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.

Xinger Delay Lines in Feedforward Amplifier Applications

Document #AAN-232

Abstract

The use of feedforward linearization circuits in next generation power amplifiers is becoming more common especially with multi-carrier or multi-channel power amplifiers (MCPAs). This application note describes the feedforward power amplifier and a new Xinger® surface mount delay line that can be used in the main feedforward loop. This note also discusses the design technology used in the Xinger delay line and shows that it is a viable low cost alternative to coaxial cable where the Xinger delay line exhibits comparative narrow band electrical behavior and temperature stability.

Introduction

Delay lines are necessary components in feedforward amplifier applications. Figure 1 shows the basic feedforward schematic where there are two loops; the main (identified as Loop 1) and error loop (Loop 2). The purpose of the feedforward circuit is to isolate the intermodulation products generated in a high power main amplifier and manipulate them in the error loop in such a way as to cancel when they are recombined resulting in a distortion free output signal. The intermodulation vectors from the main and error amplifiers must be phase matched and have equal propagation delays in order to achieve proper cancellation, thus the need for the delay lines in these two feedforward loops.

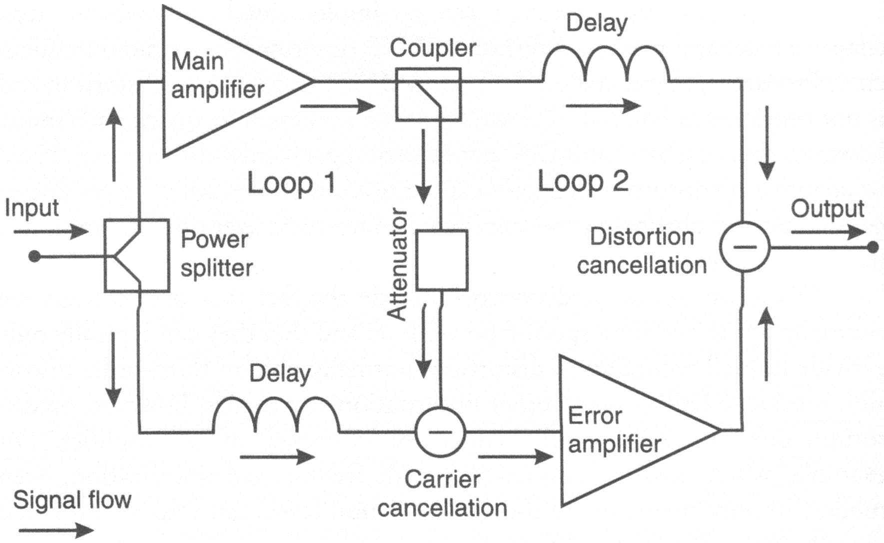

Figure 1 – Generic Feed Forward Circuit Schematic [2]

Delay elements are required to compensate for the group delay through the two amplifiers of the two-feedforward loops where coaxial cable assemblies have traditionally performed this function, however delay filter assemblies can also be used. Anaren Microwave, Inc. in East Syracuse, NY recently developed a delay line in a Xinger surface mount package for the low power delay of the main feedforward loop. Xinger delay lines can have delays of up to 15nS in a 1-inch square size package at 2GHz. The trade-offs associated with the Xinger delay line against the coaxial cable and surface mount filter options include component size, ease of use, cost and electrical performance.

Feedforward Power Amplifiers

In the feedforward circuit, the input signal is split in two; some power is routed to the main amplifier and the rest to a delay line. The output of the main amplifier is sampled with a directional coupler and the rest is transmitted to a second delay element. The sampled signal from the main amplifier is combined with the output of the main loop delay line to eliminate the original input signal (destructive interference) resulting in 'pure' intermodulation that is to be amplified in the error amplifier. The output of the feedforward amplifier is the result of destructive interference between the output from the main and error amplifiers, producing an error-free output signal.

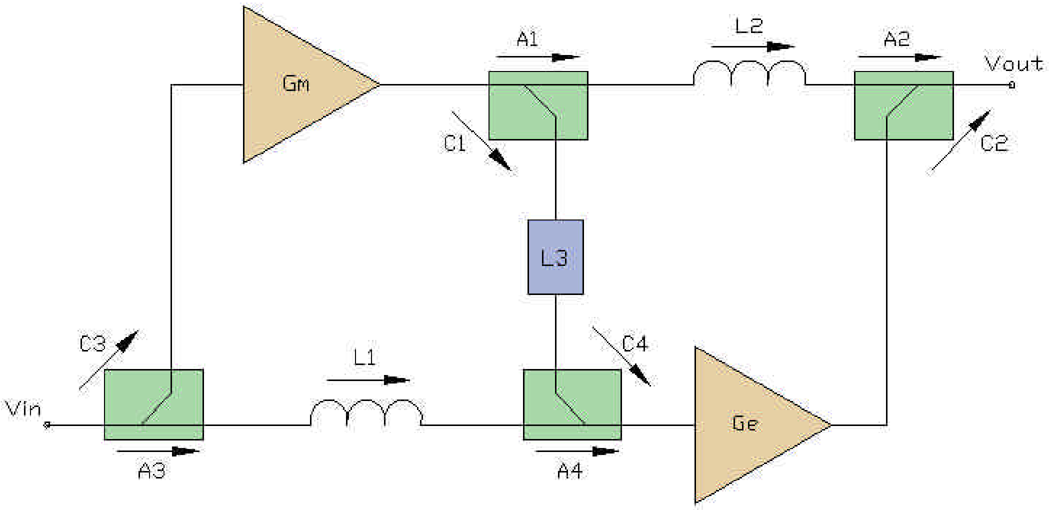

Figure 2 – Feed Forward Flow Diagram

Feedforward networks make use of couplers, attenuators and amplifiers to achieve overall feedforward gain and intermodulation suppression. Figure 2 shows the feedforward network with the appropriate power splits, amplifiers, attenuators and delay lines [1]. Couplers have insertion loss A and coupling factor C, amplifiers have gain G, and delay lines and attenuators have loss L. When the first loop is perfectly balanced, (1) is the result and when the second loop is perfectly balanced, (2) is the result [2]. The overall feed forward gain (G_{ff}) (when both loops are balanced) is defined by (3), where the overall gain through the feedforward amplifier is a function of the passive components selected and not the gain of the main or error amplifiers [2]. It is also important to note that the feedforward gain will always be less than the gain of either amplifier in the network [2].

$$a_3 \cdot l_1 \cdot a_4 = c_3 \cdot g_m \cdot c_1 \cdot l_3 \cdot c_4 \tag{1}$$

$$a_1 \cdot l_2 \cdot a_2 = c_1 \cdot l_3 \cdot c_4 \cdot g_e \cdot c_2 \tag{2}$$

$$g_{ff} = \frac{a_1 \cdot a_2 \cdot a_3 \cdot a_4 \cdot l_1 \cdot l_2}{c_1 \cdot c_4 \cdot l_3} \tag{3}$$

If both feedforward loops are balanced, then the feedforward gain is independent of non-linearities in the main and error amplifiers [2]. A balanced feedforward amplifier's output contains no distortion and therefore behaves as a linear amplifier [2]. Further analysis of Equations (1) and (3) shows that the feedforward gain will not be effected if the main loop delay line (L1) has higher insertion loss if the input coupler (C3 & A3) is modified to compensate for the additional loss (unfortunately this may not always be valid). However, the gain of the main and error amplifiers will need to be adjusted, as shown in Equations (4) and (5).

$$G_m = G_{ff} - C_3 - A_1 - L_2 - A_2 \quad \text{[dB]} \tag{4}$$

$$G_e = G_{ff} - A_3 - L_1 - A_4 - C_2 \quad \text{[dB]} \tag{5}$$

The critical performance parameters of the feedforward delay line elements are low insertion loss, stable amplitude and linear phase [2]. However, the delay of the main loop is lower in power and not as sensitive to attenuation, as described earlier. Component properties such as temperature stability, size, cost and overall ease of use in the feedforward assembly must be considered. The coaxial delay line is used for its excellent linear behavior, however high volume-manufacturing problems exist. This note will show that the Xinger delay line has linear performance that is comparable to coaxial cable and is an excellent option for the low power delay of the main loop.

Linear Transmission Line

This section will discuss the electrical performance and delay of a linear TEM transmission line, such as a coaxial cable (these same principles apply with all TEM structures, however this discussion will be focused on the coaxial cable). Coaxial cable provides a linear phase over frequency where electrical delay is the derivative of phase with respect to frequency, $\frac{dq}{dw}$. Because the phase-frequency response of a coaxial cable is linear, the electrical (or group) delay will be the same at all frequencies. Figure 3 shows the phase vs. frequency response for three lengths of coaxial cable, one with an electrical delay of 5nS, one with an electrical delay that is slightly less than 5nS and the third is for a delay greater than 5nS. From this figure, the concept of absolute phase length of the coaxial cable will be introduced.

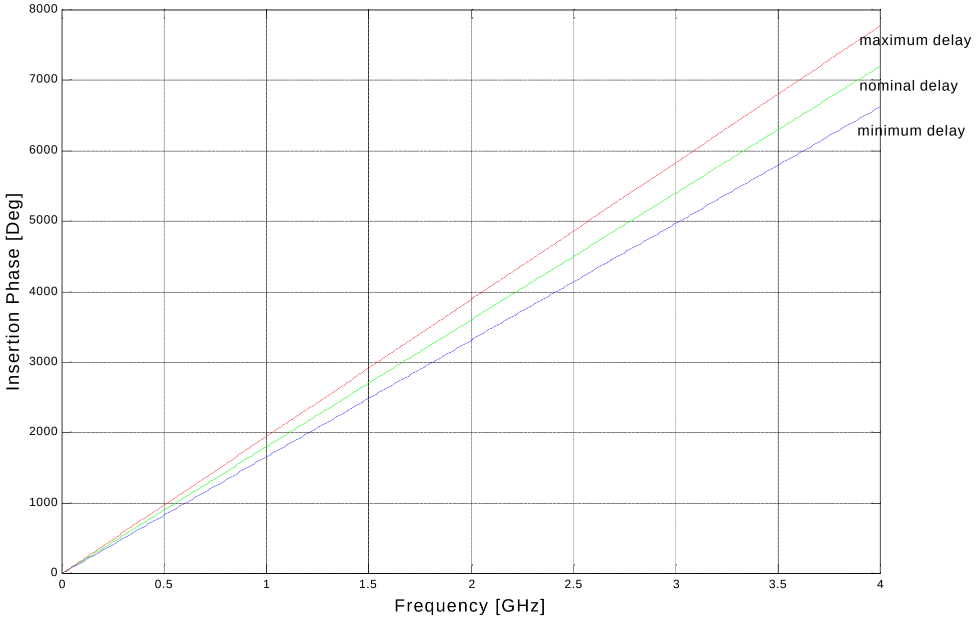

Figure 3 – Insertion Phase for Three Lengths of Coaxial Cable

Consider the PCS frequency range 1930 – 1990 MHz, where Figure 4 shows the electrical delay of the three cable lengths to be 4.95nS, 5.0nS and 5.05nS (5 ± 0.05nS). Notice that it appears as if there are three traces of the same slope where a phase offset has occurred. Actually, each slope is slightly different from the others (as will be shown) where a phase offset of about 35 degrees between traces at 1.96GHz exists. This offset varies from 0 degrees for a perfect 5nS delay line to ± 35 degrees for a delay variation specification of ± 0.05nS. The phase-offset range can easily be calculated using the delay variation range:

Phase Offset [Deg] = 360 * t * F (6)

where F = frequency [Hz] and t = delay deviation from nominal

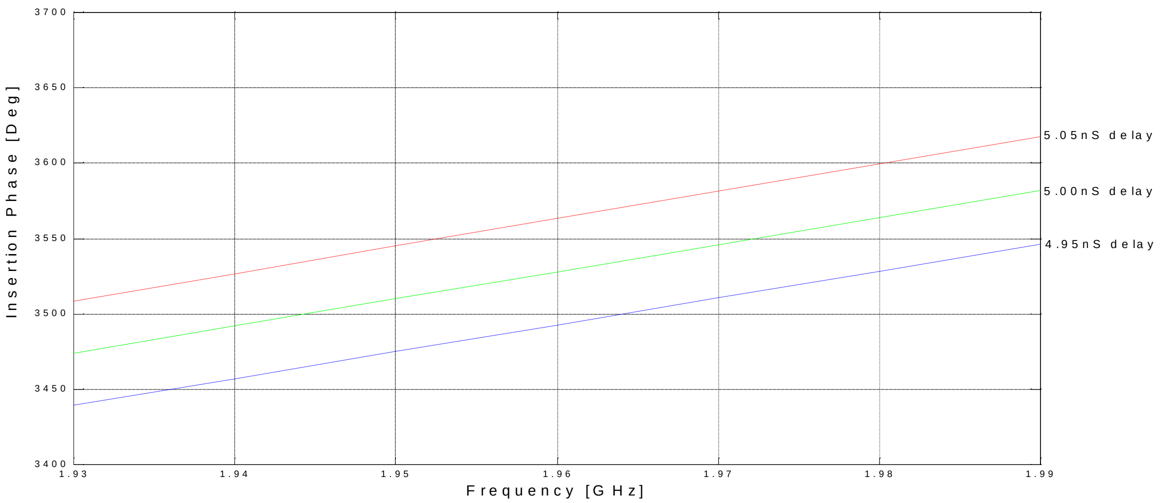

Figure 4 – Narrow Band Insertion Phase for Three Lengths of Coaxial Cable

Finally, the slope differential between the nominal value delay line and the other values of delay within the specification range must be considered. This difference in slope is called phase error (sometimes referred to as deviation from linear phase). To find this difference, the measured insertion phase data will be compared to the ideal nominal delay line insertion phase and the offset component will be removed. This operation was performed on the data in Figure 4 and the results are plotted in Figure 5. The phase error in the ideal linear case can be calculated as follows:

pk-to-pk phase error = 360 * peak delay variation * (Fhigh – Flow) (7)

In this example: delay variation = ± 0.05nS so peak variation is 0.05nS and:

Fhigh – Flow = 1930 –1990 MHz = 60 Mhz

pk-to-pk phase error = 360 * 0.05nS * 60 Mhz = 1.08°

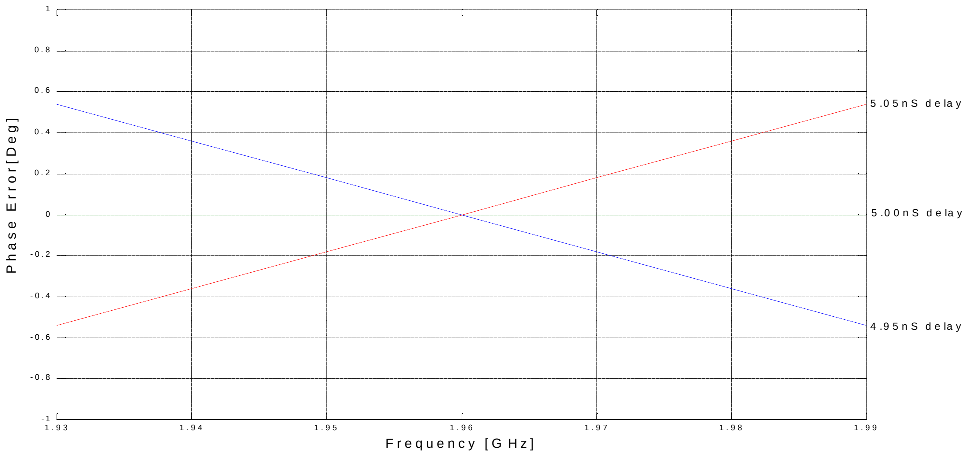

Figure 5 – Phase Error for Three Lengths of Coaxial Cable

The following statements can be concluded for the ideal analysis used above:

1.) A delay line specified at 5 ± 0.05nS will introduce a range of phase offsets from –35° to +35°.

2.) A phase error of ± 0.54° will occur due to insertion phase slope differentials.

The Xinger Delay Line

When the insertion phase vs. frequency response of a device is not linear, it is said to be dispersive. This means that $\frac{dq}{dw}$ is not the same for all frequencies and therefore the delay is not constant with frequency. The Xinger surface mount delay line uses multiple printed lines placed in close proximity to one another and connected in series at the ends. The network can be described as a series of Schiffman[3] phase shifters connected together. This structure (described in [3] & [4]) is commonly used in wideband fixed phase-shifters that are often used in Butler matrices, phase discriminators and monopulse comparators. The use of the Schiffman phase shifter allows for a larger delay than what the physical length of transmission line would normally generate. This configuration produces a non-linear phase vs. frequency response that has the slope and corresponding electrical delay maximized at a specific frequency.

The end result is increased time delay per unit area as compared to printing linear line in the same space. Figure 6 shows the non-linear properties described above. Notice that in the region where this device is tuned (2GHz), it closely approximates a linear response but the frequency axis crossing is not at zero. This "linear" region of the response behaves very much like linear transmission line, however it intersects the y-axis at a point other than the origin (where linear line intersects). The slope in the region where the device is tuned is the same as the slope of a 5nS linear transmission line. The offset is much different, however this can easily be accounted for in systems where the objective is canceling a signal from a different path where the delay is the same. This y-axis origin offset changes with delay variation in the same manner as the linear coaxial cable case, described earlier.

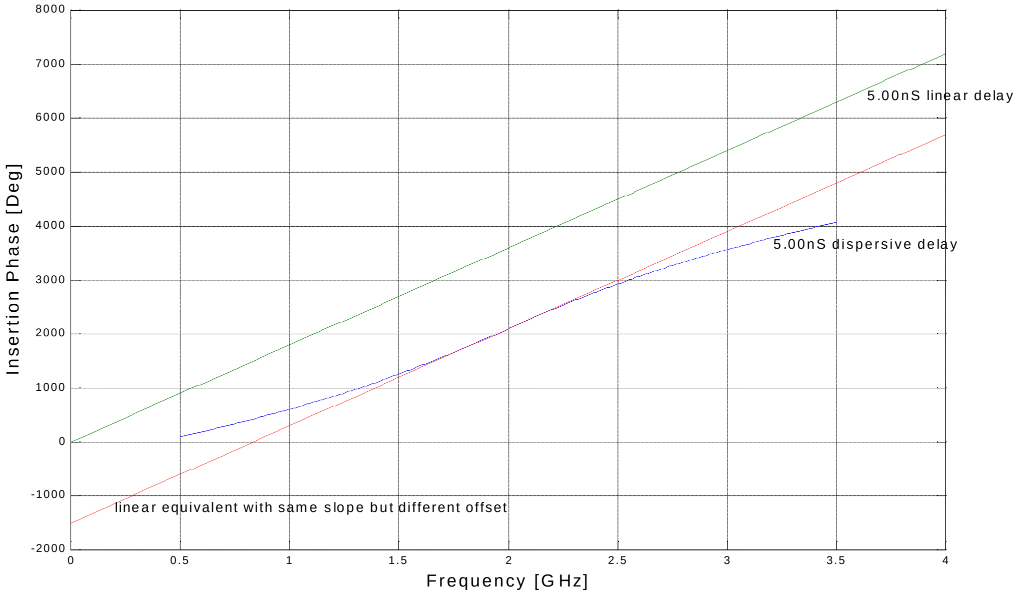

Figure 6 – Insertion Phase of a 5nS Length of Coaxial Cable and Anaren Delay Line

The phase error for the Anaren surface mount delay line is found by comparing the measured phase data to the phase response of an ideal linear transmission line with a delay equal to the nominal specified value for the model being tested. An example of test data for a 5nS nominal device is shown in Figure 7. The actual measured delay for this device was 4.957 nS (a compliant device @ 5.0 ± 0.05 nS). The phase error is approximately $\pm 0.46°$ which is the value that the equation for phase error (above) would yield.

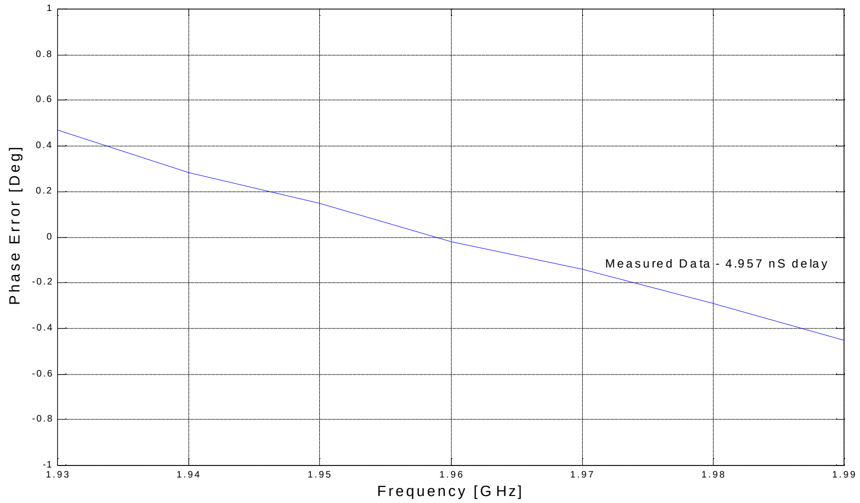

Figure 7 – Phase Error for the 5nS Xinger Delay Line

This demonstrates that the dispersive device described behaves like a linear transmission line in the regions near where the circuit is tuned. The one difference being the phase offset. This offset however, is constant with frequency and can be compensated for. Broadband performance of a 5nS Xinger delay line is presented in Figures 8 through 10, where the electrical delay, insertion loss and return loss are shown. This particular design has a Schiffman centered at 2GHz for maximum delay in the DCS, PCS and UMTS bands of 5nS and at frequencies further away from 2GHz, the delay is reduced to a nominal 3nS delay. In narrow band applications, such as the transmission frequencies in wireless base stations, this particular structure allows for very good performance in delay stability and linear phase.

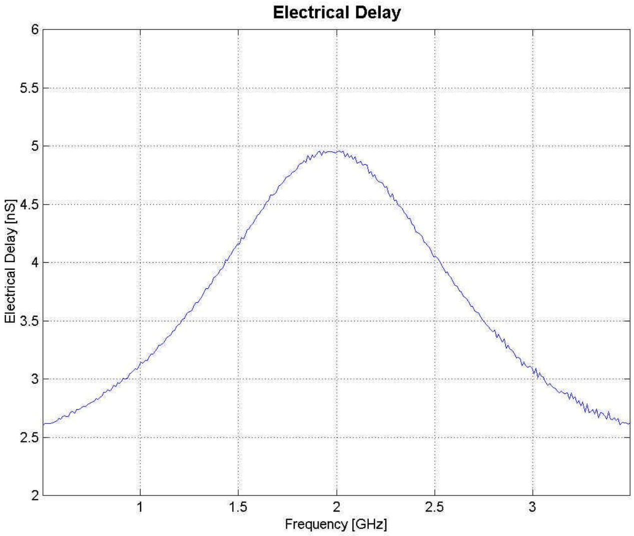

Figure 8 – Broad Band Electrical Delay of the XDL20-3-050 Xinger Delay Line

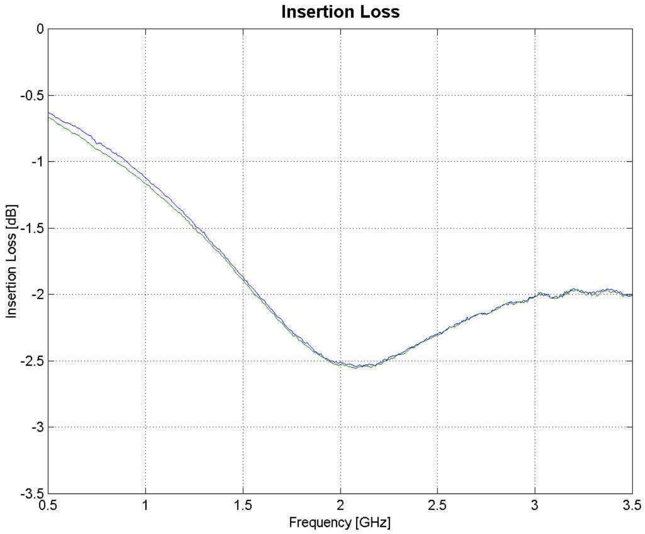

Figure 9 – Broad Band Insertion Loss Performance of the XDL20-3-050 Xinger Delay Line

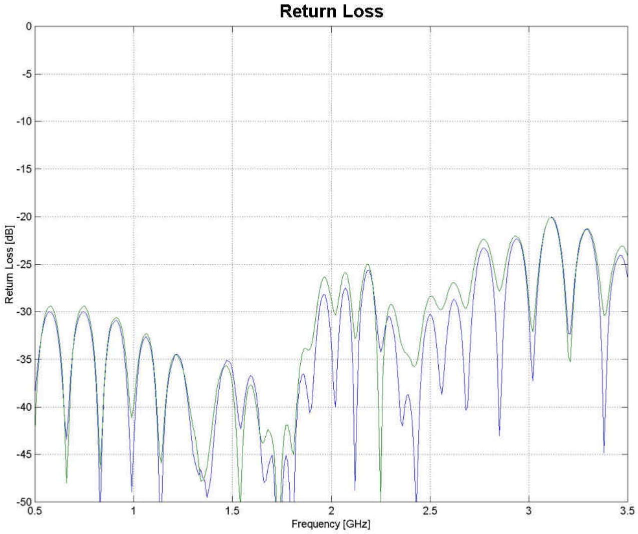

Figure 10 – Broad Band Return Loss Performance of the XDL20-3-050 Xinger Delay Line

Delay lines for feedforward power amplifier applications must also be stable over temperature, as base stations can be placed in very extreme environments and feedforward amplifiers must have excellent accuracy for optimal linearity. Although the use of vector modulators or other correction circuitry is common, the delay line must exhibit very stable delay characteristics over the specified temperature range. The data in Figure 11 shows the Xinger delay lines have excellent stability over extreme temperature variations and as expected, has better insertion loss at very low temperatures with some degradation at higher temperatures.

Currently, the Xinger delay lines are available with delay values (maximized at 2GHz) of 5nS (XDL20-3-050) and 10nS (XDL20-6-100), with more to follow. Each feedforward design will require unique delay values and custom Xinger delay lines can be manufactured, however to minimize the development time, designs should first use a number of serial delay lines and fine tune the delay using printed TEM transmission lines on microstrip. Should you have any particular requirement for a low cost, compact delay line please contact Anaren Microwave, Inc. at sales@anaren.com for further details.

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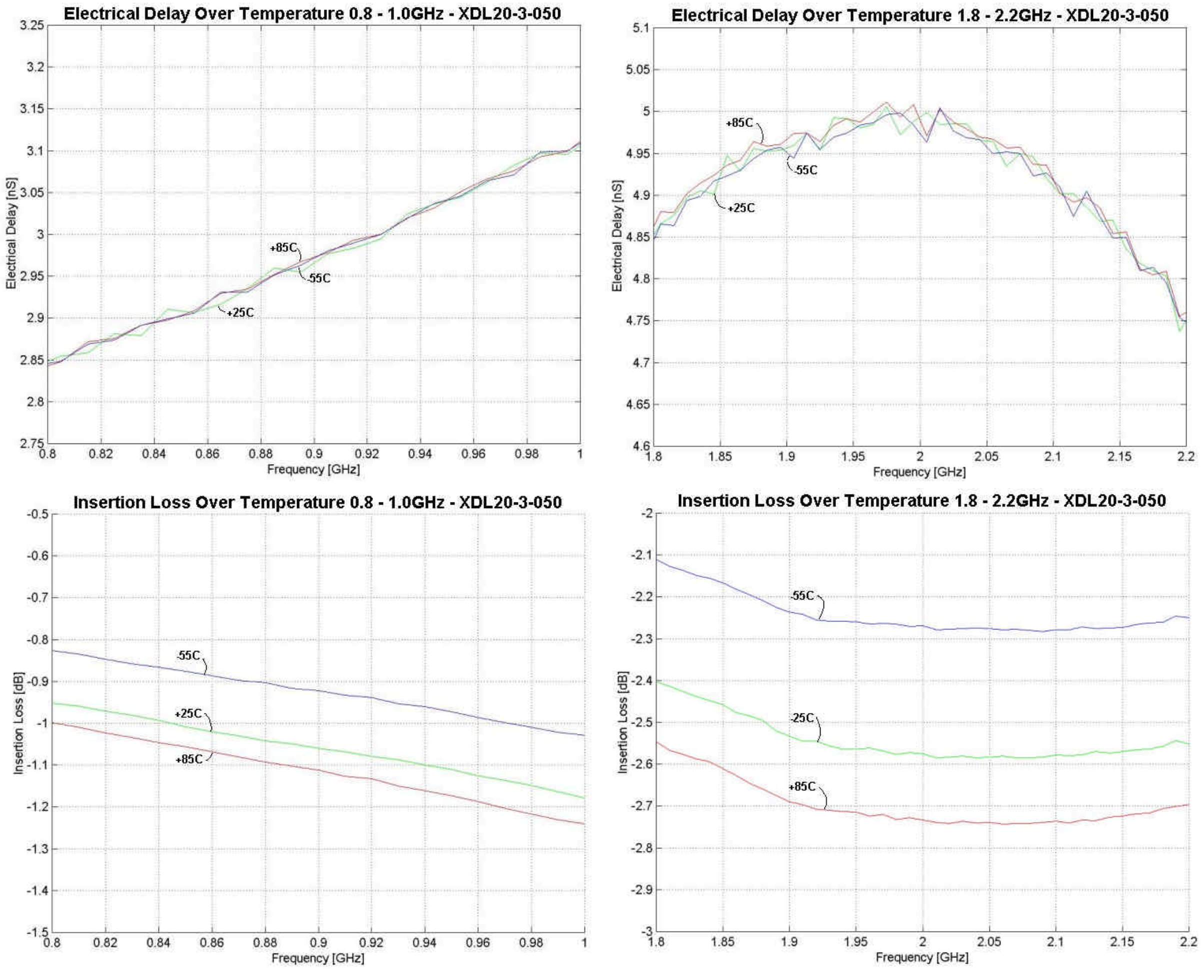

Figure 11 – Temperature Stability of the XDL20-3-050 Xinger Delay Line

Summary

The new Xinger delay lines are intended for use in the main loop of the feedforward linearization circuit commonly used in 2.5 and 3G MCPAs and are a low cost alternative to coaxial cable and delay filters in these low power applications. The Xinger delay lines take advantage of the Schiffman phase shifter structure that allows for the maximum amount of electrical delay in the smallest possible package and has been shown to be extremely stable over temperature. The Xinger delay lines are currently available in 5nS and 10nS delays with others in development. Custom delay lines are also available for qualified leads. Contact sales@anaren.com for more details on these and other innovations available at Anaren Microwave, Inc.

References:

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[3] B.M.Schiffman; “A New Class of Broad-Band Microwave 90-Degree Phase Shifters”; IRE Transactions on Microwave Theory and Techniques; April1958; pp. 232-237

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