consider significant to your project.
3. The picture of the geometry model and finite element mesh,
4. The description of chosen boundary condition,
5. Some explanation about the position of "infinitely far" artificial boundaries.
   It is highly recommended to do a few numerical experiments with different position of such edges and prove your choice.
6. Another decision has to be discussed is how to choose appropriate mesh density.
7. The procedure of capacitance calculation and the result
8. The tables and plots of Z_0 and v_p/c versus variable parameter, where c is the speed of light in free space.
9. The picture of geometry model of magnetic problem with finite element mesh.
10. The picture or explanation of the boundary condition for magnetic problem
11. The AC and DC values of the line inductance and resistance. Also provide the R_{AC}/R_{DC} ratio as well as L_{AC}/L_{DC} ratio. Also compare the L_{AC} value with the inductance L calculated via electrostatic analysis by the equation (3).
12. It is good to provide a short conclusion summarizing your work. It would be excellent to compare in the conclusion your results with some transmission line calculator, for example the AppCad available here: http://www.hp.woodshot.com/ , or any similar free tool.
13. Bonus part (+1 mark): do the frequency sweep for calculation the L_{AC} versus frequency. If you do that, provide the plot $L_{AC}(f)$ with logarithmic scale of the frequency axis as we do in the presentation Seminar_8.