Delay Line Phase Shifter

T050250-01
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Theory of Operations

The delay line phase shifter uses a variable length stripline to delay the input signal by a selectable amount. Eighteen RF switches are used to route the signal either through fixed delay taps or short bypass paths (see schematics D050339). The fixed delay taps are $\frac{1}{16}$ ns, $\frac{1}{8}$ ns, $\frac{1}{4}$ ns, $\frac{1}{2}$ ns, 1 ns, 2 ns, 4 ns, 8 ns and 16 ns in length. Any delay between 0 ns and 31.9375 ns can bee added in steps of 0.0625 ns by using front-panel mounted toggle switches or through a digital interface such as EPICS. Since insertion loss is to be kept small, the RF switches have been specially selected and the stripline has been constructed with as large a copper cross-section as possible. The RF switches are PE4220 silicon-on-sapphire devices from Peregrine Semiconductor and have a nominal insertion loss of 0.1 – 0.2 dB between 10 MHz and 500 MHz. Their 1 dB compression point is at 22 dBm. The striplines are built on a 4 layer board with a total thickness of 0.125". This keeps the layer separation around 30 mils and requires 30 mil traces to yield 50 Ω transmission lines. With 3 oz. copper the cross-section becomes 0.87 mm^2. A 16 ns delay will require a trace length around 2.2 m. With a conductivity of $59.6 \times 10^6 \frac{1}{\Omega m}$ the resistance will be around 40 mΩ. It is clear that at RF frequencies skin effects will play a role as well. At 25 MHz the skin depth in copper is about 0.5 mils.

Specifications

	Minimum	Nominal	Maximum
Supply	9 V		24 V
Input power			20 dBm
1 dB compression point		22.5 dBm	
Intrinsic delay		3.7 ns	
Steps	0		511
Delay per step (design)		0.0625 ns	
Delay per step (at 50 MHz)	0.02 ns	0.0602 ns	0.10 ns
Differential non-linearity (at 50 MHz)	−0.06 ns		+0.06 ns
Fixed insertion loss (1 MHz to 200 MHz)		2.7 dB	
Variable insertion loss (phase shift < 180 °)	−0.6 dB		1.2 dB
Return loss	14 dB		

Setup

```
Needs["BarCharts`"]; Needs["Histograms`"]; Needs["PieCharts`"]
Needs["ErrorBarPlots`"]
Needs["PlotLegends`"]
Needs["Controls`LinearControl`"]
```

```
$TextStyle = {FontFamily → "Helvetica", FontSize → 13};
```

```
plotopt = PlotStyle → {{Thickness [0.007], RGBColor [1, 0, 0]},
              {Thickness [0.007], RGBColor [0, 0, 1]},
              {Thickness [0.007], RGBColor [0.1, 0.7, 0.2]},
              {Thickness [0.007], RGBColor [0.5, 0.5, 0.2]}};
```

```
pathname = "C:/User/Daniel/Protel/DelayLinePhaseShifter/Data/";
filename1 = pathname <> "Delay_Xns.txt";
filename2 = pathname <> "Power.txt";
filename3 = pathname <> "DelayTaps.txt";
```

Import Data

■ Delay as function of frequency

```
data = Import[filename1, "Table"];
x = First /@ data;
y[0] = (#[[2]] + i #[[3]]) & /@ data;
y[1 / 16] = (#[[4]] + i #[[5]]) & /@ data;
y[1 / 8] = (#[[6]] + i #[[7]]) & /@ data;
y[1 / 4] = (#[[8]] + i #[[9]]) & /@ data;
y[1 / 2] = (#[[10]] + i #[[11]]) & /@ data;
y[1] = (#[[12]] + i #[[13]]) & /@ data;
y[2] = (#[[14]] + i #[[15]]) & /@ data;
y[4] = (#[[16]] + i #[[17]]) & /@ data;
y[8] = (#[[18]] + i #[[19]]) & /@ data;
y[16] = (#[[20]] + i #[[21]]) & /@ data;
```

■ Power sweep at 50 MHz

```
pwrdata = Import[filename2, "Table"];
pwrx = First /@ pwrdata;
pwry = Last /@ pwrdata;
```

■ Delay steps at 50 MHz

```
dtapdata = Import[filename3, "Table"];
dtapx = First /@ dtapdata;
dtaploss = (#[[2]]) & /@ dtapdata;
dtapphase = Last /@ dtapdata;
```

Functions

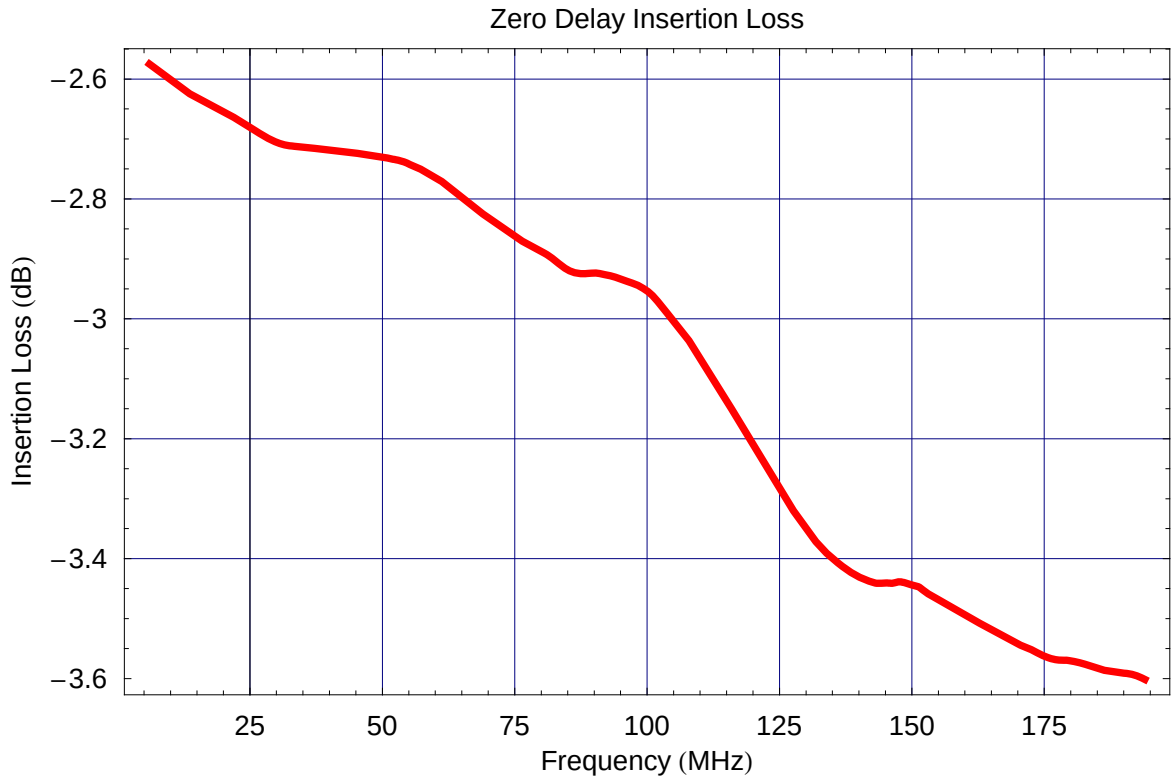
```
smooth[l_List, n_: 5] := Plus @@ # / n & /@ Partition[l, n, 1];

unwrap[l_List] := Block[{ret = {l[[1]]}, ofs = 0},
   For[i = 2, i <= Length[l], ++i,
    ofs += Which[l[[i]] - l[[i - 1]] > 180, -360, l[[i]] - l[[i - 1]] < -180, 360, True, 0];
    AppendTo[ret, l[[i]] + ofs]];
   ret];
```

Plot of Insertion Loss Data

```
delays = {1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, 16};
Clear[dbmag];
dbmag[0] := Transpose[{x / 1*^6, dB[y[0]]}];
dbmag[n_] := Transpose[{x / 1*^6, dB[y[n] / y[0]]}];
dbmagall = dbmag /@ delays;

Clear[dbmagsmooth];
dbmagsmooth[n_] := Interpolation[smooth[dbmag[n], 5]]
dbmagsmoothall = dbmagsmooth /@ delays;
```

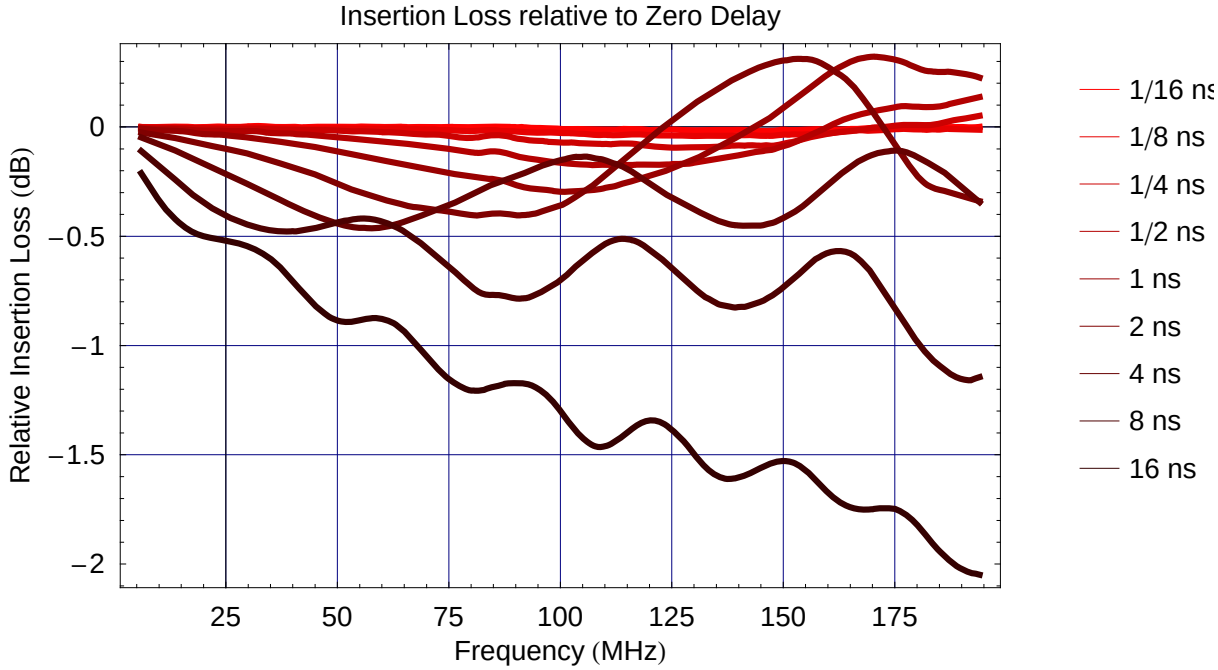
■ Insertion Loss with No Delay

```
f = dbmagsmooth[0];
Plot[f[x], {x, 6, 194},
 PlotStyle → {{Thickness [0.007], RGBColor [1, 0, 0]}},
 PlotLabel → "Zero Delay Insertion Loss",
 FrameLabel → {"Frequency (MHz)", "Insertion Loss (dB)"},
 PlotRange → All, Frame → True, GridLines → Automatic]
```

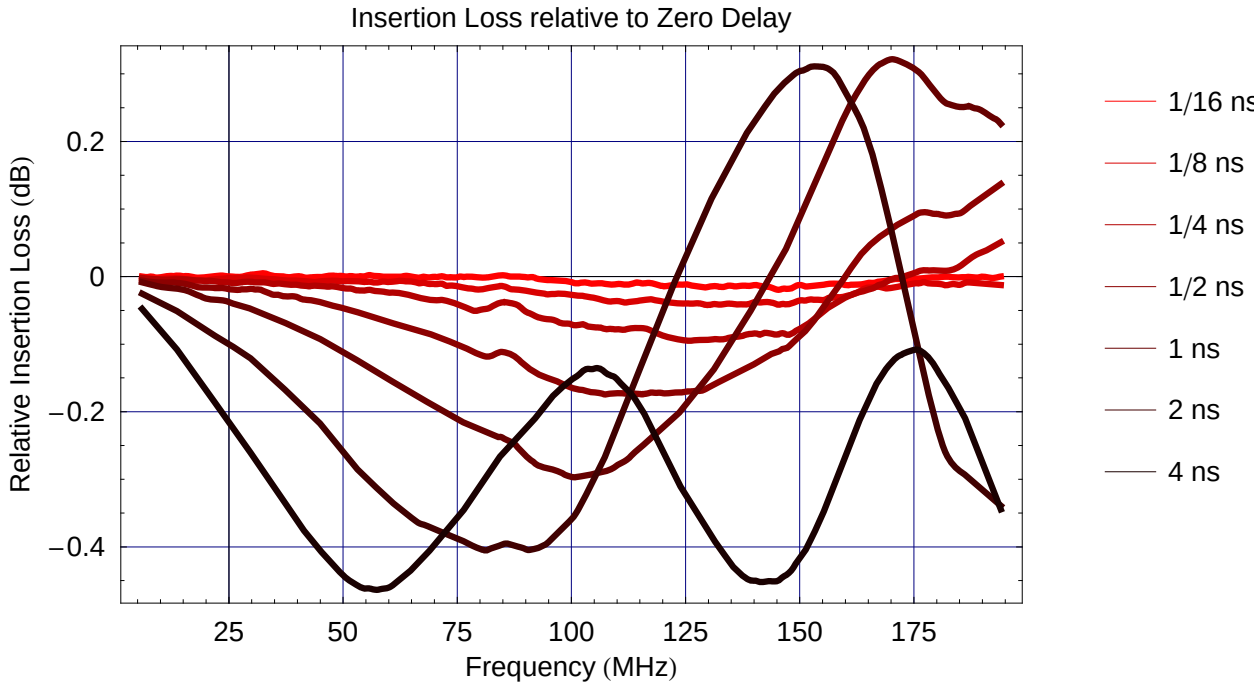


■ Insertion Loss as Function of Delay

```
Plot[{dbmagsmoothall[[1]][x], dbmagsmoothall[[2]][x], dbmagsmoothall[[3]][x],
  dbmagsmoothall[[4]][x], dbmagsmoothall[[5]][x], dbmagsmoothall[[6]][x],
  dbmagsmoothall[[7]][x], dbmagsmoothall[[8]][x], dbmagsmoothall[[9]][x]}, {x, 6, 194},
 PlotStyle → {{Thickness [0.007], RGBColor [1, 0, 0]},
              {Thickness [0.007], RGBColor [0.9, 0, 0]},
              {Thickness [0.007], RGBColor [0.8, 0, 0]},
              {Thickness [0.007], RGBColor [0.7, 0, 0]},
             {Thickness [0.007], RGBColor [0.6, 0, 0]},
             {Thickness [0.007], RGBColor [0.5, 0, 0]},
             {Thickness [0.007], RGBColor [0.4, 0, 0]},
             {Thickness [0.007], RGBColor [0.3, 0, 0]},
             {Thickness [0.007], RGBColor [0.2, 0, 0]}},
 PlotLabel → "Insertion Loss relative to Zero Delay",
 FrameLabel → {"Frequency (MHz)", "Relative Insertion Loss (dB)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotLegend →
  {"1/16 ns", "1/8 ns", "1/4 ns", "1/2 ns", "1 ns", "2 ns", "4 ns", "8 ns", "16 ns"},
 LegendPosition → {1.05, -0.3},
 LegendShadow → None]
```



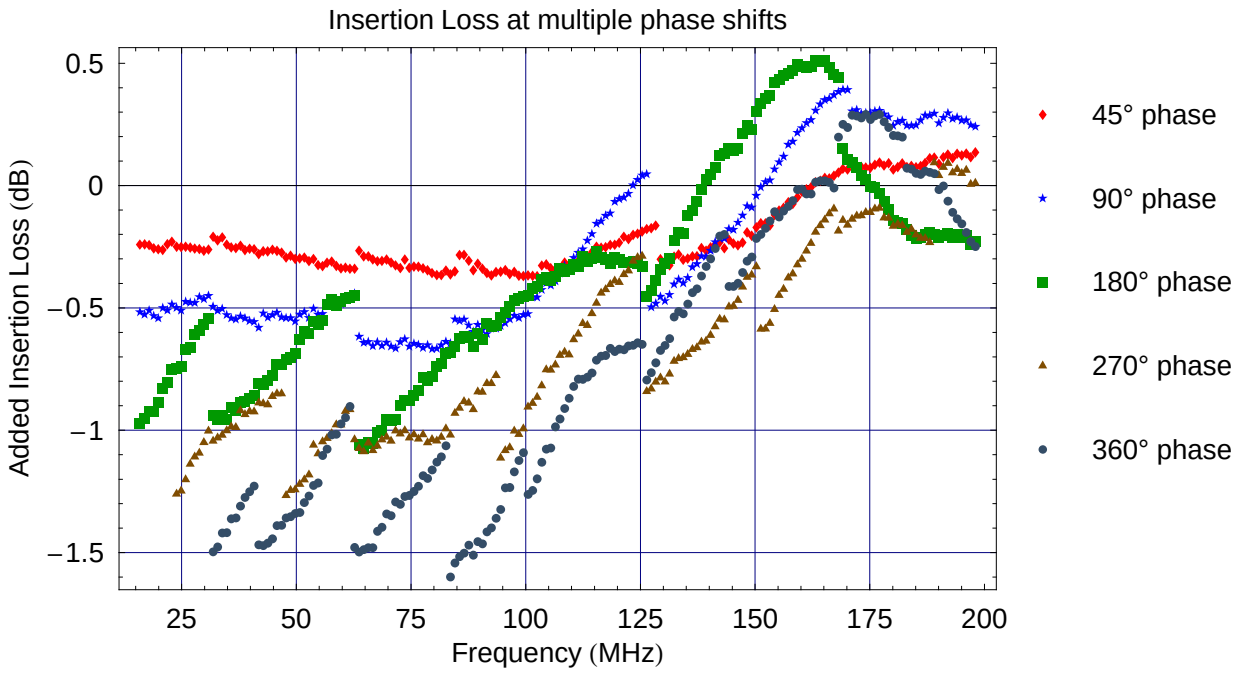
```
Plot[{dbmagsmoothall[[1]][x], dbmagsmoothall[[2]][x], dbmagsmoothall[[3]][x],
  dbmagsmoothall[[4]][x], dbmagsmoothall[[5]][x], dbmagsmoothall[[6]][x], dbmagsmoothall[[7]][x]},
 {x, 6, 194}, PlotStyle → {{Thickness[0.007], RGBColor[1, 0, 0]},
              {Thickness[0.007], RGBColor[0.85, 0, 0]},
              {Thickness[0.007], RGBColor[0.7, 0, 0]},
              {Thickness[0.007], RGBColor[0.55, 0, 0]},
             {Thickness[0.007], RGBColor[0.4, 0, 0]},
             {Thickness[0.007], RGBColor[0.25, 0, 0]},
             {Thickness[0.007], RGBColor[0.1, 0, 0]}},
 PlotLabel → "Insertion Loss relative to Zero Delay",
 FrameLabel → {"Frequency (MHz)", "Relative Insertion Loss (dB)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotLegend → {"1/16 ns", "1/8 ns", "1/4 ns", "1/2 ns", "1 ns", "2 ns", "4 ns"},
 LegendPosition → {1.05, -0.3},
 LegendShadow → None]
```



■ Projected Insertion Loss at 45°, 90°, 180°, 270° and 360°

```
seldel[freq_, phase_: 180] := IntegerDigits[Round[16*^9 phase/(360 freq)], 2, 9]
```

```
del45 = {x[[#]]/1.*^6, seldel[x[[#]], 45].Reverse[Last /@ Transpose[dbmagall][[#]]]} & /@
   Range[16, Length[x] - 2];
del90 = {x[[#]]/1.*^6, seldel[x[[#]], 90].Reverse[Last /@ Transpose[dbmagall][[#]]]} & /@
   Range[16, Length[x] - 2];
del180 = {x[[#]]/1.*^6, seldel[x[[#]], 180].Reverse[Last /@ Transpose[dbmagall][[#]]]} & /@
   Range[16, Length[x] - 2];
del270 = {x[[#]]/1.*^6, seldel[x[[#]], 270].Reverse[Last /@ Transpose[dbmagall][[#]]]} & /@
   Range[24, Length[x] - 2];
del360 = {x[[#]]/1.*^6, seldel[x[[#]], 360].Reverse[Last /@ Transpose[dbmagall][[#]]]} & /@
   Range[32, Length[x] - 2];

MultipleListPlot[{del45, del90, del180, del270, del360},
 PlotLabel → "Insertion Loss at multiple phase shifts",
 FrameLabel → {"Frequency (MHz)", "Added Insertion Loss (dB)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotLegend → {"45°", "90°", "180°", "270°", "360°"},
 SymbolStyle → {{RGBColor[1, 0, 0]}, {RGBColor[0, 0, 1]},
   {RGBColor[0, 0.6, 0]}, {RGBColor[0.5, 0.3, 0]}, {RGBColor[0.2, 0.3, 0.4]}},
 LegendPosition → {0.9, -0.3},
 LegendShadow → None]
```



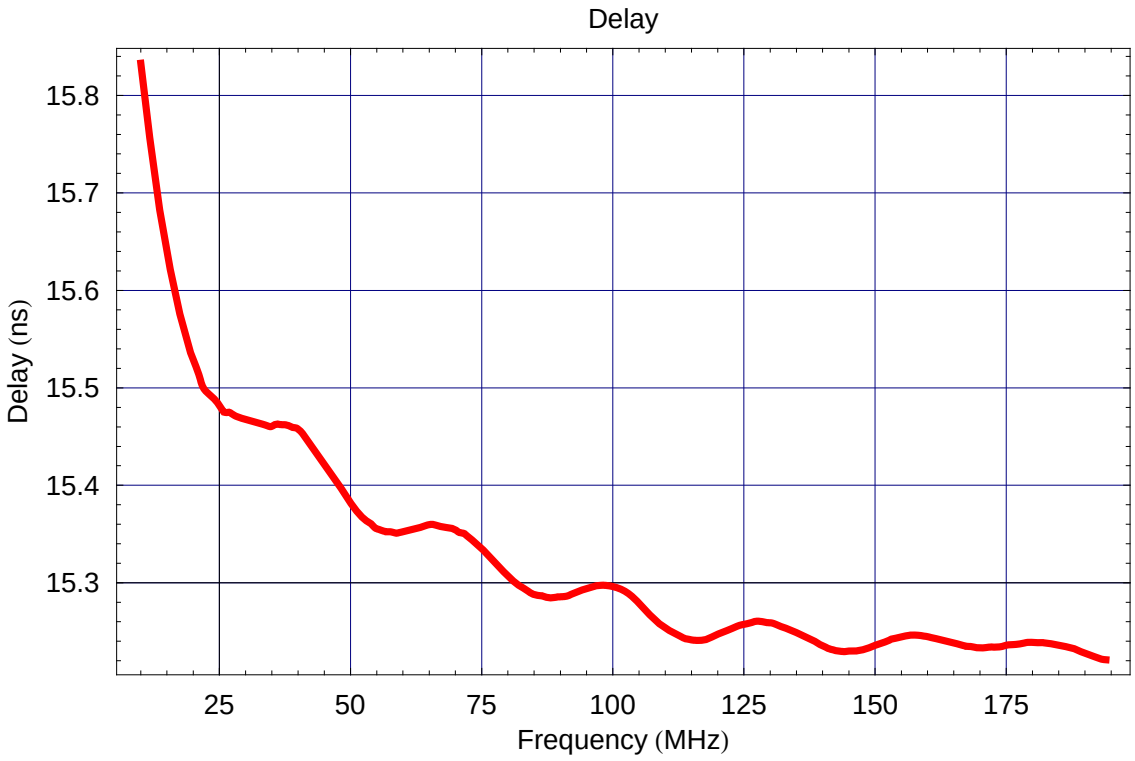
Plot of Delay Data

```
delays = {1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, 16};
Clear[delay];
delay[n_] := Transpose[{x / 1*^6, 1*^9 unwrap[-Phase[y[n] / y[0]]] / (360 x)}];
delayall = delay /@ delays;

Clear[delaysmooth];
delaysmooth[n_] := Interpolation[smooth[delay[n], 5]]
delaysmoothall = delaysmooth /@ delays;

1*^9 unwrap[-Phase[y[#] / y[0]]] / (360 x) & /@ delays;
d50 = Reverse[Transpose[%][[100]]]
dseries50 = d50.# & /@ (IntegerDigits[#, 2, 9] & /@ Range[0, 511]);
ddiff50 = Drop[dseries50, 1] - Drop[dseries50, -1];
ListPlot[ddiff50, PlotRange → All]
```

```
{15.2993, 7.60334, 3.80206, 1.8605, 0.942471, 0.481698, 0.242551, 0.12733, 0.0643351}
```

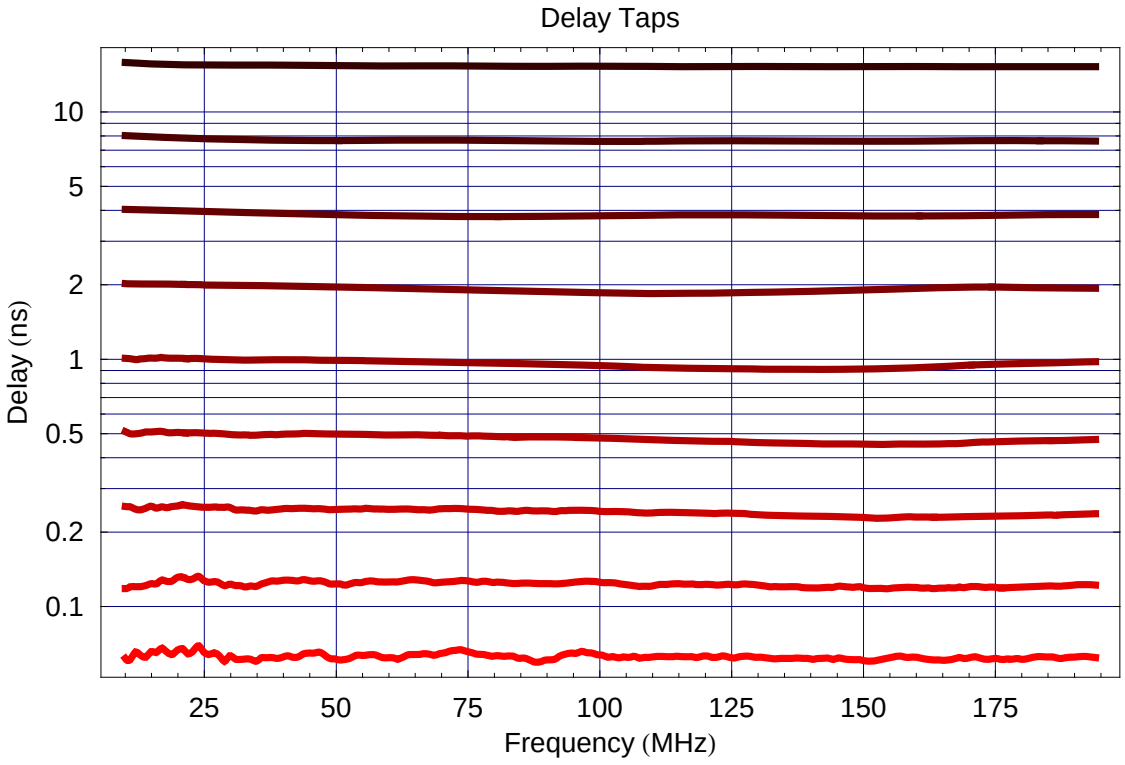
16ns Delay as Function of Frequency

```
f = delaysmooth[16];
Plot[f[x], {x, 10, 194},
 PlotStyle → {{Thickness [0.007], RGBColor [1, 0, 0]}},
 PlotLabel → "Delay",
 FrameLabel → {"Frequency (MHz)", "Delay (ns)"},
 PlotRange → All, Frame → True, GridLines → Automatic]
```



■ Delay Taps as Function of Frequency

```
LogPlot[{delaysmoothall[[1]][fr], delaysmoothall[[2]][fr], delaysmoothall[[3]][fr],
  delaysmoothall[[4]][fr], delaysmoothall[[5]][fr], delaysmoothall[[6]][fr],
  delaysmoothall[[7]][fr], delaysmoothall[[8]][fr], delaysmoothall[[9]][fr]}, {fr, 10, 194},
 PlotStyle → {{Thickness[0.007], RGBColor[1, 0, 0]},
              {Thickness[0.007], RGBColor[0.9, 0, 0]},
              {Thickness[0.007], RGBColor[0.8, 0, 0]},
              {Thickness[0.007], RGBColor[0.7, 0, 0]},
             {Thickness[0.007], RGBColor[0.6, 0, 0]},
             {Thickness[0.007], RGBColor[0.5, 0, 0]},
             {Thickness[0.007], RGBColor[0.4, 0, 0]},
             {Thickness[0.007], RGBColor[0.3, 0, 0]},
             {Thickness[0.007], RGBColor[0.2, 0, 0]}},
 PlotLabel → "Delay Taps",
 FrameLabel → {"Frequency (MHz)", "Delay (ns)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotLegend →
  {"1/16 ns", "1/8 ns", "1/4 ns", "1/2 ns", "1 ns", "2 ns", "4 ns", "8 ns", "16 ns"},
 LegendPosition → {1.05, -0.3},
 LegendShadow → None]
```



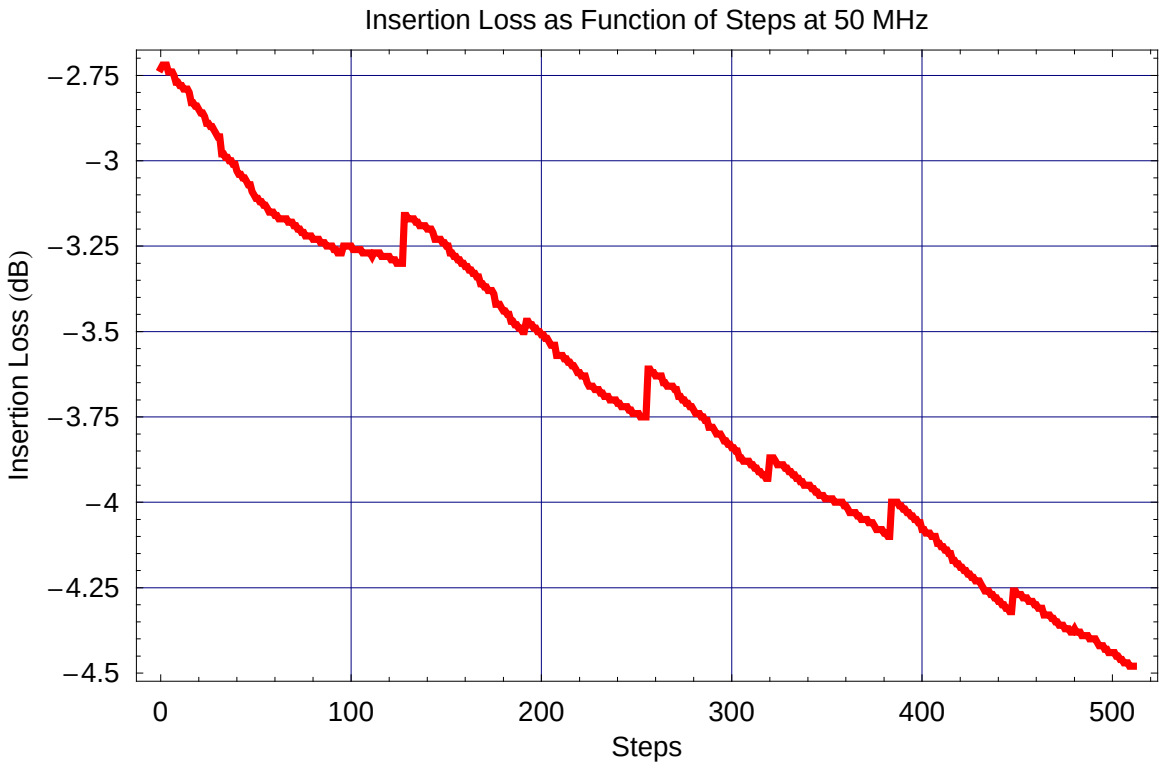
Plot of Step Data (at 50 MHz)

```
taploss = Transpose[{dtapx, dtaploss}];
tapphase = Transpose[{dtapx, unwrap[dtapphase] - dtapphase[[1]]}];
dtapdelay = 1*^9 × 1/(50*^6) (-unwrap[dtapphase] + dtapphase[[1]])/360;
tapdelay = Transpose[{dtapx, dtapdelay}];
difftapdelay = Drop[dtapdelay, 1] - Drop[dtapdelay, -1];
tapslope = Fit[tapdelay, {ns}, ns] /. ns → 1
dnldelay = (Range[0, Length[dtapdelay] - 1] tapslope) - dtapdelay;
```

```
0.0602106
```

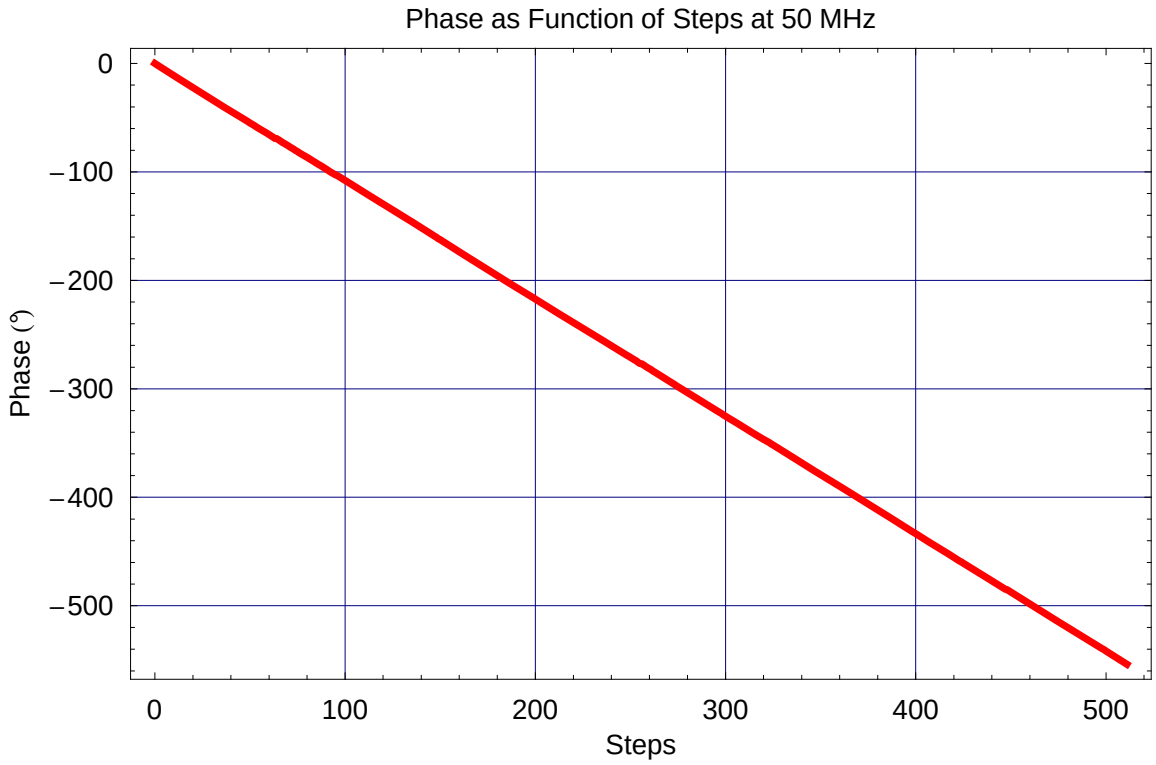
■ Insertion Loss as Function of Steps

```
ListPlot[taploss,
 Joined → True,
 PlotLabel → "Insertion Loss as Function of Steps at 50 MHz",
 FrameLabel → {"Steps", "Insertion Loss (dB)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotStyle → {Thickness [0.007], RGBColor [1, 0, 0]}]
```



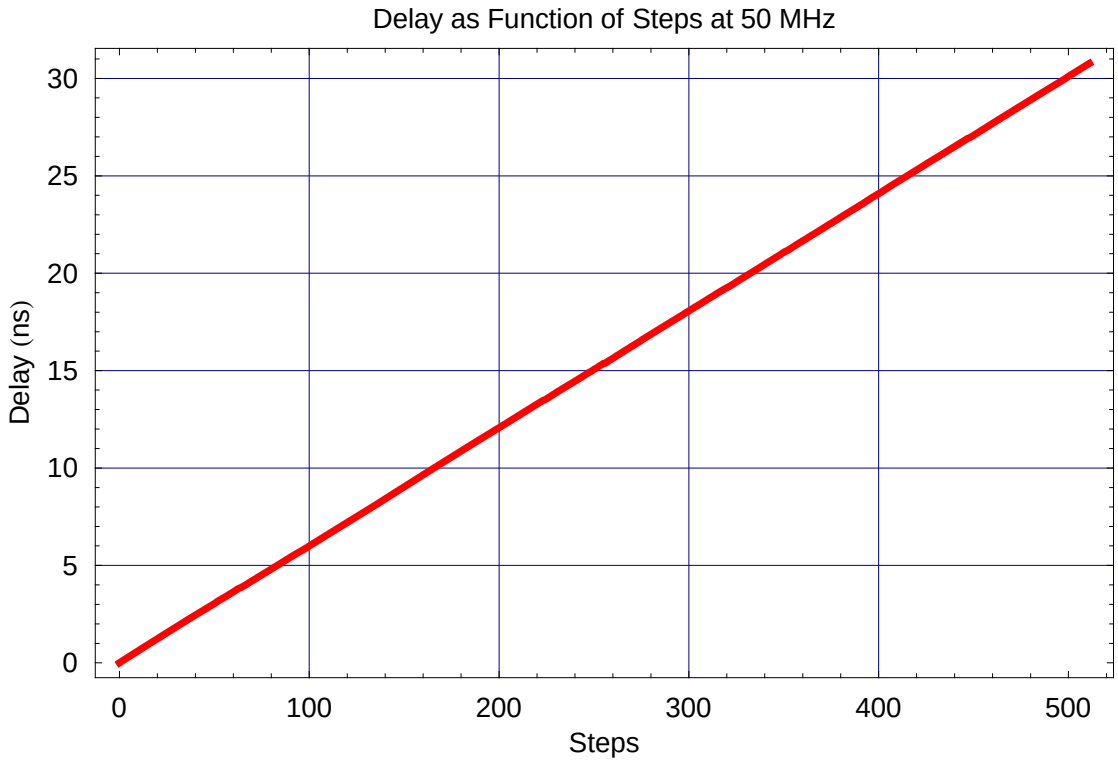
■ Phase Shift as Function of Steps

```
ListPlot[tapphase,
 Joined → True,
 PlotLabel → "Phase as Function of Steps at 50 MHz",
 FrameLabel → {"Steps", "Phase (°)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotStyle → {Thickness [0.007], RGBColor [1, 0, 0]}]
```



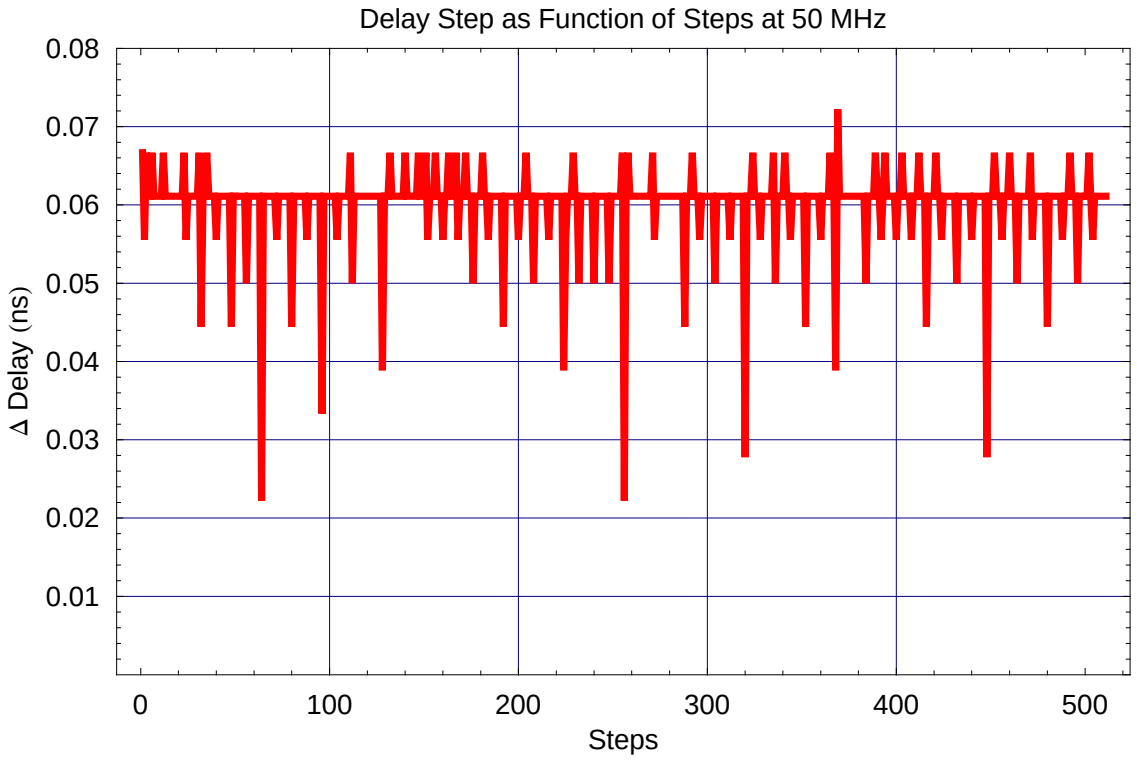
Delay as Function of Steps

```
ListPlot[tapdelay,
 Joined → True,
 PlotLabel → "Delay as Function of Steps at 50 MHz",
 FrameLabel → {"Steps", "Delay (ns)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotStyle → {Thickness [0.007], RGBColor [1, 0, 0]}]
```

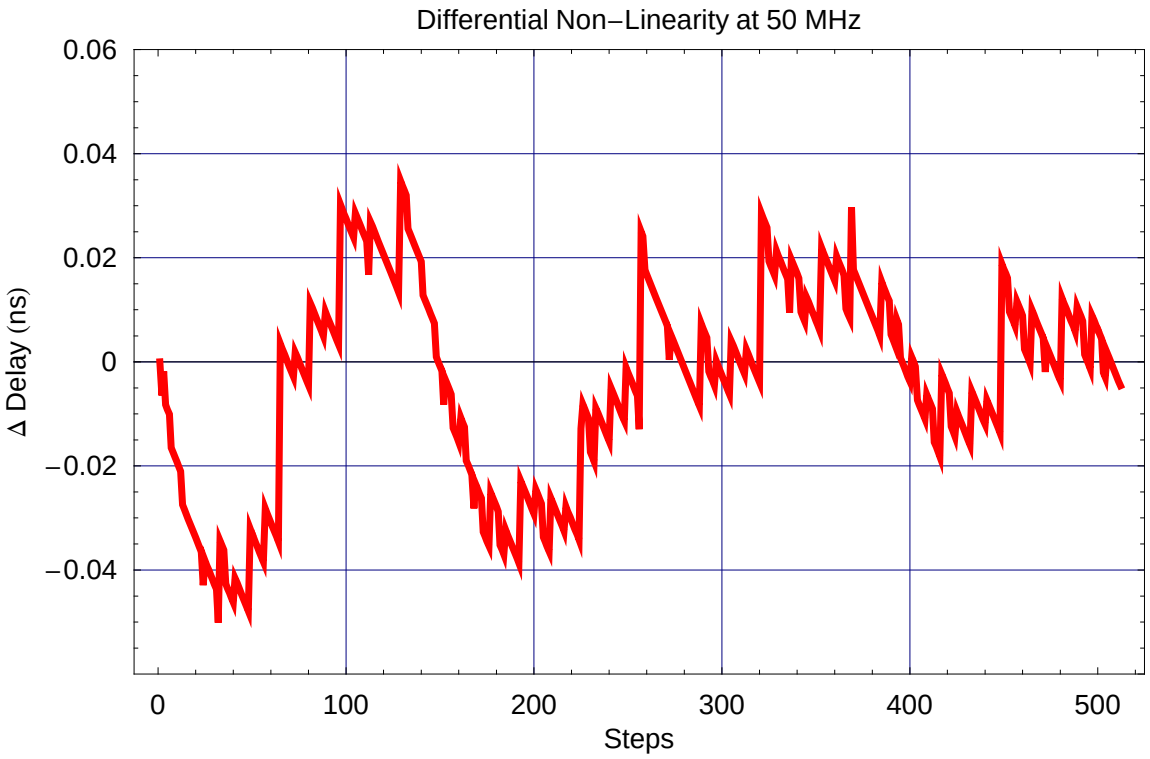


■ Differential Non-Linearity

```
ListPlot[difftapdelay,
 Joined → True,
 PlotLabel → "Delay Step as Function of Steps at 50 MHz",
 FrameLabel → {"Steps", "Δ Delay (ns)"},
 PlotRange → {0, 0.08}, Frame → True, GridLines → Automatic,
 PlotStyle → {Thickness [0.007], RGBColor [1, 0, 0]}]
```



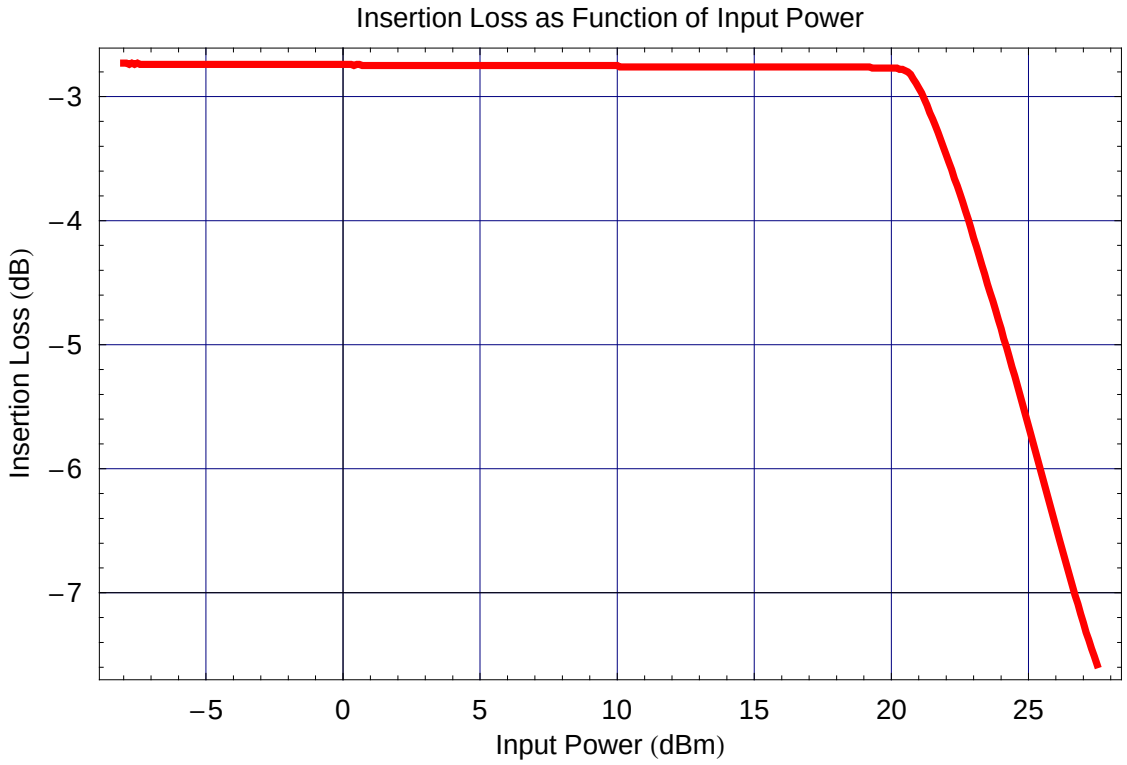
```
ListPlot[dnldelay,
 Joined → True,
 PlotLabel → "Differential Non-Linearity at 50 MHz",
 FrameLabel → {"Steps", "Δ Delay (ns)"},
 PlotRange → {-0.06, 0.06}, Frame → True, GridLines → Automatic,
 PlotStyle → {Thickness [0.007], RGBColor [1, 0, 0]}]
```



Plot of Power Sweep

■ Insertion Loss as Function of Input Power

```
ListPlot[pwrdata,
 Joined → True,
 PlotLabel → "Insertion Loss as Function of Input Power",
 FrameLabel → {"Input Power (dBm)", "Insertion Loss (dB)"},
 PlotRange → All, Frame → True, GridLines → Automatic,
 PlotStyle → {Thickness[0.007], RGBColor[1, 0, 0]}]
```



```
ListPlot[pwrdata,
 Joined → True,
 PlotLabel → "Insertion Loss as Function of Input Power",
 FrameLabel → {"Input Power (dBm)", "Insertion Loss (dB)"},
 PlotRange → {-3.0, -2.6}, Frame → True, GridLines → Automatic,
 PlotStyle → {Thickness [0.007], RGBColor [1, 0, 0]}]
```