Attenuator Design Tutorial

Introduction

Attenuators are devices used to adjust signal levels, to control impedance mismatch and to isolate circuit stages.

Passive design

Passive attenuators consist of two types ‘pi’ and ‘Tee’ attenuators.

(1) Pi Attenuator

The circuit for the Pi attenuator is shown in Figure 1.

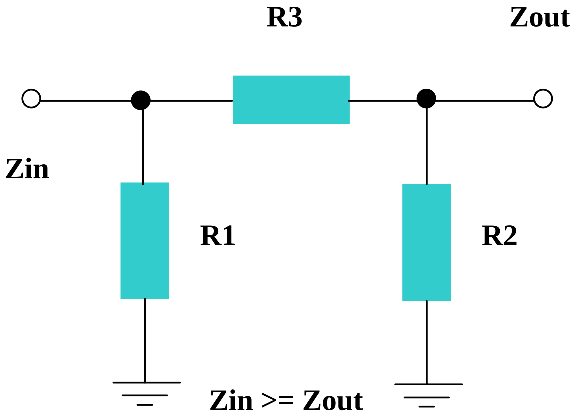


Figure 1 Pi Attenuator

$$R3 = \frac{1}{2}\left(10^{\frac{L}{10}} - 1\right)\sqrt{\frac{Zin * Zout}{10^{\frac{L}{10}}}}$$

$$R2 = \frac{1}{\dfrac{10^{\frac{L}{10}} + 1}{Zout\left(10^{\frac{L}{10}} - 1\right)} - \dfrac{1}{R3}}$$

$$R1 = \frac{1}{\dfrac{10^{\frac{L}{10}} + 1}{Zin\left(10^{\frac{L}{10}} - 1\right)} - \dfrac{1}{R3}}$$

Where L = desired loss in dB
Zin = desired input impedance (ohms)
Zout = desired output impedance (ohms)

(2) Tee Attenuator

The circuit for the T attenuator is shown in Figure 2

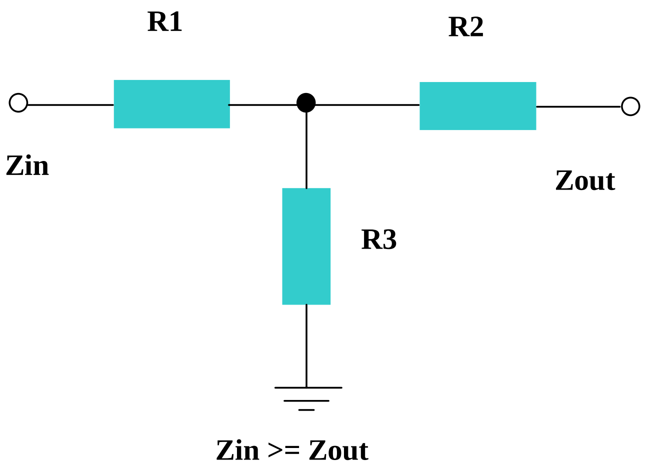


Figure 2 Circuit of the T attenuator

$$R3 = \frac{2\sqrt{Zin * Zout * 10^{\frac{L}{10}}}}{10^{\frac{L}{10}} - 1}$$

$$R2 = \frac{10^{\frac{L}{10}} + 1}{10^{\frac{L}{10}} - 1} Zout - R3$$

$$R2 = \frac{10^{\frac{L}{10}} + 1}{10^{\frac{L}{10}} - 1} Zin - R3$$

Where L = desired loss in dB
Zin = desired input impedance (ohms)
Zout = desired output impedance (ohms)

(3) Bridged T Attenuator

The circuit of the bridge T attenuator is shown in Figure 3

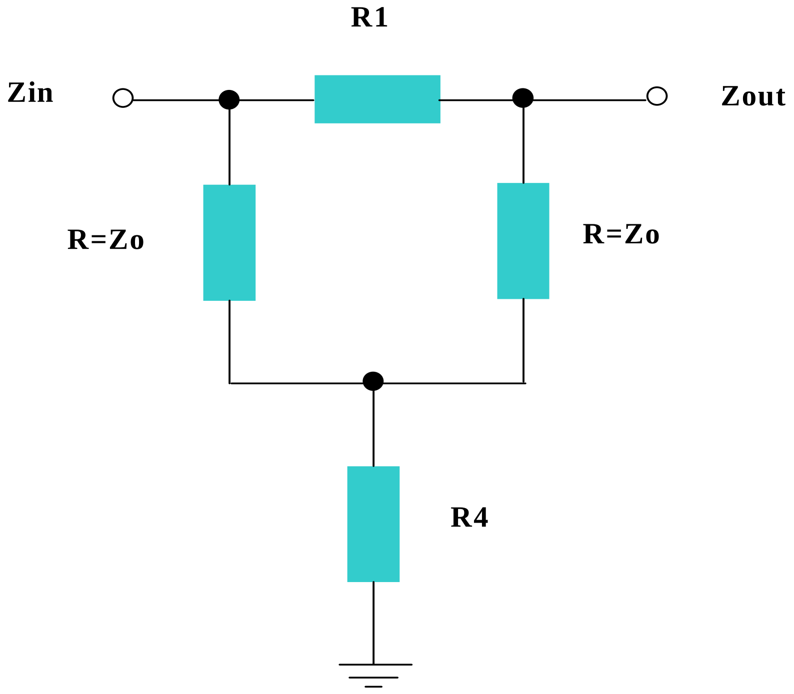


Figure 3 Circuit of the Bridged-T attenuator

$$R1 = Zo\left(10^{\frac{L}{20}} - 1\right)$$

$$R4 = \frac{Zo}{10^{\frac{L}{20}} - 1}$$

Where L = desired loss in dB
Zin = desired input impedance (ohms)
$Zout$ = desired output impedance (ohms)
Zo = Circuit characteristic impedance (ohms)

This circuit is commonly used with PIN diodes to form an electronic attenuator, as only two variable resistors are required (instead of 3 for the Pi or T attenuators).

Narrow-band active variable attenuator design

If we use the bridged-T network as a basis of an active attenuator we need to add the bias circuits to complete a basic design. Figure 4 Shows the complete electronic bridged-T attenuator together with the correct bias circuits.

The circuit has been set up such that the currents through D1 and D4 are inverse to each other ie when D1 current is high then D4 current is low and visa versa. When the PIN diode is on (high current)is has low attenuation. So when D1 is on and D4 is off, the two R’s and D4 are out of circuit and the attenuation through the circuit is low.

When D1 is off and D4 is on the signal instead of passing through D1 will pass to ground via D4 and the circuit will be in a high attenuation state. Intermediate currents through D1 & D4 will allow attenuation from max to min.

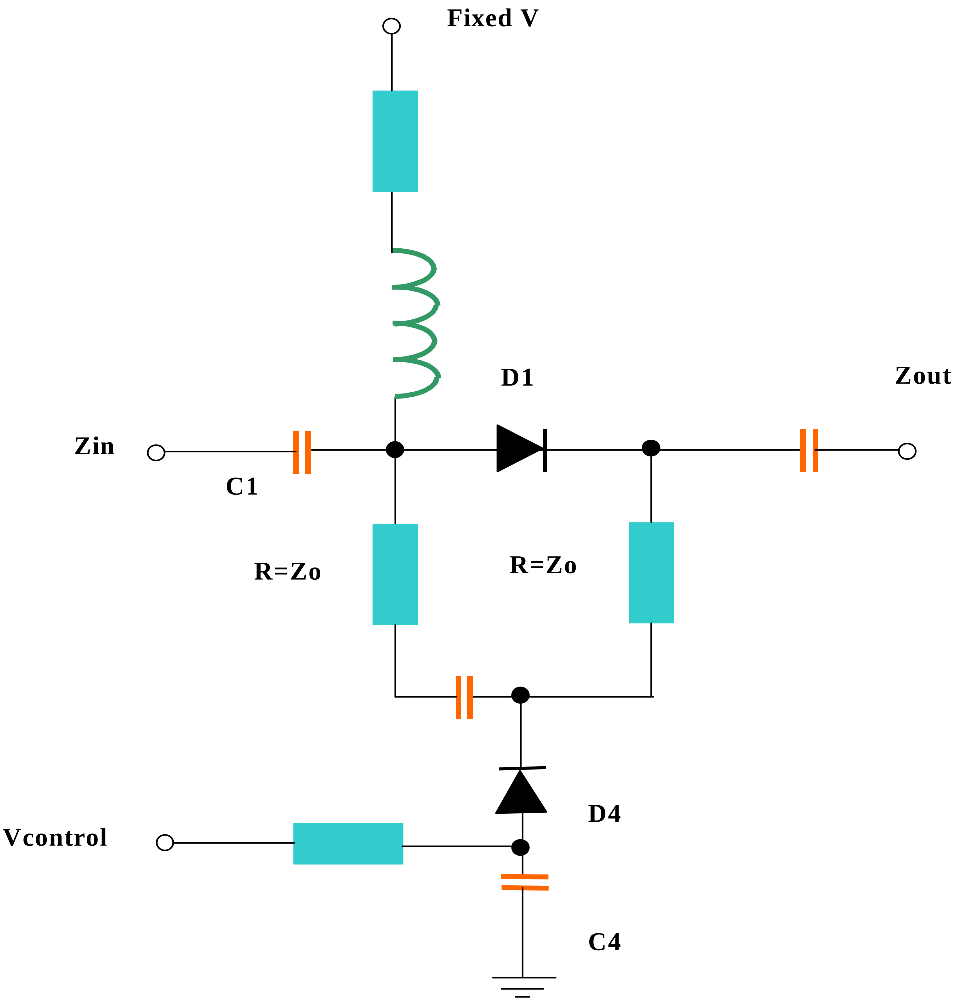


Figure 4 Electronic version of the Bridged T attenuator, where resistors R1 & R4 have been replaced by PIN diodes D1 and D4.

A typical microwave PIN diode is from Agilent HSMP-3810 has a low resistance of 10 ohms and a high resistance of 1500 ohms.

Therefore, using such a device we could design an attenuator with the following min and max attenuations:-

Minimum attenuation

$$L = 20\log\left(\frac{R1}{50}+1\right) = 20\log\left(\frac{10}{50}+1\right) = 1.58\text{dB approx}$$

Where $L = \text{desired loss in dB}$

Maximum attenuation

$$L = 20\log\left(\frac{R1}{50}+1\right) = 20\log\left(\frac{1500}{50}+1\right) = 29\text{dB approx}$$

Using the data sheet it is possible to design a model in ADS and the resulting circuit is shown in Figure 5.

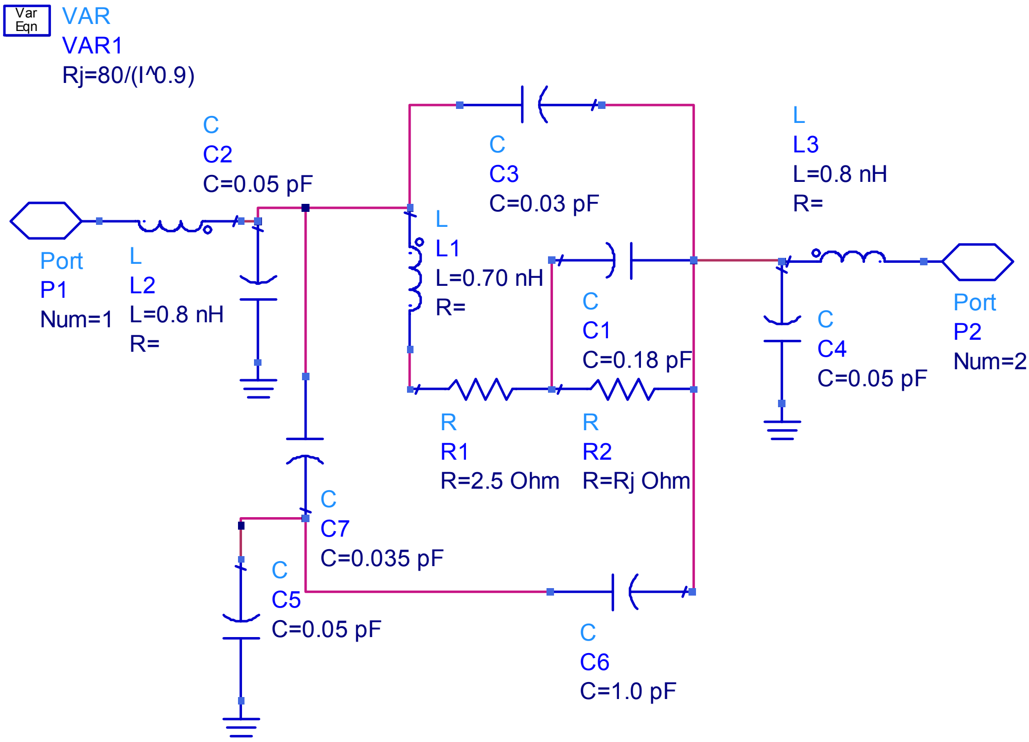


Figure 5 ADS sub-circuit of the PIN diode Agilent HSMP-3810. The diode chip consists of R1, C2 and the variable resistor R2 defined by the equation Rj. When designing sub-circuits in ADS you need to select File-Design Parameters and add any variables you want to pass through a higher simulation in this case I has been added and given a default value of 1mA. You can also switch to create/edit schematic symbol (under the view menu) to draw the component symbol.

The Bridge-T circuit was set up in ADS to include an S-parameter simulation box set to 2-2GHz and is shown in .

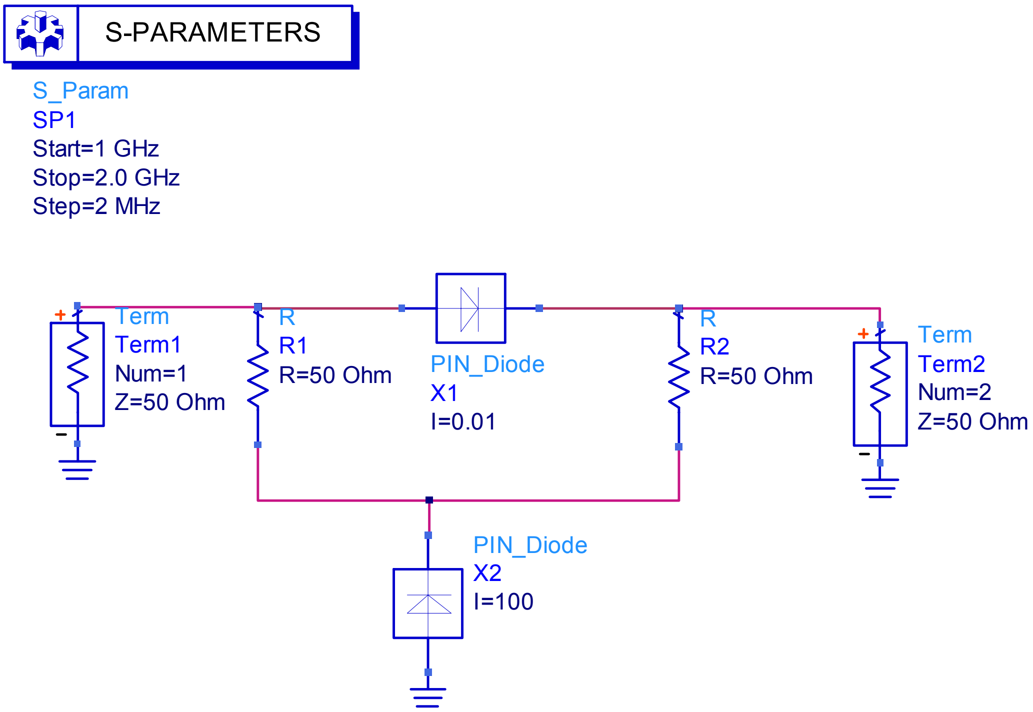


Figure 6 ADS schematic of the bridged-T attenuator. If you push into either X1 or X2 you will see the circuit shown in Figure 5. The values of I are set to 0.01 and 100 and then swapped to view the resulting simulations.

The two resulting simulations of the circuit shown above in Figure 6 are shown in Figure 8 (Minimum attenuation state) and Figure 9 (High attenuation state).

Note how the slope changes with frequency and attenuation. It’s possible to ‘match’ the PIN diodes using lumped or distributed matching circuits to minimise this slope. If look at the input return loss of the diode at mid-bias using the circuit shown in Figure 7, we obtain the smith chart shown in

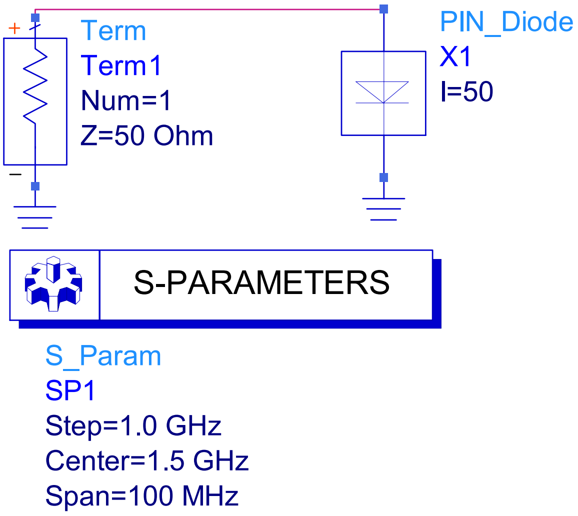


Figure 7 ADS schematic to measure the input return loss of the PIN diode at 1.5GHz.

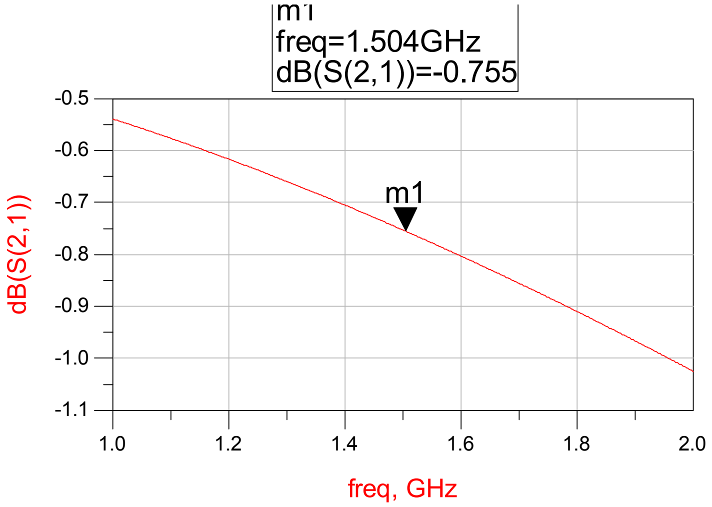


Figure 8 Minimum attenuation state with D1 set to 100mA and D4 set to 0.01mA (ie off)

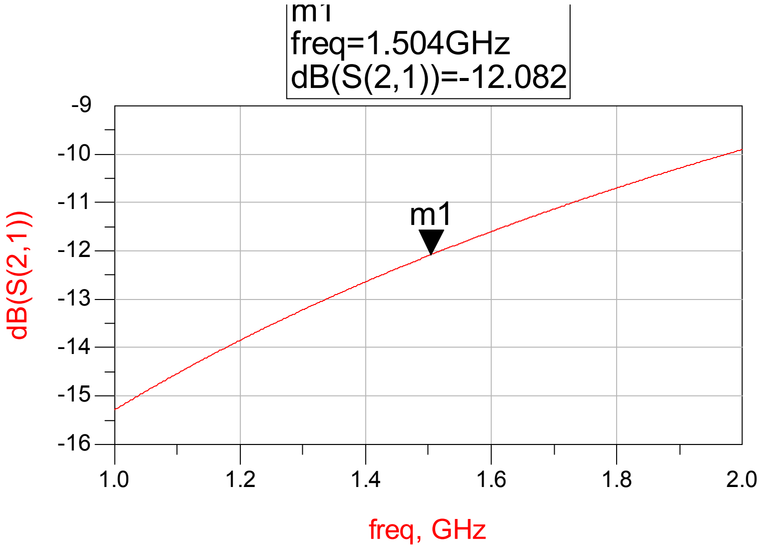


Figure 9 High attenuation state with D1 set to 0.01mA (ie off) and D4 set to 100mA.

Figure 10 Shows the input return loss of the Pin diode showing that it has inductance at 1.5GHz of some 22 ohms this equates to an inductance of ~ 2nH. So if we resonate this inductance with a capacitor of 4pF we should improve our frequency response. The new set of plots is shown in

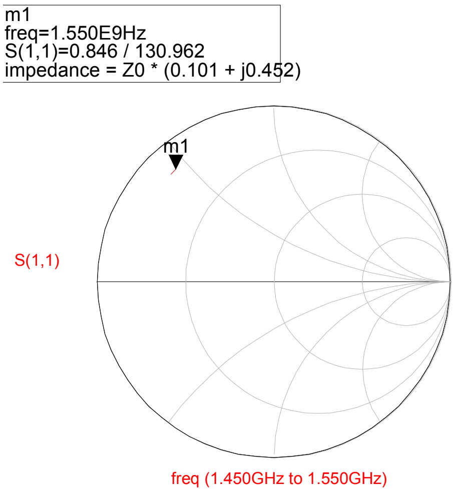


Figure 10 Input return loss of the PIN diode showing that at 1.5GHz it has an inductive impedance with a value of +j0.452*50 = 22 ohms.

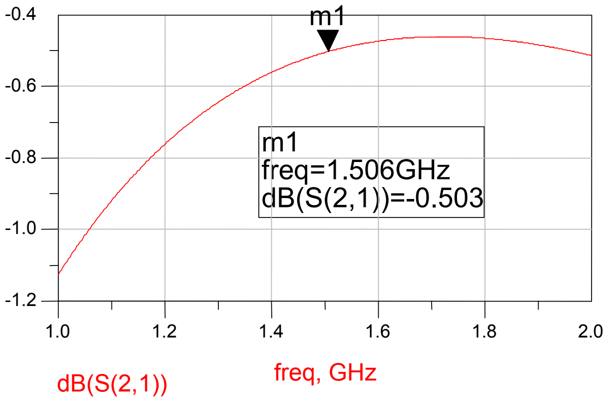


Figure 11 Minimum attenuation state with series 4pF capacitors added to each Pin diode.

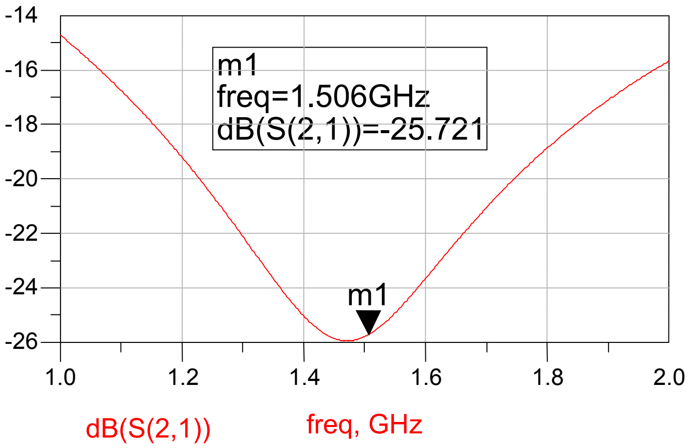


Figure 12 Maximum attenuation state with series 4pF capacitors added to each PIN diode.

Clearly such circuits have narrow band attenuation and for broader band type circuits lange couplers can be used:

Broad-band active variable attenuator design

In many situations it is better to have a broad-band attenuator that can be used at many different frequencies. So for example assume we to design a broad-band attenuator with the following parameters:-

Parameter		Units
Frequency range	6 to 10	GHz
Minimum attenuation	<1	dB
Maximum attenuation	>20	dB
Frequency ripple	< 2	dB pk-pk
Return loss	< -10	dB

The first thing we need to do is select a Pin diode that is designed for these frequencies. In this case a MaCom MA4P202 PIN diode was chosen as it's operating frequency range is specified as 50MHz to 18GHz and is available in chip form.

The model of the Pin is very simple and is shown in Figure 13. The variable resistance is actually non-linear but for the purposes of this example we will only be looking at max and min attenuation cases ie currents of 20uA and 10mA.

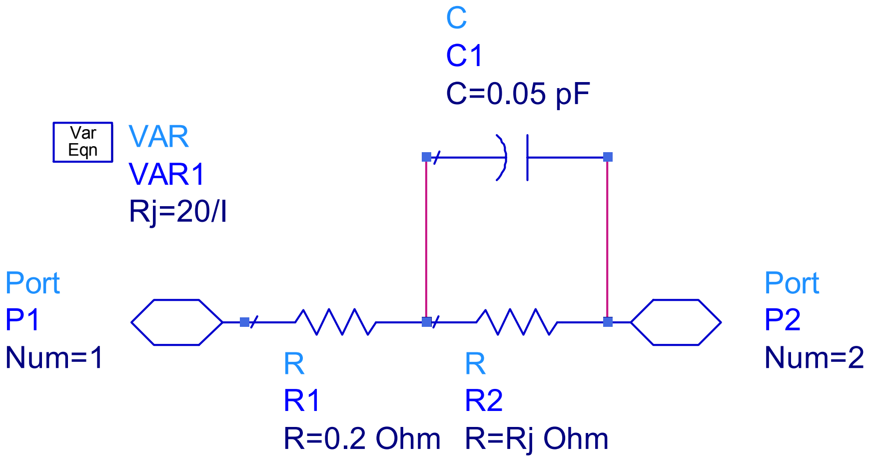


Figure 13 Simple model of the MACOM MAP202 PIN diode in chip form.
The full circuit of the broad-band attenuator circuit is shown in Figure 14.

The circuit is configured as a balanced attenuator with the use of the two Lange couplers – as with balanced amplifiers the poor return loss of the PIN diodes is greatly improved using quadrature hybrids. The inductors LB are the bond wires required to connect the chip to micro-strip lines either side of it (the other connection to ground is made on the underside of the PIN diode).

Capacitor CB is added to cancel out the effects of the bond wires and is set as an optimised variable as are the Lange variables Finger_spacing, Finger_length and Lange length.

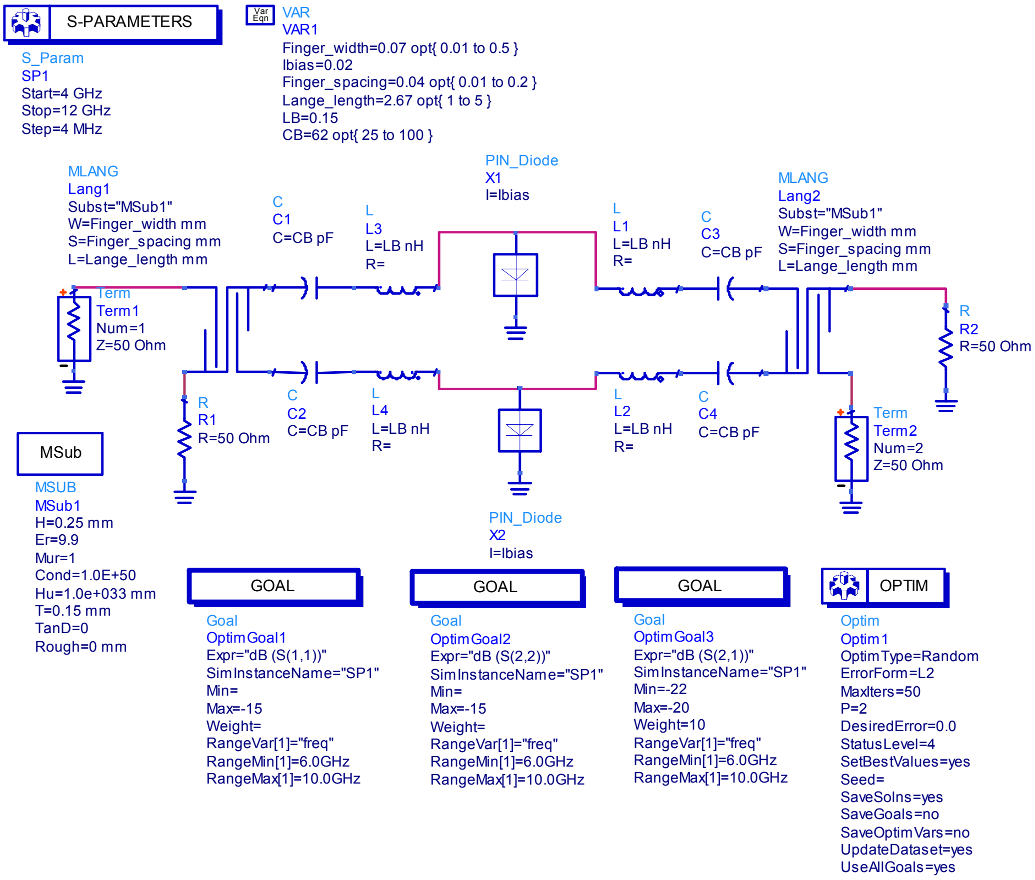
The Msub box defines the micro-strip substrate the circuit is to be made on – in this case Alumina 10 thou (0.25mm) thick.

There are three goals each tied to the S-parameter simulation 'SP1'. Each goal has a specified parameter in these cases dB S-parameters, a frequency range and a minimum/maximum goal.

The OPTIM box is used to specify the optimiser ie how many runs, the type of optimisation etc.

When a simulation is run and completed and the results satisfactory – update optimisation variables under the simulate menu to update the schematic – you can then check the simulation after disabling the OPTIM dialogue.

The first case to be run was minimum attenuation setting and for this the diodes were set to 20uA through the Ibias variable. The results of the optimisation are shown in



S-PARAMETERS
S_Param
SP1
Start=4 GHz
Stop=12 GHz
Step=4 MHz

VAR
VAR1
Finger_width=0.07 opt{ 0.01 to 0.5 }
Ibias=0.02
Finger_spacing=0.04 opt{ 0.01 to 0.2 }
Lange_length=2.67 opt{ 1 to 5 }
LB=0.15
CB=62 opt{ 25 to 100 }

MLANG
Lang1
Subst="MSub1"
W=Finger_width mm
S=Finger_spacing mm
L=Lange_length mm

C
C1
C=CB pF

L
L3
L=LB nH
R=

PIN_Diode
X1
I=Ibias

L
L1
L=LB nH
R=

C
C3
C=CB pF

MLANG
Lang2
Subst="MSub1"
W=Finger_width mm
S=Finger_spacing mm
L=Lange_length mm

Term
Term1
Num=1
Z=50 Ohm

R
R2
R=50 Ohm

R
R1
R=50 Ohm

C
C2
C=CB pF

L
L4
L=LB nH
R=

L
L2
L=LB nH
R=

C
C4
C=CB pF

Term
Term2
Num=2
Z=50 Ohm

MSub
MSUB
MSub1
H=0.25 mm
Er=9.9
Mur=1
Cond=1.0E+50
Hu=1.0e+033 mm
T=0.15 mm
TanD=0
Rough=0 mm

PIN_Diode
X2
I=Ibias

GOAL
Goal
OptimGoal1
Expr="dB (S(1,1))"
SimInstanceName="SP1"
Min=
Max=-15
Weight=
RangeVar[1]="freq"
RangeMin[1]=6.0GHz
RangeMax[1]=10.0GHz

GOAL
Goal
OptimGoal2
Expr="dB (S(2,2))"
SimInstanceName="SP1"
Min=
Max=-15
Weight=
RangeVar[1]="freq"
RangeMin[1]=6.0GHz
RangeMax[1]=10.0GHz

GOAL
Goal
OptimGoal3
Expr="dB (S(2,1))"
SimInstanceName="SP1"
Min=-22
Max=-20
Weight=10
RangeVar[1]="freq"
RangeMin[1]=6.0GHz
RangeMax[1]=10.0GHz

OPTIM
Optim
Optim1
OptimType=Random
ErrorForm=L2
MaxIters=50
P=2
DesiredError=0.0
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=no
SaveOptimVars=no
UpdateDataset=yes
UseAllGoals=yes

Figure 14 ADS simulation of the broad-band attenuator – see text for details on all the elements.

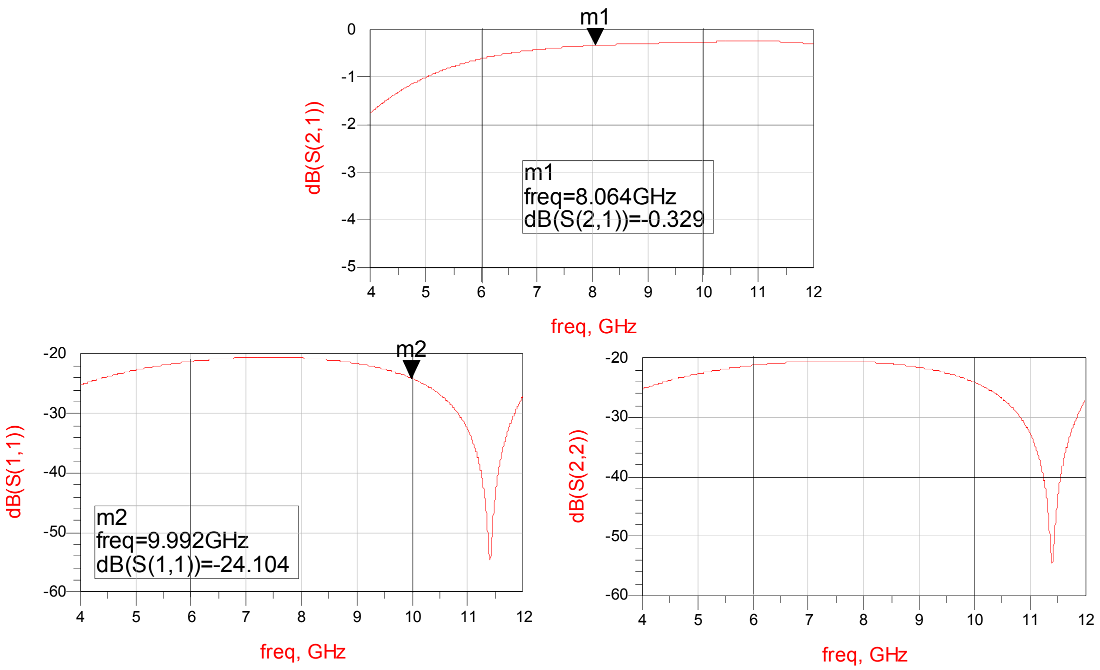


Figure 15 Minimum attenuation result after optimisation

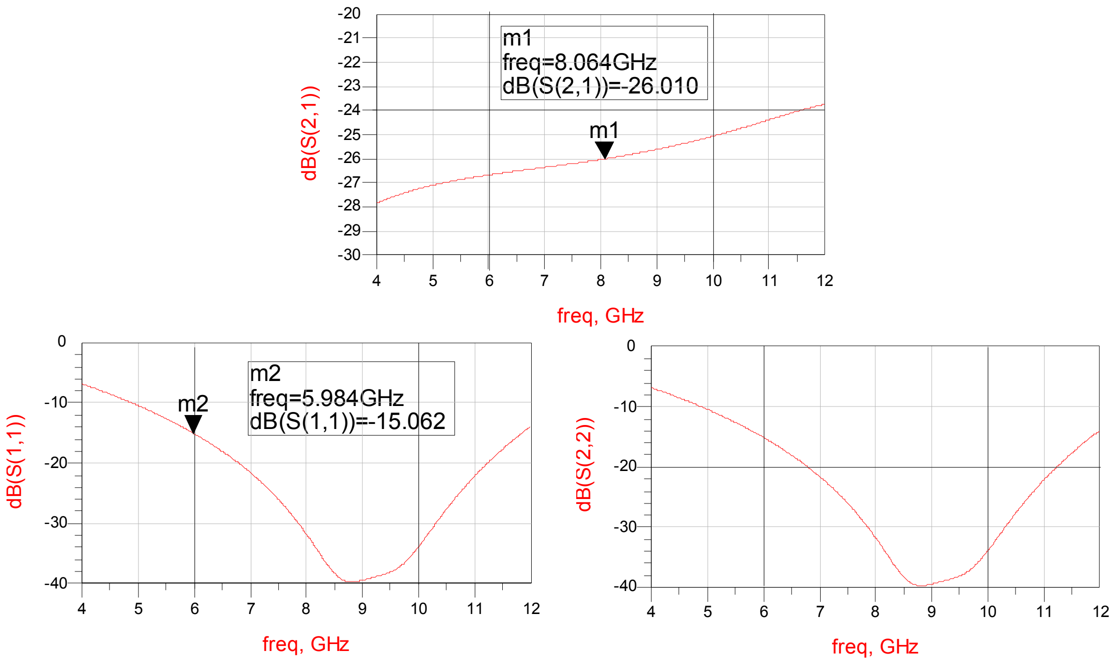


Figure 16 Maximum attenuation result, using values obtained during the minimum attenuation optimisation. The return losses have degraded but are still > 15dB as required by our specification.

Summary

The broad-band attenuator uses Lange couplers to provide a wide bandwidth attenuator capable of providing < 1dB loss over the pass-band with return losses >15dB as shown in Figure 15. In maximum attenuation state, the attenuator can insert >20dB of attenuation with again >15dB return loss as shown in Figure 16.

Broad-band active switched attenuator design

In some circumstances we want to be able to switch in a fixed amount of attenuation. The easiest way of doing this is to use two SPDT FET switches and a broad-band fixed attenuator as shown in.

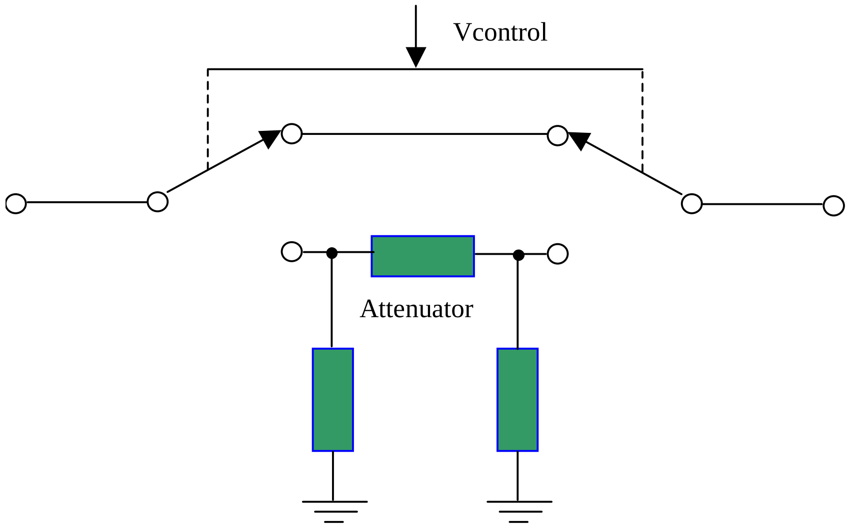


Figure 17 Switching fixed attenuator circuit – used in gain step applications where the switches are formed by GaAs SPDT switches eg MA4AGSW2 50MHz to 70GHz SPDT MMIC.

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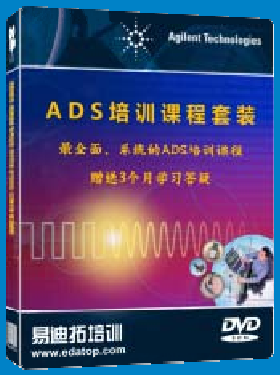

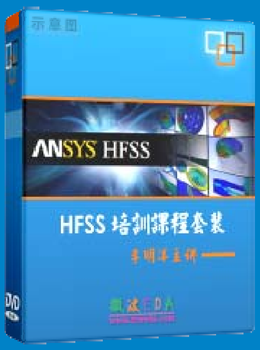

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