EM Analysis of RFIC Transmission Lines

Purpose of this document:

In this document, we will discuss the analysis of single ended and differential on-chip transmission lines, the interpretation of results and the use of extracted models.
For those readers who are interested in some theoretical background, the document includes an introduction to transmission line concepts, such as characteristic line impedance and impedance transformation.

Table of contents:

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Transmission line basics

A transmission line consists of signal and return path. In RFIC, line pairs are widely used, which consist of two signal lines over a conducting substrate. These lines have effectively two good conductors (the signal lines) plus one weak conductor (the conducting substrate) which can carry differential signals, common mode signals or any combination.

The idea of all transmission line analysis in this document is this: For analysis, we consider a homogeneous piece of transmission line, so that the cross section of the line is constant over the entire length of the line. We can analyze a short piece of line, and then get the response of a longer line by just cascading multiple segments.

To get started, we will look at a simple single mode (two conductor) transmission line, like a microstrip line. Later in this document, we will extend this to differential transmission lines, as used in RFIC.

The image below[1] shows the equivalent circuit model of a short piece of transmission line. This piece of line has a series resistance R and a series inductance L, as well as a lossy shunt capacitance C with conductance G. All these values scale with the length of the line, so that the concept of "values per unit length" has been developed. These per unit length values are usually noted R', L', C' and G'.
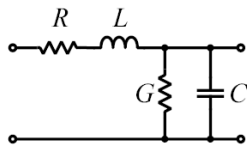
This is a valid description for a piece of line up to a certain length, which depends on the frequency of operation, or to be more precise, on the signal's wavelength. The equivalent circuit is valid for electrical lengths up to 1/20 wavelength or so. For longer pieces of line, multiple of these segments must be cascaded to get the overall response.
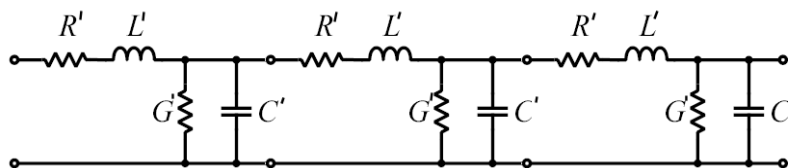
At DC, the line is characterized by the DC series resistance R (ohmic conductor loss). Conductance G describes the dielectric loss of the isolator and will usually be 0 at DC.

At high frequencies, the inductance and capacitance per unit length become relevant and the line starts to show a frequency dependent behaviour. However, there is one case where we can transfer a signal over the line with distorting the frequency response: if we use a "matched" line where the "characteristic line impedance" matches the source and load impedance.

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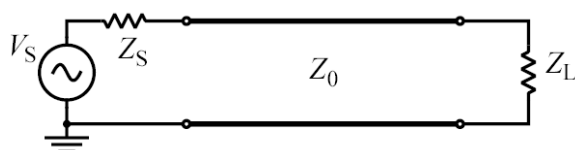
[1] From: http://en.wikipedia.org/wiki/Transmission_line

Line Impedance

The characteristic transmission line impedance is defined as

$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

and for the lossless case, with no dielectric or conductor loss, this can be simplified to

$$Z_0 = \sqrt{\frac{L'}{C'}}$$

This ratio of inductance and capacitance per unit length, in combination with the matching impedance of source and load, allows to transfer a signal over the line with no degradation in the signal waveform. That is why matched lines are of great interest.
In the real world, a line has some frequency dependent loss which will affect the signal waveform and give some kind of low pass behaviour. But still, the matched line guarantees the best possible power transfer from the source to the load.

A typical line impedance value in measurement instruments is 50 Ohm, and one might ask why we call it "50 Ohm". Sure, this is the mathematical result of the equation above, but can we actually measure a 50 Ohm resistance somewhere?
Yes, we can! If we terminate a lossless 50 Ohm transmission line properly, with the termination resistor equal to the line impedance, then we will measure a resistance of 50 Ohm at the input of the line at all frequencies. The input of the line then behaves like a physical resistor when the other end of the line is properly terminated with the line impedance.

Impedance transformation

Now, what happens if the line is terminated with a different value? That depends on the electrical length of the line. For a lossless line, the impedance at the input of the line Z_{in} is

$$Z_{in}(l) = Z_0 \frac{Z_L + jZ_0 \tan(\frac{2\pi l}{\lambda})}{Z_0 + jZ_L \tan(\frac{2\pi l}{\lambda})}$$

where Z_L is the load impedance, Z_0 is the line impedance, l is the electrical length of the line and λ is the wavelength. In this context, "electrical length" means the electrically effective length with the extension factor $\sqrt{\varepsilon_r}$ from dielectric materials included.

It can be seen that in general, the input impedance can be a complex number. Depending on the load impedance and the length of the line, we can get a resistive, inductive or capacitive input impedance into the line. For proper termination with $Z_L = Z_0$, we get $Z_{in} = Z_L = Z_0$
independent of the line length and frequency/wave length. This is the special "matched line" case which we want to use for transmission lines.

Above, a rule of thumb was mentioned that transmission line effects must be considered when the electrical line length exceeds ~1/20 wavelength. For shorter lines, we do not

have to consider impedance transformation, and it is sufficient to consider the corresponding series and shunt elements as discrete values. A short piece of line with small cross section might behave simply like a resistor, due to the conductor losses, with some small series inductance and some capacitance to the substrate.

For longer lines, which are not properly terminated, a high load impedance Z_L is transformed into a low impedance Z_{in} at the input of the line, and vice versa, when the line length is ¼ wavelength, ¾ wavelength etc. If the length of the line is a multiple of ½ wavelength, then the input impedance is equal to the load impedance. The bigger the difference between line impedance and termination impedance, the stronger is the frequency dependent variation of the input impedance.

A common method to calculate the complex input impedance is the Smith Chart[2] as shown below, where the center 1+i0 is normalized to the reference impedance. The transformation from a line appears as circles in this diagram, where the center of the circle is the line impedance Z_0.
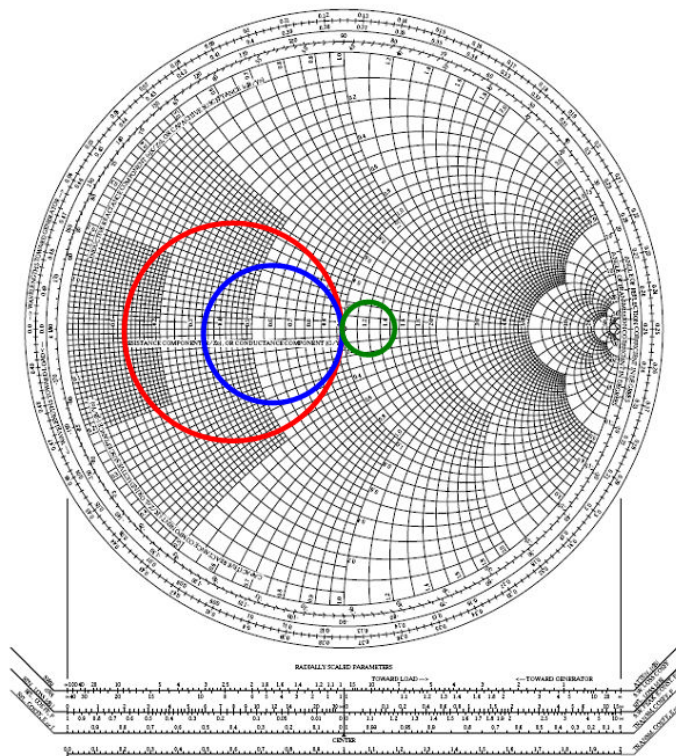
For short pieces of lossless transmission line, the impedance at the input of the line is essentially the load impedance, no matter what line impedance we have. If the line is lossy, then the low frequency input resistance is the load impedance plus the total ohmic series resistance of the line.

The whole concept of matched transmission lines with a line impedance is only relevant when the line reaches a critical length of more than 1/20 wavelength or so. For short pieces of line, it is much easier to just consider the RLCG values with the simple equivalent circuit model shown above.

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[2] Graphics from: http://www.printfreegraphpaper.com/gp/smith-a4.pdf
Tutorial on using the Smith chart: http://sss-mag.com/smith.html

Reflection and Transmission, S-Parameters

Often, the so called S-parameters (scattering parameters) are used when specifying transmission lines and other high frequency structures. This is a concept which uses ports rather than nodes. Each signal node and the corresponding reference/ground node are grouped together into one port.

This reduction from nodal parameters to modal parameters is for one specific mode of operation only. When we talk about attenuation between port 1 and port 2, we do not know if that was from the signal current in the signal line, or from return current in the return line. Actually, we do not care because S-parameters are given for a specific mode, like differential mode or common mode, which defines the ratio of current of the conductors, so that the description of the line is complete for this specific mode. For other modes of operation, we have another set of S-parameters.

S-parameters are given as a function of frequency, with all ports properly terminated. The idea is that we measure our device under test by incident waves at the ports, and specify the magnitude and phase of reflected and transmitted waves (voltages). The image[3] below gives an overview:
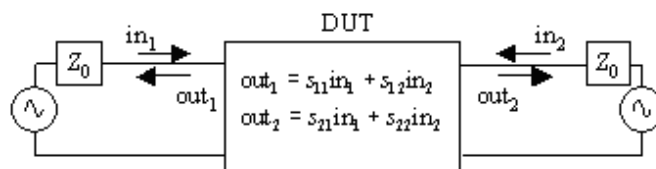
$$s_{11} = \frac{out_1}{in_1}\bigg|_{in_2 = 0} \qquad s_{12} = \frac{out_1}{in_2}\bigg|_{in_1 = 0}$$

$$s_{21} = \frac{out_2}{in_1}\bigg|_{in_2 = 0} \qquad s_{22} = \frac{out_2}{in_2}\bigg|_{in_1 = 0}$$

This is an efficient way to describe the frequency dependent effects of the line.
For a matched line, the input reflection S11 and output reflection S22 is zero, or -∞ dB.
The transmitted signal is then S21=1 and S12=1, or 0dB.

To optimize a transmission line for a flat frequency response, we optimize for minimum reflection. Then, the transmission factor S21 gives the attenuation due to mismatch and loss.

The table below gives the relationship between reflection factor S11, the reflected signal and the transmitted signal for a lossless line.

| S11 (dB)	reflected power	transmitted power
-3dB	50%	50%
-10dB	10%	90%
-16dB	2.5%	97.5%
-20dB	1%	99%
-30dB	0.1%	99.9%

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[3] From: www.sigcon.com/images/news/v6_03a.gif

A simple transmission line in Sonnet

In Sonnet, we always have a closed environment (box) which can be used as the ground reference for analysis. For microstrip lines, which consist of a signal line with a large ground below, we can use the bottom of the box as ground.

Box side wall = ground reference for port

Bottom of the analysis box =
back side metalization for microstrip
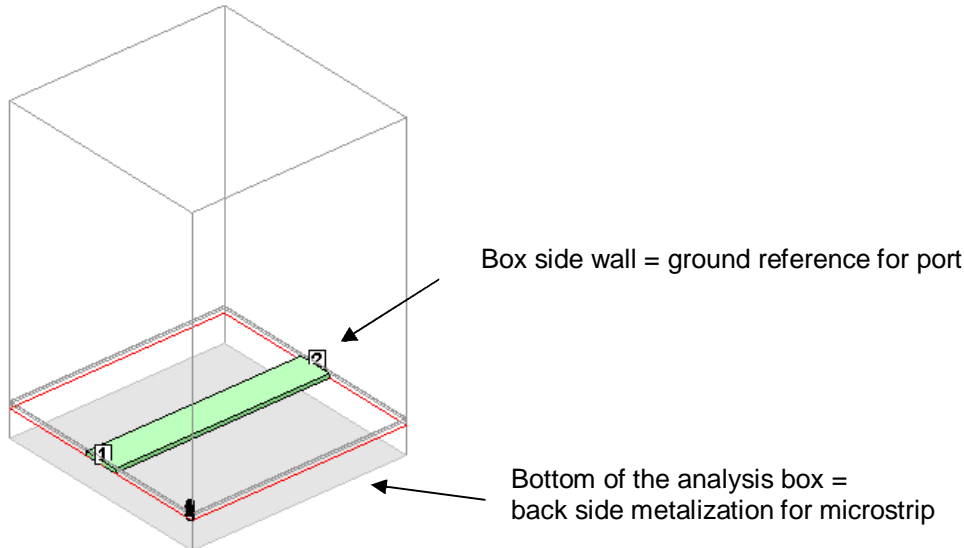
Now, current can flow through the conductor that we have modelled, and return through the ground plane = bottom of the analysis box. If needed, we can also model an explicit return ("ground") metal and force the return current to flow there.

Assuming that we have modelled a short piece of line, shorter than ¼ wavelength at the highest analysis frequency, the analysis result might look like this:
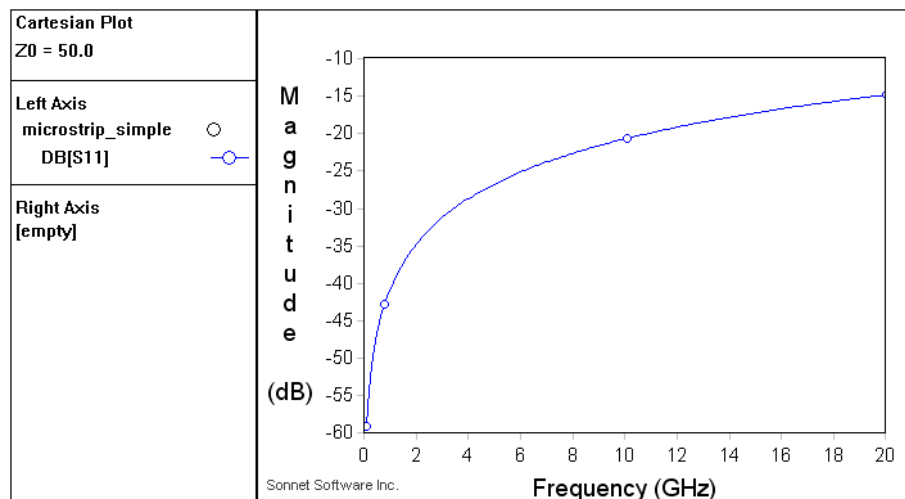
We see very little reflection (S11) at low frequencies, where the line has no effect because it is short compared to the wavelength, and increasing reflection to higher frequencies where the line starts to do some impedance transformation. From the plot above, with reflection S11 as high as -15dB, we can see that the line is not properly matched to the 50 ohm port impedance, but we cannot read the related line impedance directly. There are a multiple ways to find out that line impedance value, as discussed below.

If there is only one port on the box side, the easiest possibility is to look at the result of the Sonnet port calibration. As a part of the EM analysis, the solver will analyze different calibration standards and, as a side result, plot the resulting line impedance and effective dielectric constant.

Plot the "Data Type" Port Z0 and choose which port calibration result you want to plot. For example, PZ1 is the line impedance at port 1. For the example shown above, where the line at port 1 and port has the same geometry, results for PZ1 and PZ2 are identical. The plot shows a data point for each EM analyzed frequency. We can see that the line impedance is ~26 Ohm in our example. The change of Z0 with frequency results from the losses of the line.
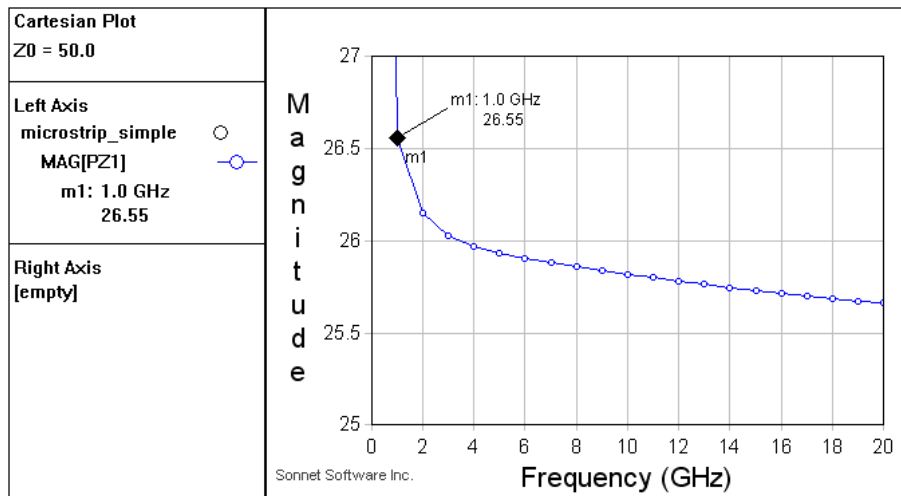

We will now verify the result Z_0 = PZ1 = 26 Ohm with a different extraction method. The S-parameter results obtained from analysis can be exported in different formats, and it is also possible to extract equivalent circuit models. In the emGraph data display, among other options, we can choose to extract a Pi model and an N coupled line (RLCG) model.

R'L'C'G' Extraction

We choose the N coupled line model, which gives the per unit length values for R' L' C' G' discussed in the section on transmission line basics. One set of values is extracted for each frequency point, including the interpolated frequencies.

The format has changed from Sonnet 11 to Sonnet 12, so that both versions are described below. Let's have a look at the 1GHz extracted values from Sonnet 11:

```
*   Analysis frequency: 1000 MHz
*   *****Place terminations after this line.*****
.model ymod tra nlines=1
+ lmatrix=0.055721n
+ rmatrix=0.074681
+ cmatrix=0.080604p
+ gmatrix=7.439e-9
```
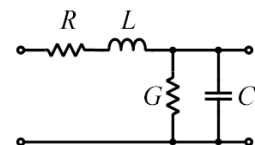
These values are for the analyzed length of line, which is 320µm.

Accounting for that length, we get the per meter values as listed in the table:

L′	0.055721nH / 320µm	174nH/m
R′	0.074681 Ohm / 320µm	233 Ohm/m
C′	0.080604pF / 320µm	250pF/m
G′	7.4nS / 320µm	23µS/m

In Sonnet 12, the N coupled line model has been re-designed to create output for the Cadence Spectre directly (mtline from analogLib) with values per meter. This means that in Sonnet 12, the results are independent of the analyzed line length and no re-normalization is required.

By using the approximation for a lossless line, $Z0=\sqrt{(L'/C')}$, we can calculate $Z0 = \sqrt{(174nH / 250pF)} = 26.4$ Ohm which agrees well with the value obtained from the port calibration.

The reason for the small difference between the two values is that we used the approximation for Z0, which is only correct for a lossless line. To calculate the exact value, we would need to do the complex math with the full equation including R′ and G′.

$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

That leads to a larger, complex value of Z0, which increases towards DC. It might be unexpected to see that increase at low frequency, but is indeed correct, and Z_0 changes from $Z0=\sqrt{(L'/C')}$ at high frequencies to $\sqrt{(R'/G')}$ at DC. The practical effect of that is very limited, because at low frequencies, the line is short compared to the wavelength and thus the impedance transformation is not an issue, no matter what the value of Z_0 is.

One requirement for using the Sonnet N coupled line model in Sonnet 11 and before is that the analyzed piece of line is electrically short up to the highest analysis frequency. We have not yet checked that, so let's have a look: we simply plot the transmission (S21) phase.

Our limit for "electrically short" was an electrical length of 1/20 wavelength, which means a transmission phase shift of less than 360°/20 = 18°.
According to that definition, our piece of line is electrically short up where the phase shift is less than 18°, and we can extract the R′L′C′G′ model at these frequencies using the Sonnet N coupled line model. If we want to extract at higher frequencies, a shorter piece of line should be simulated.
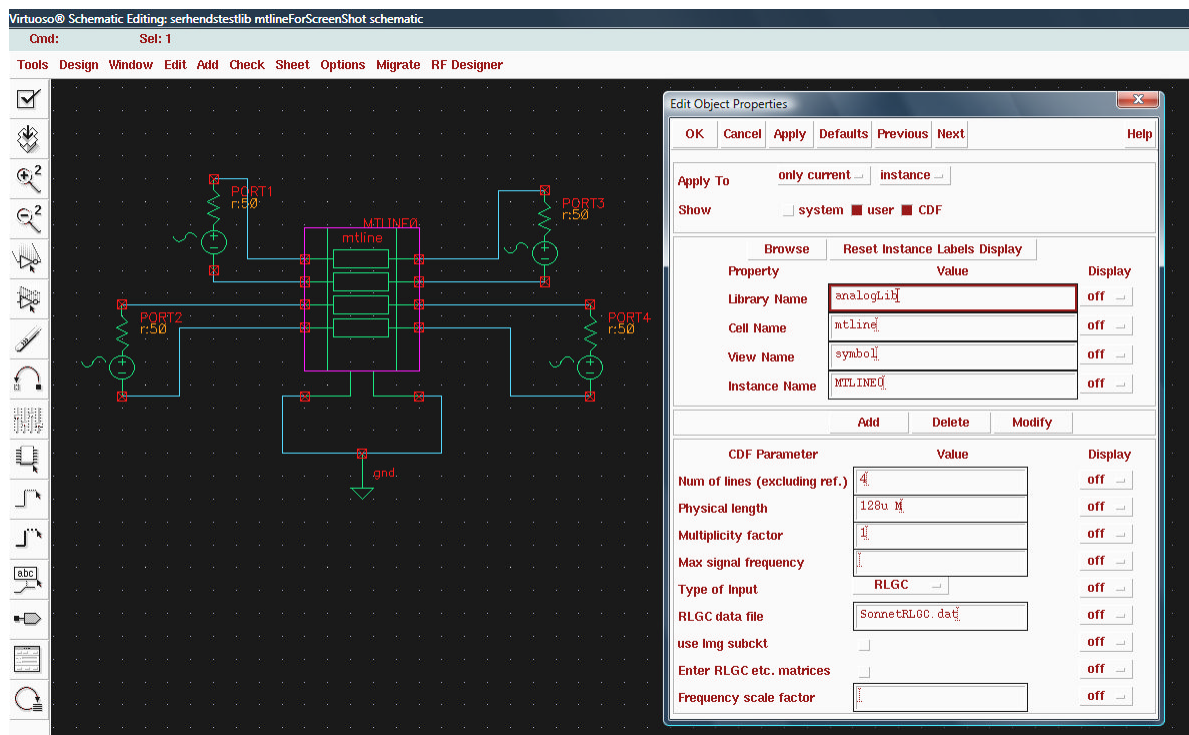
In Sonnet 12.54 and later, another method of R′L′C′G′ extraction is used and the analyzed length of line does not have to be electrically short.

Use extracted R'L'C'G' data for the Cadence mtLine element

One practical application of the N coupled line model is the mtLine transmission line element in the Cadence analogLib, which offers scalable length and can be used with single lines or multiple coupled lines. The input to that model is an R'L'C'G' data file, which can be created by Sonnet.

The benefit is that you can analyze one piece of line, and then use the extracted results with the scalable mtLine element to simulate other lengths of line in Cadence.
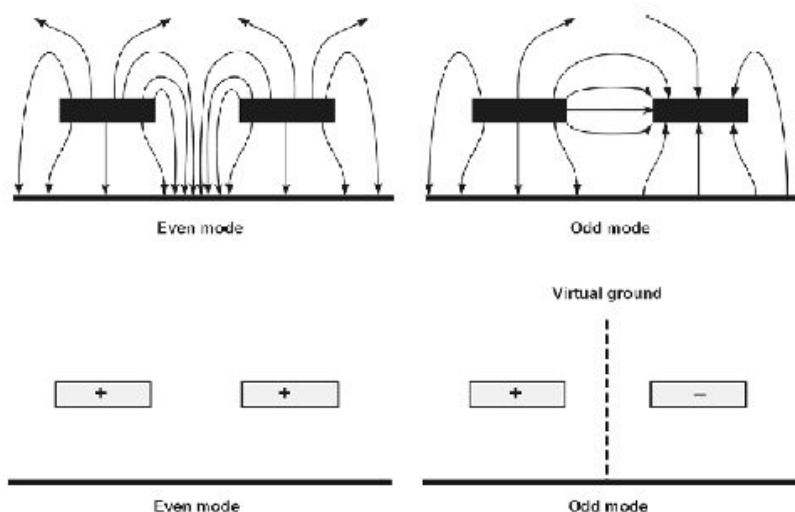
Differential transmission lines

In RFIC, the widely used differential circuit designs require balanced, differential transmission lines. These consist of two lines, which are driven with 180° phase shift, and ideally, all current is only flowing through these lines. However, in the practical implementation there is another "global ground" somewhere and we have to consider a three conductor system. The differential mode is the desired mode of operation, but due to asymmetry, we might also have some common mode signal on the lines.

Common mode and differential mode, Zeven and Zodd

For the configuration with two conductors and ground, any signal can be decomposed into a differential and a common mode component. For the Sonnet analysis, we can simulate a general case with 4 independent ports, or we can simulate specifically the differential or common mode.
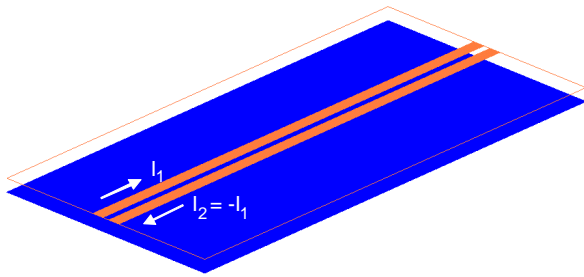

The image below[4] shows the configuration and electric field for these two cases: common mode where the two lines have same polarity (connected in parallel) and differential mode where the two lines have 180° phase shift (connected in series).

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[4] From: http://www.microwaves101.com/encyclopedia/evenodd.cfm
and http://www.polarinstruments.com/support/cits/AP157.html

For differential mode, the so called "odd mode impedance" $Z_{0, odd}$ or Z_{oe} is found in tables and line impedance calculators. It is important to understand what that value means. In the schematic below, a pair of lines is driven in differential mode.

The line of symmetry indicates that only half of that setup is considered to get the $Z_{0, odd}$ value: the source and load resistance are cut in half effectively.
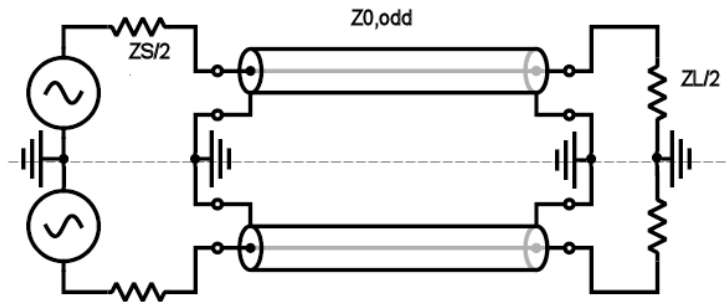

For a differential circuit with 100 Ohm source impedance and 100 Ohm load impedance, we need a transmission line with 100 Ohm characteristic impedance. It is important to understand that $Z_{0, odd}$ of that line is 50 Ohm because of the definition of $Z_{0, odd}$. That might be confusing if you use tables or tools where that odd mode impedance is used, and you have to consider that factor 2 from symmetry.

Impedance definition in Sonnet for differential lines

If you only work in Sonnet, don't get confused by that even and odd mode line impedance definition! Within Sonnet, you will be working with the "true" differential values and port impedance = source impedance = load impedance = differential line impedance = 100 Ohm in the example above.

To define a differential port in Sonnet, place two port symbols and assign positive and negative port numbers. To assign a port impedance, select both symbols and assign the required port impedance with Modify > Port Properties. That port impedance is the total source/load impedance between the + and – ports. In Sonnet, you assign 100 Ohm to the ports symbols if you are working in a 100 Ohm system, and this sets the total port impedance.
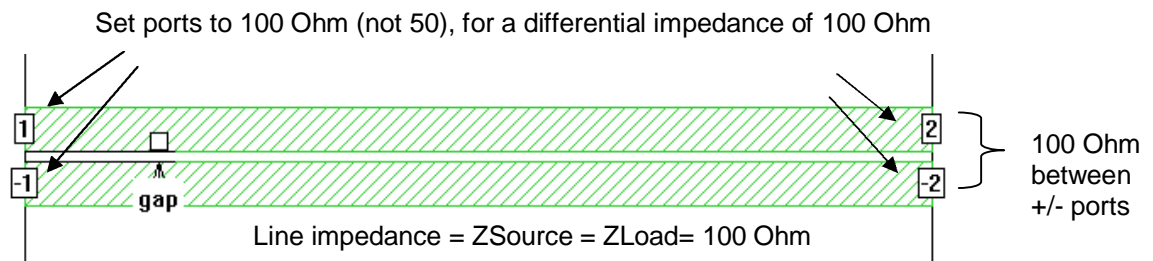

As discussed earlier for a single line, Sonnet will calculate the line impedance for ports, as a side result of the port calibration. When you plot the "Data Type" Port Z0 for a line, you need a 100 Ohm differential line impedance to match to the 100 Ohm ports. Sonnet uses the differential impedance values, instead of the somewhat confusing $Z_{0, odd}$ or Z_o definitions.

Differential mode and common mode in Sonnet

We have seen above that a differential mode can be defined in Sonnet by using multiple ports with the same number, but opposite polarity. In a similar way, common mode can be defined by defining multiple ports with the same port number and the same polarity.

However, be careful with these ports which force a specific mode. Signals with other modes will not be "visible" at the port, and they will not be terminated properly.

Let's look at an example: the line below has a differential port on the left side and a common mode port on the right side. This means that there is no transmission, because this line does not convert from differential to common mode, and that both ports show a strong reflection because the other end of the line is not properly terminated ("open") for the excited mode.

differential port +/-   MISTAKE!   common mode port +/+
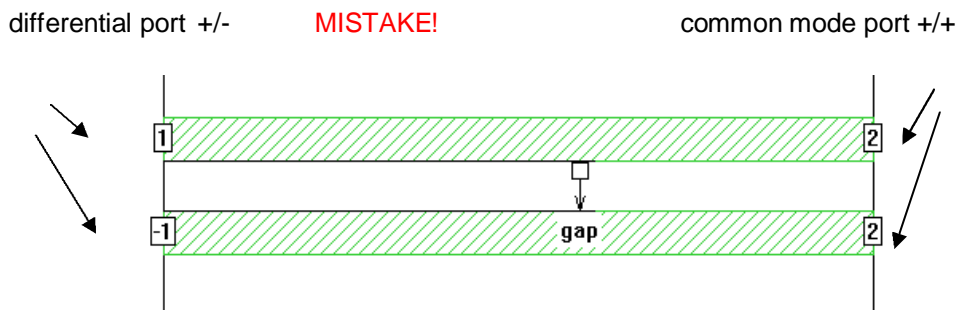
We could actually use such a configuration if we want to study mode conversion, for example from lines which are not perfectly symmetric. But these are special cases, and we always have to consider the termination for the different modes. A common mode port represents an open circuit to a differential signal, and vice versa.

One way to overcome this issue of modes is to analyze a generic configuration, where we use one port for each signal line, and do not enforce any specific mode during Sonnet analysis. This is the general case, which includes the solution for differential and common mode case. Sonnet will not print out a line impedance for this general case, because a line impedance is always tied to one specific mode. But once we have designed and fixed the geometry for a certain mode, we can use the general case to take the EM analysis result into Cadence without forcing specific modes.

To use the analysis result in Cadence, we can simply use the four port S-parameters, or take the output to Cadence as an N coupled line model for the mtLine transmission line element in the Cadence analogLib, or use an extracted broad band SPICE block.
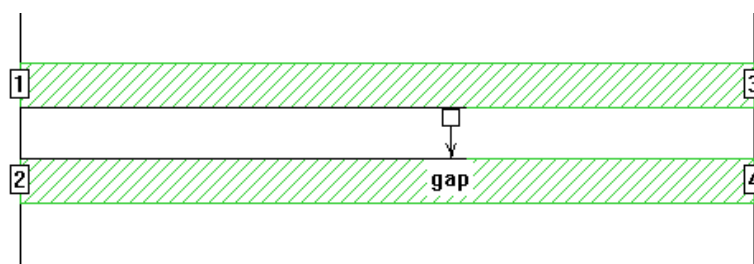
Where is the return path?

A popular question from new users is: How can I model a two conductor system and see the effect of each conductor individually in the results?
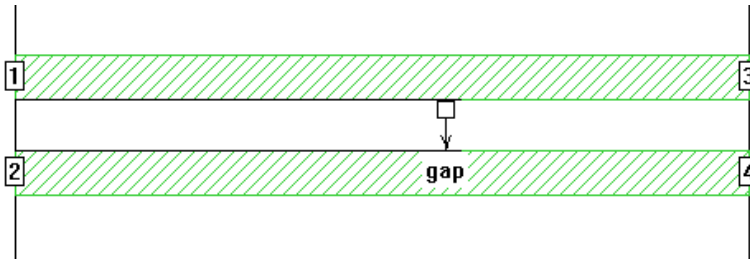
This is a simple question, but the answer is not so simple.

If we model this with one differential port on each end (+1/-1 and +/-2), we get results for "the line", which include the effects of signal and return path. We can tell what the total values of resistance, inductance and capacitance are but we cannot tell where these are physically located in the signal or return path. With this port definition, the current in one conductor will always return in the other conductor, and from the differential voltage & current at the ports we cannot measure the effect of each conductor individually.

To measure each conductor individually, we would need to drive a signal through that conductor only, but then we need a different return path. There must always be a physical return path to close the current loop! If we define the two conductors as a four port, as shown above, then the Sonnet box will act as the return path. To be more specific: the return current will now flow through the box walls and/or through the top and/or bottom of the analysis box, and this is part of the analysis result. Be careful when using these results, because the return path in your hardware might be different. If possible, you should include a return path in the simulation which is close to the actual hardware, to get physically meaningful results.