

Delay Line Phase Shifter

T050250-v1
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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 be 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 mm². A 16 ns delay will require a trace length around 2.2 m. With a conductivity of $59.6 \times 10^6 \frac{1}{\Omega\text{m}}$ the resistance will be around 40 m Ω . 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] :=  $\frac{\text{Plus}@@\#}{n}$  & /@ 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 = { $\frac{1}{16}$ ,  $\frac{1}{8}$ ,  $\frac{1}{4}$ ,  $\frac{1}{2}$ , 1, 2, 4, 8, 16};

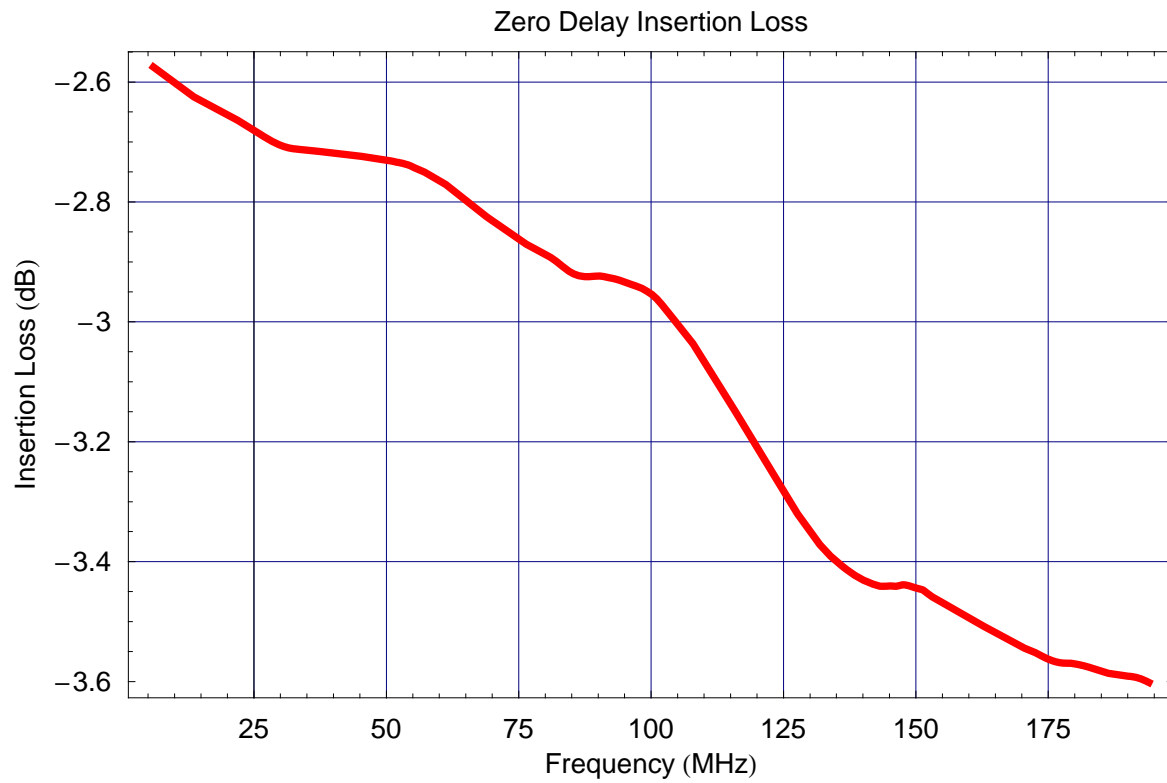
Clear[dbmag];
dbmag[0] := Transpose[{x / 1*^6, dB[y[0]]}];
dbmag[n_] := Transpose[{x / 1*^6, dB[y[n] / y[0]]}];
dbmagall = dbmag /@ delays;

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]
```

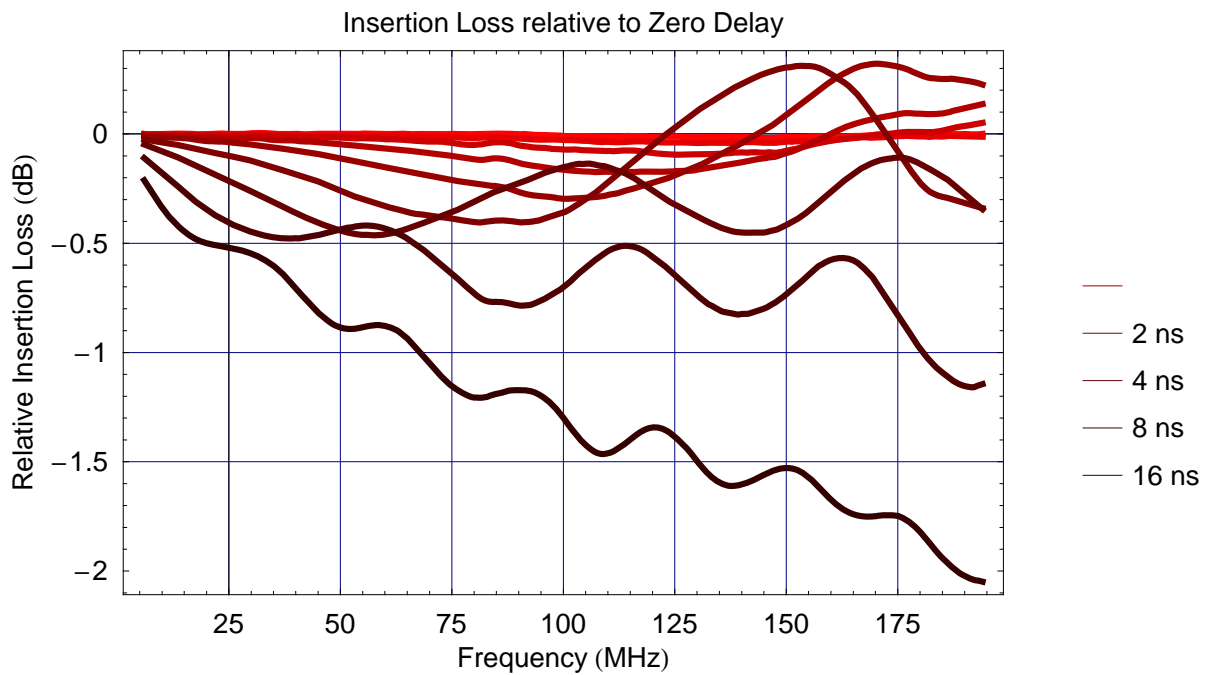


■ Insertion Loss as Function of Delay

```

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]

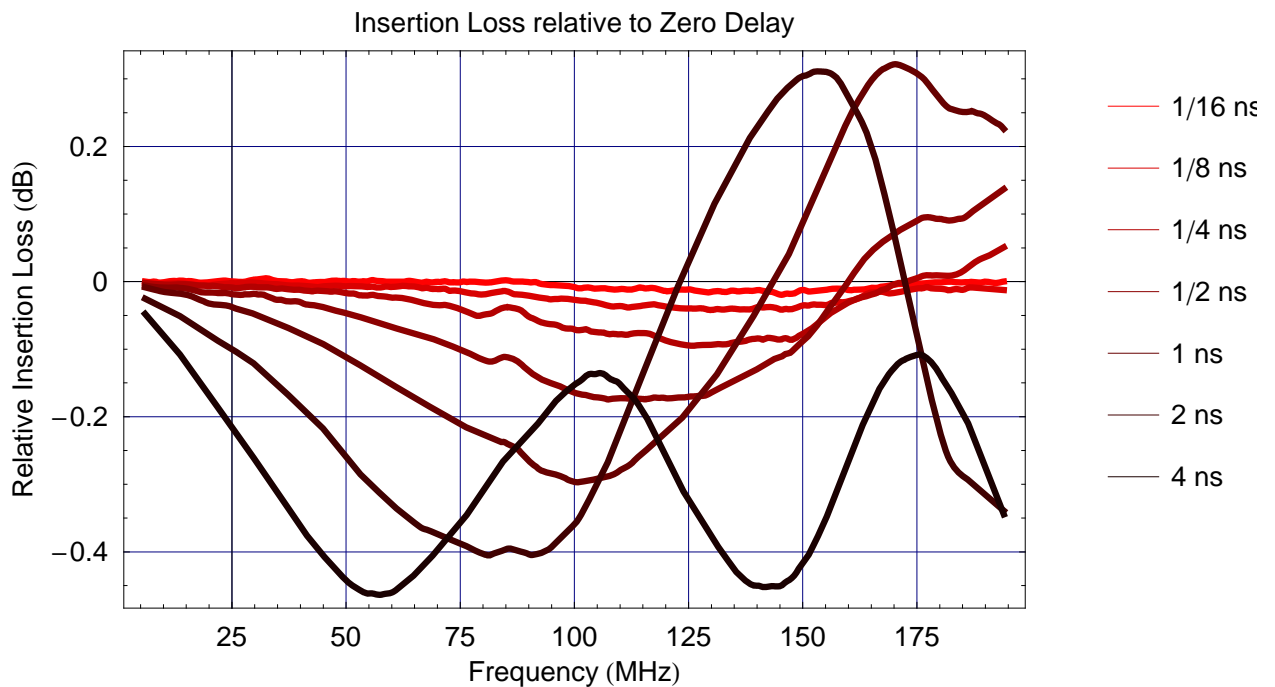
```



```

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  $\frac{\text{phase}}{360 \text{ freq}}$ ], 2, 9]

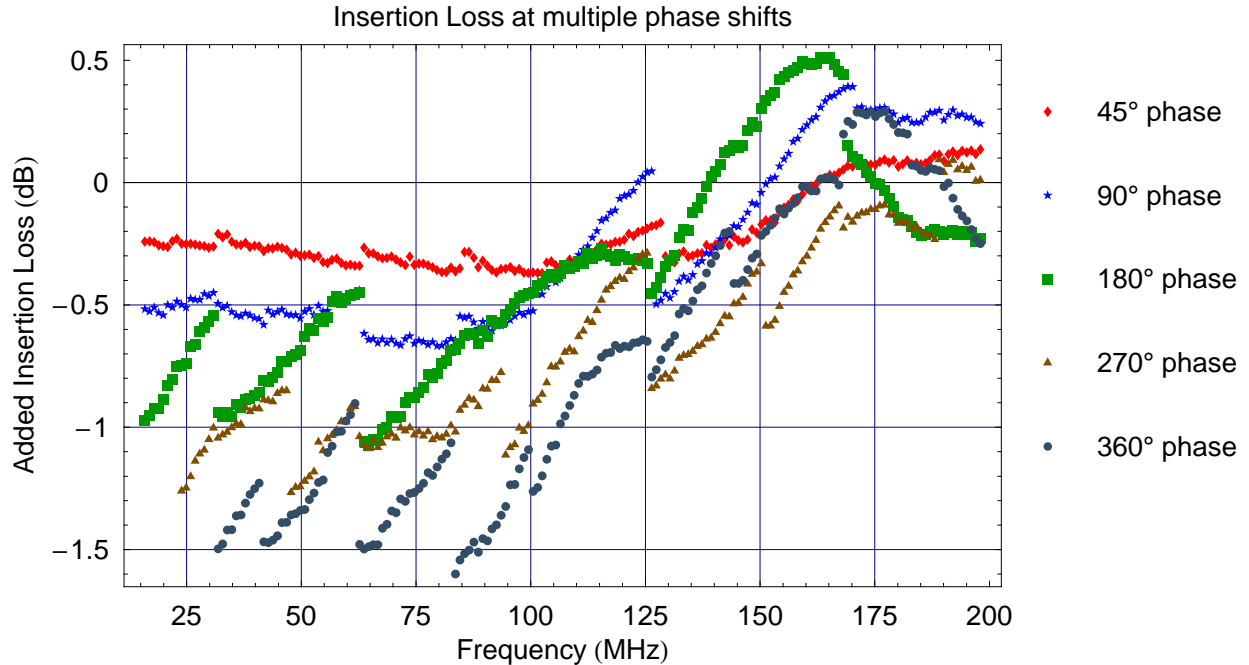
```

```

del145 = {  $\frac{x[[\#]]}{1.*^6}$ , seldel[x[[#]], 45].Reverse[Last /@ Transpose[dbmagall][[#]]] } & /@
  Range[16, Length[x] - 2];
del190 = {  $\frac{x[[\#]]}{1.*^6}$ , seldel[x[[#]], 90].Reverse[Last /@ Transpose[dbmagall][[#]]] } & /@
  Range[16, Length[x] - 2];
del180 = {  $\frac{x[[\#]]}{1.*^6}$ , seldel[x[[#]], 180].Reverse[Last /@ Transpose[dbmagall][[#]]] } & /@
  Range[16, Length[x] - 2];
del270 = {  $\frac{x[[\#]]}{1.*^6}$ , seldel[x[[#]], 270].Reverse[Last /@ Transpose[dbmagall][[#]]] } & /@
  Range[24, Length[x] - 2];
del360 = {  $\frac{x[[\#]]}{1.*^6}$ , seldel[x[[#]], 360].Reverse[Last /@ Transpose[dbmagall][[#]]] } & /@
  Range[32, Length[x] - 2];

MultipleListPlot[{del145, del190, 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 = { $\frac{1}{16}$ ,  $\frac{1}{8}$ ,  $\frac{1}{4}$ ,  $\frac{1}{2}$ , 1, 2, 4, 8, 16};
Clear[delay];
delay[n_] := Transpose[{x/1*^6, 1*^9  $\frac{\text{unwrap}[-\text{Phase}[y[n] / y[0]]]}{360 x}$ ]}];
delayall = delay /@ delays;

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

1*^9  $\frac{\text{unwrap}[-\text{Phase}[y[\#] / y[0]]]}{360 x}$  & /@ delays;

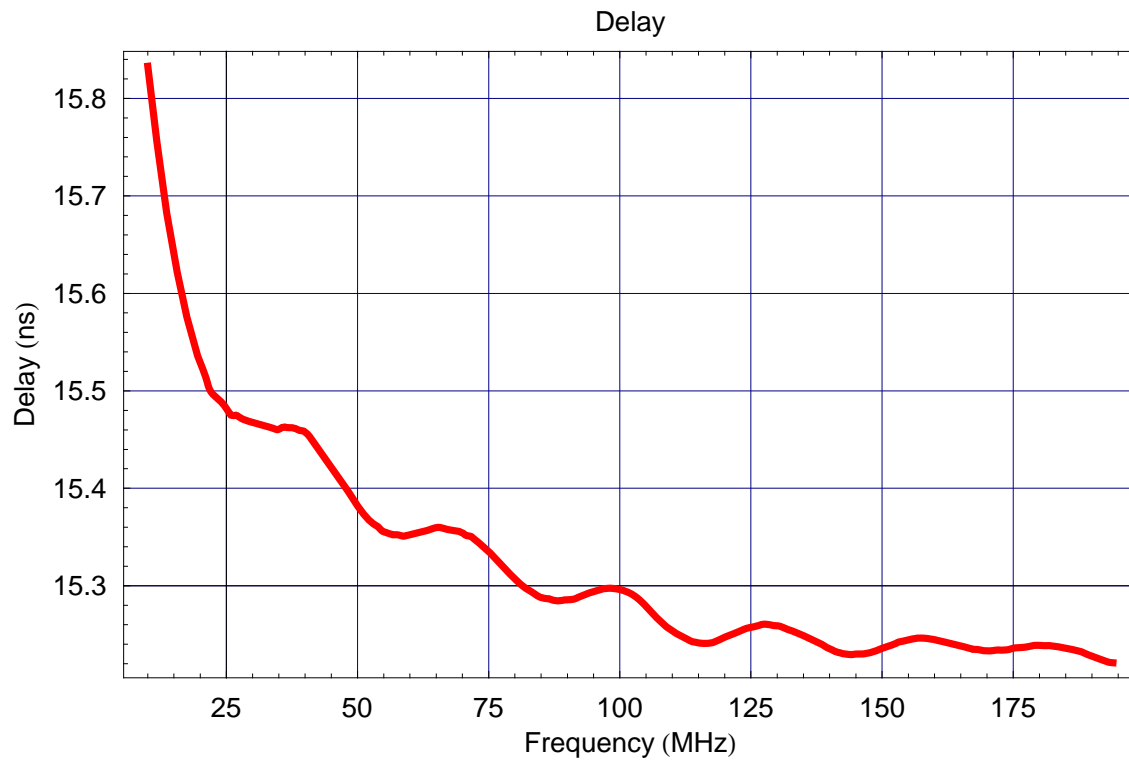
d50 = Reverse[Transpose[%][[100]]]
dseries50 = d50.# & /@ (IntegerDigits[#, 2, 9] & /@ Range[0, 511]);
ddiff50 = Drop[dseries50, 1] - Drop[dseries50, -1];
ListPlot[ddiff50, PlotRange -> All]

{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]
```

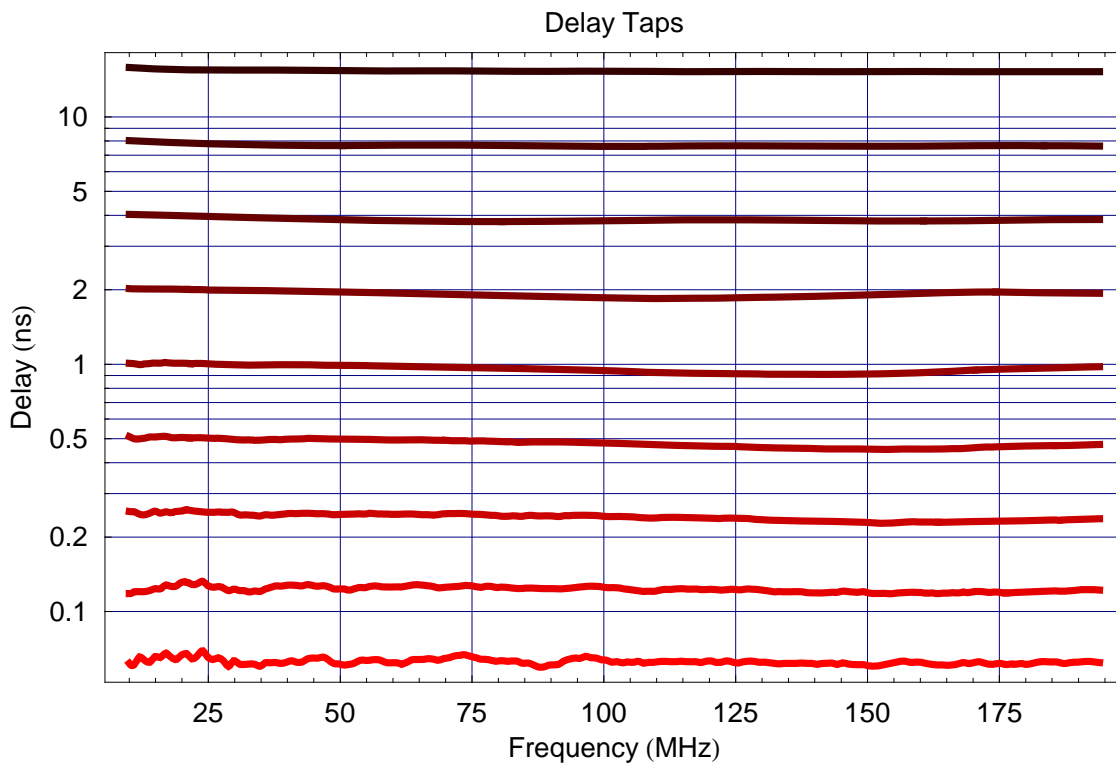


■ Delay Taps as Function of Frequency

```

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 *  $\frac{1}{50*^6} \frac{-\text{unwrap}[dtapphase] + dtapphase[[1]]}{360}$ ;
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

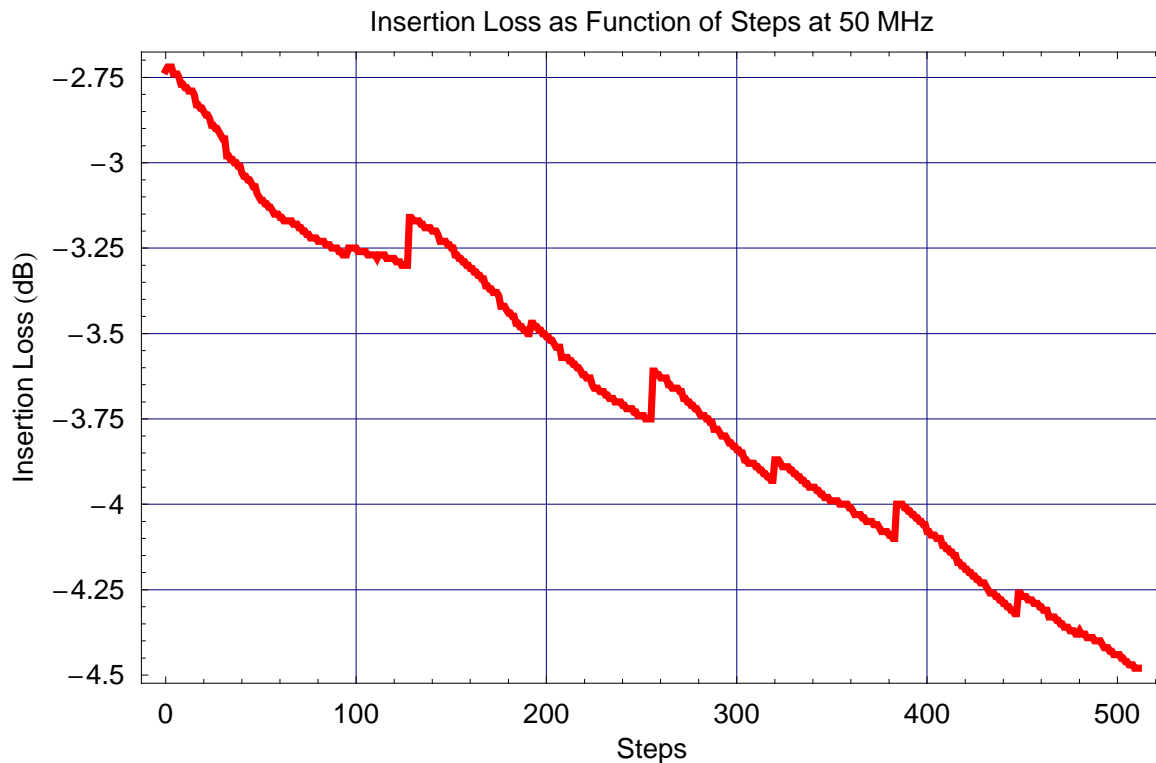
```

■ Insertion Loss as Function of Steps

```

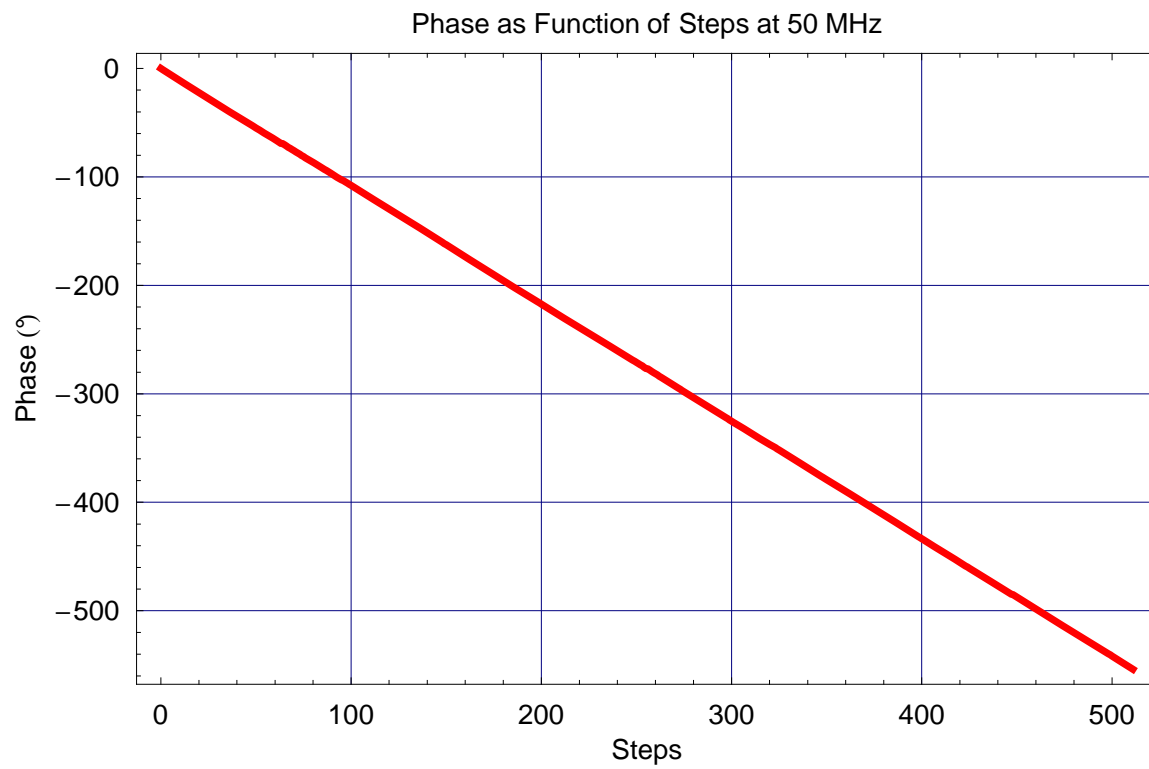
ListPlot[taploss,
  Joined -> True,
  PlotLabel -> "Insertion Loss as Function of Steps at 50 MHz",
  FrameLabel -> {"Steps", "Insertion Loss (dB)"},
  PlotRange -> All, Frame -> True, GridLines -> Automatic,
  PlotStyle -> {Thickness [0.007], RGBColor [1, 0, 0]}

```



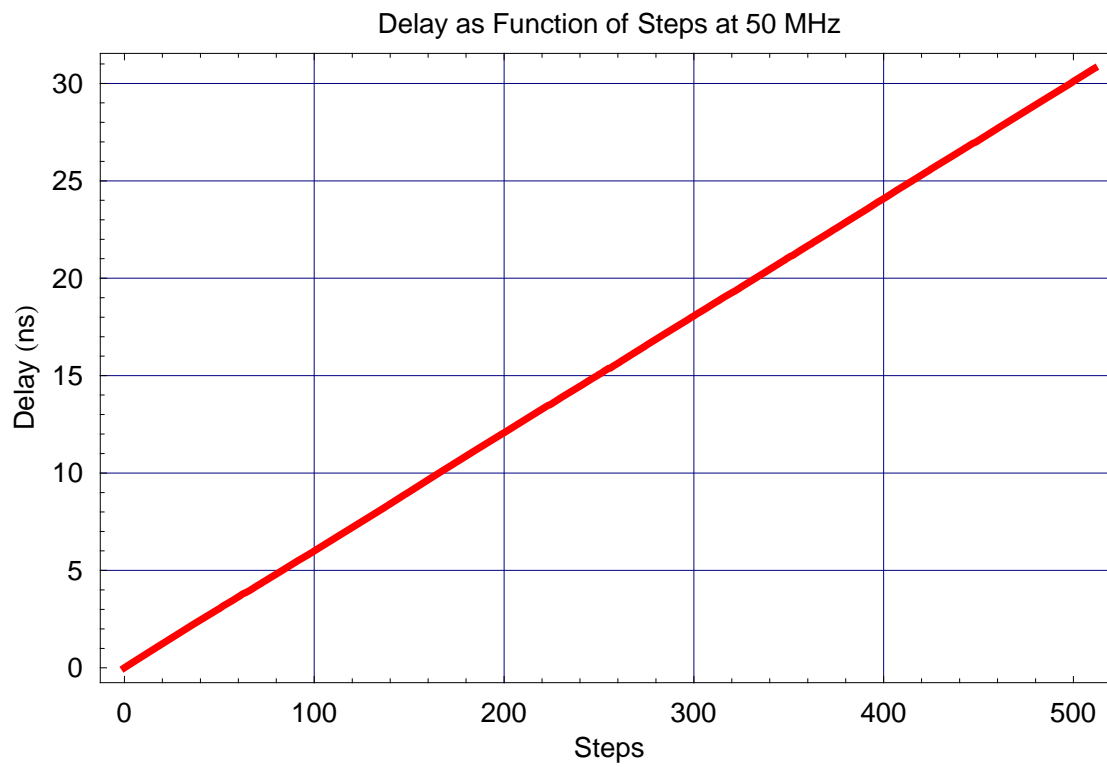
■ Phase Shift as Function of Steps

```
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]}]
```



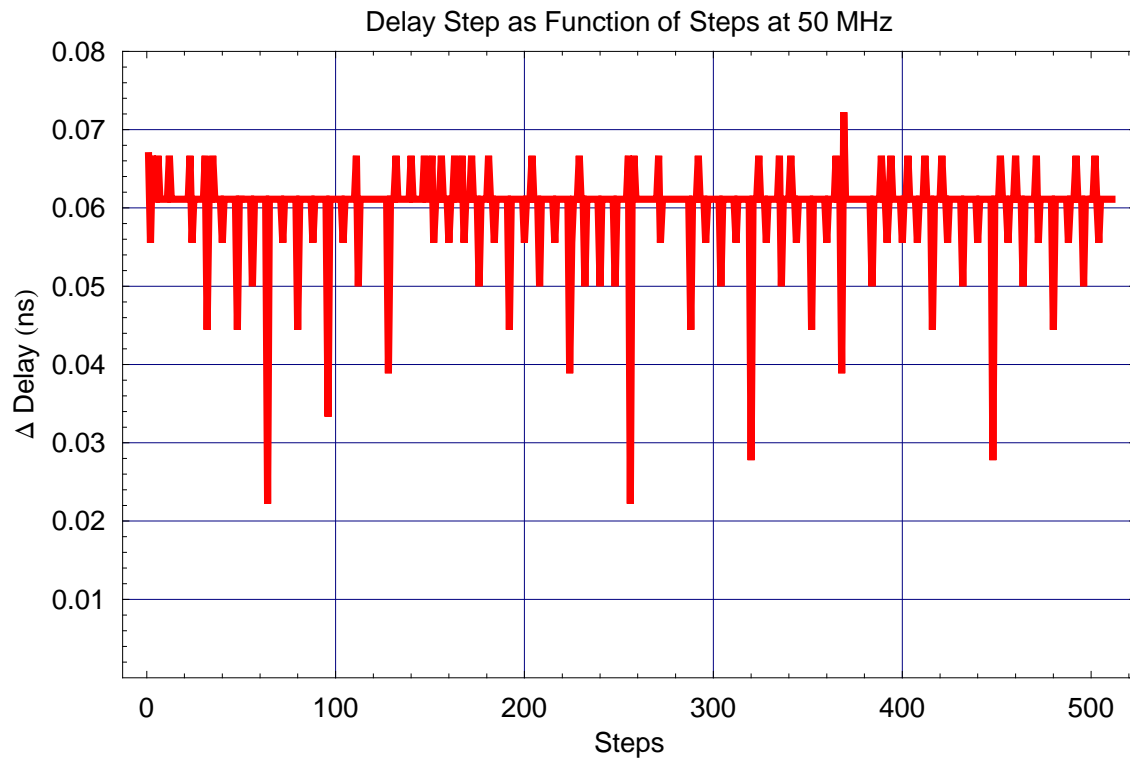
■ Delay as Function of Steps

```
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]}]
```

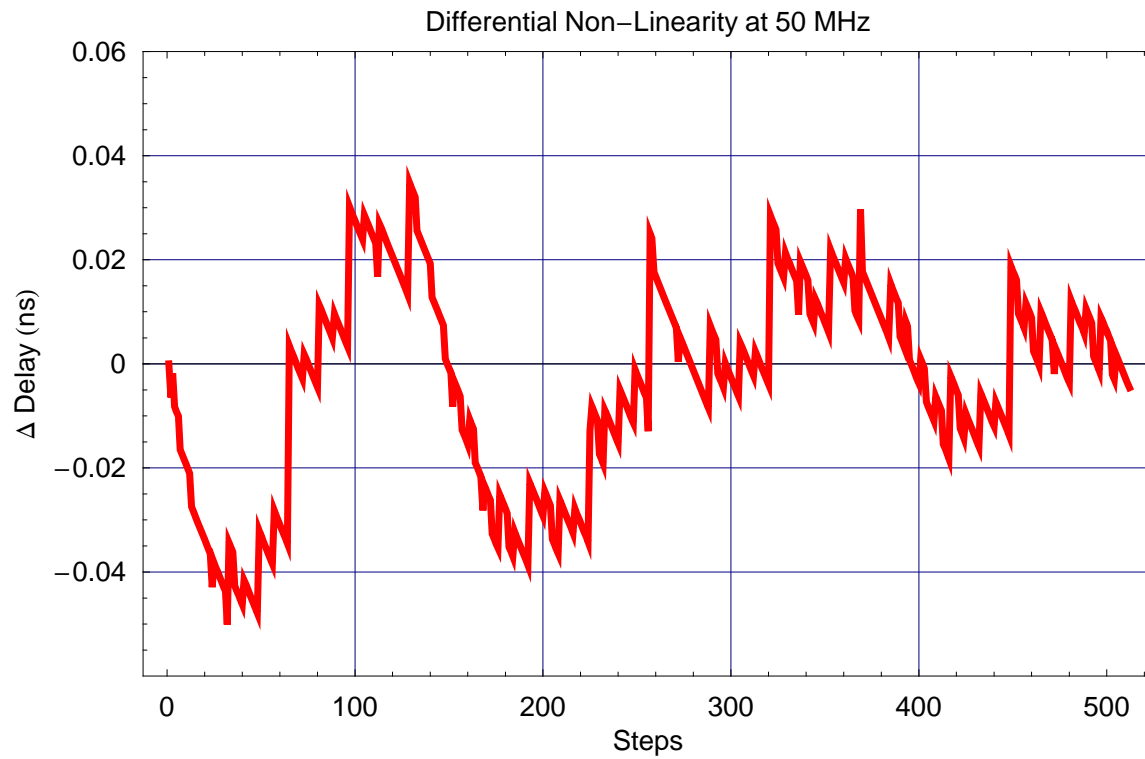


■ Differential Non-Linearity

```
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]}]
```



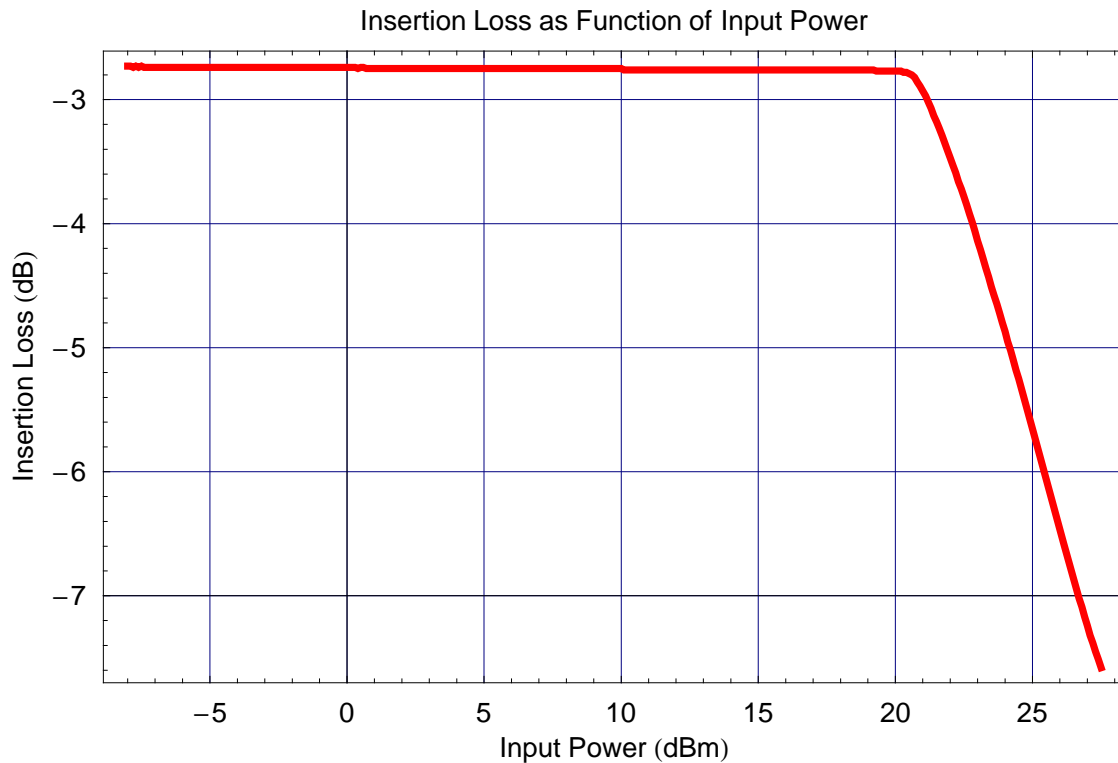
```
ListPlot[dnldelay,  
  Joined → True,  
  PlotLabel → "Differential Non-Linearity at 50 MHz",  
  FrameLabel → {"Steps", "Δ Delay (ns)"},  
  PlotRange → {-0.06, 0.06}, Frame → True, GridLines → Automatic,  
  PlotStyle → {Thickness [0.007], RGBColor [1, 0, 0]}]
```



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]}]
```

