

# **An N-Bit Digitally Variable Ultra Wideband Pulse Generator for GPR and UWB Applications**

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**Abstract** - This paper presents a low-cost Ultra Wideband (UWB) pulse generator that can vary the pulse duration digitally by using a Step Recovery Diode (SRD), microstrip transmission lines and PIN diodes. First, a sharp edge is generated by using a SRD circuitry. Then a pulse is formed from the sharp edge through the use of transmission lines and the PIN diodes. Based on the number of transmission lines ( $N$ ), the duration of the pulse can be varied in  $2^N$  steps. The UWB pulse generator circuits are implemented on an FR-4 substrate using microstrip line technology and UWB pulses with durations of 550 to 2400 psec are measured.

**Key words:** Ultra wide-band, pulse generator, UWB impulse radio.

## **Introduction**

UWB technology has found military applications such as ground penetrating radar (GPR), wall penetrating radar, secure communications and precision positioning/tracking [1, 2]. However, there is also a growing interest in commercial use of UWB technology such as in Wireless Personal Area Networks (WPAN) [3, 4]. This interest has been the result of increasing demand for much higher data rates on the order of hundreds of megabits since future wireless networks requires very large transmission bandwidths to reach these data rates. Currently, most wireless data technologies such as Bluetooth, IEEE 802.11b have baseband signals up to tens of megabits, and the baseband signal is sent using an RF carrier, which is basically a narrowband communication technique.

FCC recently allocated the frequency range from 3.1 to 10.6 GHz for UWB communications. UWB signal is defined as the signal that has the bandwidth to center frequency ratio greater than 0.25 or bandwidth of 500 MHz or higher. There are mainly two alternative ways of UWB systems from the point of view of generating the UWB signal. One system is so called the impulse radio in which ultra narrow pulses in picoseconds are generated and the generated time pulses may span of a few GHz bandwidth. It is mostly preferred in the GPR and precision positioning/tracking system. The other system is the multi-banded approach so that multiple narrowband signals are generated independently and then combined to form the larger bandwidth of UWB signal [5]. The multi-banded orthogonal frequency-division multiplexing (OFDM) approach is used in the commercial UWB systems.

In the impulse GPRs, the pulse widths of the generated time pulses have influence on the resolution of the radar. If the impulse radio is used as GPR to provide high penetration depth, higher pulse durations are preferred; however, it also brings about low resolution. Decreasing

of the sounding pulse duration and increasing the resolution is considered as one of the most promising ways for increase the quality of primary GPR data. However, excessively high resolution can also have inverse effect. Rather, use of more durational sounding signals can improve the primary GPR data [6]. Therefore, tuning the pulse width of the signal provides more flexibility and improved performance in UWB application systems. Particularly, in UWB ground penetrating radar, a digitally tunable pulse generator allows the pulse width to be changed digitally to achieve varying penetration depths and resolution [7].

In this paper, a digitally tunable UWB pulse generator for an impulse type of pulse generator is described. The pulse generator is realized with a simple circuitry by using Step Recovery Diode (SRD), PIN diodes and transmission lines. These components are also employed in the many equivalent basic UWB pulse generation circuits [8, 9]. The pulse generator as shown in Figure 1 generates initial sharp edges by using a Step Recovery Diode (SRD) from the input sinusoidal signal; then converts the sharp edges into short pulses with desired durations by using parallel short-circuited stub with variable length. This variable length is obtained by many PIN Diodes and transmission line sub-sections. The digitally tunable UWB pulse generator has been designed and implemented using microstrip line technology and yielded reasonable performance. Typical pulse durations varying from 550 to 1750 psec and from 900 to 2500 psec have been obtained experimentally for 2-bit and 4-bit pulse generator, respectively. Experimental results are also duplicated using simulations based on Agilent Advance Design System (ADS) platform.

### **N-Bit digitally tunable UWB pulse generator**

N-bit digitally tunable UWB pulse generator is implemented with two main sub-circuits; Step Recovery Diode (SRD) circuit and the Phase Shifter circuit as shown in Figure 1. The figure

shows the input step recovery diode circuit, phase shifter circuit with N PIN diodes and transmission line sub-sections and the output load. The basic formation of an UWB pulse is obtained first by creating a sharp edge by using SRD and then followed by the sharp edge being splitted into two components and then followed through two different signal paths. One signal component goes directly to the circuit output, the other component is delayed by the phase shifter circuit and also the polarity of the pulse is reversed through the use of a short circuit. The summation of these two components will yield the desired UWB pulse at the output as shown in the Figure 2. In the figure, generation of the pulse is mathematically modeled. In Figure 2.a, it shows the generated sharp edge with 1 Volt amplitude and 200 psec rise time by SRD. In Figure 2.b, the 400 psec delayed version of the sharp edge with the opposite polarity is shown and the sum of the graphs 2.a and 2.b generates the desired pulse as shown in Figure 2.c. Note that, the same circuitry can be used to obtain a Gaussian Monocycle waveform, in other words; adding two mono pulses back to back with one of them being with opposite polarity generates a Gaussian monocycle waveform.

Step recovery diodes (SRDs) have remained extremely useful in wave-shaping applications in the last few decades since they were first presented. No other device rivals their combination of fast switching speed and ease of use [10]. Figure 3 shows the typical circuit configurations for SRD pulse sharpening. In both circuits, the SRD is initially biased with a constant forward bias current  $I_{BIAS}$ , which stores charge in the SRD. When the voltage source  $V_{IN}$  rises, reverse biasing the SRD, the SRD conducts for a short period of time, removing the stored charge. This keeps the voltage across the diode very low. Then the stored charge is abruptly exhausted, and the SRD switches to a high-impedance, high-voltage state, resulting in a sharpening of the output voltage waveform. Therefore in the step recovery diode circuit, the SRD generates a sharp edge on the order of picoseconds from a low frequency sinusoidal signal applied to the input port of SRD diode circuit.

The phase shifter circuit is connected in parallel to the SRD circuit and the main purpose of the phase shifter circuit is to delay the sharp edge generated by the SRD, and to reverse the polarity of the delayed edge by a short circuit which terminates the phase shifter (or delay line) circuit. Actually, phase shifter circuit is a true time delay (TTD) circuit. In addition to SRD circuitry, phase shifter circuit implemented with microstrip lines constitutes the rest of the UWB pulse circuit. A section of a phase shifter circuit includes a microstrip transmission line, PIN diodes, RF chokes ( $L_{RF}$ ) and a DC blocking capacitor ( $C_{BL}$ ). Microstrip transmission lines are planar transmission lines which are fabricated by photolithographic processes and easily integrated with passive and active microwave devices. They are used as the delay elements of the phase shifter circuit; therefore, the lengths and numbers of the transmission lines are selected in accordance with the desired pulse widths since the transmission line lengths determine the amount of time delay. Other important components of the phase shifter circuit are PIN diodes. PIN diodes find applications as high-frequency switches for RF signals up to 50 GHz. They contain an additional layer of an intrinsic (I-layer) or lightly doped semiconductor sandwiched between highly doped  $p^+$  and  $n^+$  layers. In forward direction, the diode behaves as if it possesses a variable resistance controlled by the applied current. However, in reverse direction the lightly doped inner layer creates space charges whose extent reaches the highly doped outer layers. This effect takes place even for small reverse voltages and remains essentially constant up to high voltages, with the consequence that the diode behaves similar to a dual plate capacitor [11]. The bias point setting required to operate the PIN diode has to be provided through a DC circuit that must be separated from the RF signal path. The DC isolation is achieved by a radio frequency coil (RFC) or RF choke, representing a short circuit at DC and an open circuit at high frequency. Conversely, DC blocking capacitors ( $C_{BL}$ ) represent an open circuit at DC and a short circuit at RF. Figure 4 shows a

typical switching circuit where the PIN diode is used in series connection. In the phase shifter circuit, the PIN diodes are used as RF switch to control whether the signal goes through that delay element or not. In each section, there are three PIN diodes. As shown in Figure 1, if the series PIN 1 diode is forward-biased with positive bias voltage, then the PIN 2 and 3 are reverse biased, and hence the RF signal reaches the point B from the point A over the PIN 1 diode. On the other hand, if the PIN 2 and 3 are forward biased with negative voltage, then the PIN 1 diode is reverse-biased and the RF signal reaches the point B from the point A over the transmission line, and is delayed by the transmission line length. Depending on the desired pulse width, one or more phase shifter sections may be connected in series. All these phase shifter sections can be capacitively coupled by using DC blocking capacitors connected between the adjacent phase shifter sections. Various combinations of the PIN diodes can be used to obtain  $2^N$  different durations by using only N phase shifter sections. The series PIN diodes to the transmission lines also avoids undesired reflections during the pulse generation.

### **Simulation Results and Measurements**

Both 2-section and 4-section versions of the N-bit digitally tunable UWB pulse generator were first designed and simulated using Agilent Advanced Design System version 2003c to compare their performances. The UWB pulse generator circuits were then implemented on the FR-4 glass epoxy substrate with relative dielectric constant of 4.55 and thickness of 1.55 mm as shown in Figure 5 and Figure 6. The SRDs used in the circuit are series MSD700-75 and the PIN diodes are Ultra-Fast Switching series MMP7010-CS127 Low-High Power both manufactured by Micrometrics Inc. To obtain the desired pulse widths at the outputs, two and four sections are used in the phase shifter circuits of the pulse generators. In the 2-bit digitally tunable UWB pulse generator, the transmission lines are implemented using microstrip line technology so that the widths of the transmission lines are adjusted to 3 mm for matching the

transmission lines to the 50 Ohm at working frequencies and the lengths of the transmission lines are selected as 3 and 6 cm to produce 200 and 400 psec delays, respectively. The lengths of transmission lines are calculated by using Equations (1) and (2) given by

$$v_p = \frac{c}{\sqrt{\epsilon_e}} \quad (1)$$

where  $v_p$  is the phase velocity in m/sec,  $c$  is the velocity of light and  $\epsilon_e$  is the relative dielectric constant of the material. Equation (2) relates the length of the transmission line to the desired delay and phase velocity and it is given by

$$l = \Delta t \times v_p \quad (2)$$

where  $l$  is the length in meters and  $\Delta t$  is the desired time delay in seconds.

In the 4-bit digitally tunable UWB pulse generator, the transmission lines are also implemented using microstrip line technology, the widths of the transmission lines are adjusted to 3 mm and the lengths of the transmission lines are selected as 0.75, 1.5, 3 and 6 cm to produce 50, 100, 200 and 400 psec delays, respectively.

The minimum pulse width that can be obtained is limited by the SRD's maximum transition time which is measured by Agilent 8722ES Vector network analyzer around 125 psec. Figure 7 shows the phase measurement by the network analyzer. The slope of the phase measurement is the rise time of the pulse, which is 125 psec. In addition, the group delays of the PIN diodes and the dc blocking capacitors will also affect the pulse width. The group delay of one section of the series PIN diode switch shown in the Figure 4 is measured with by network analyzer at

forward bias and gives rise to a time delay of 110 psec which can be calculated from the Figure 8 as slope of the phase component of the reflection coefficient,  $S_{11}$ . Note that the overall pulse width is affected by twice the amount of group delay of the PIN diodes and the dc blocking capacitors since the UWB pulse goes over the PIN diodes and then reflected by the short circuit, and goes over the PIN diodes once again to reach the load. Therefore, the possible shortest pulse width durations are around 550 and 900 psec for 2-bit and 4-bit pulse generator, respectively; only including the offset delay of SRDs' maximum transition times and the group delays of PIN diodes and DC blocking capacitors. The other possible pulse durations of the generator are given in the Table 1 and Table 2 with their digital codes.

The ADS simulated output pulses of the 2-Bit digitally tunable UWB pulse generator are shown in Figure 9. The pulse width range from 550 psec to 1750 psec with steps of 400 psec, which corresponds to frequency bandwidth of 550 MHz to 2 GHz. Amplitude of the pulse output is around 400 mV when the applied input has a peak of 1.4 V at a pulse repetition frequency of 20 MHz. Also, note that the residual of the 20 MHz input signal around 28-31 nsec which can easily be removed by a simple high pass filter. Measured UWB pulses are shown in Figure 10, where the different possible combinations are plotted on the same graph. The pulse amplitudes are around 300 mV for an applied signal of 1.4 V for the same frequency of 20 MHz. Measurements are done with Agilent 86100C Digital Communication Analyzer. The pulse widths are also in very good agreement with the simulations for 550 psec to 1750 psec duration pulses.

Also, the frequency domain characteristics of the output pulses of 2-bit pulse generator are obtained by taking the Fourier transform of the measured pulses in time domain. The frequency domain characteristics of the longest and shortest pulses are shown in Figure 11,



where the longest pulse has a first null bandwidth of 600 MHz, and the shortest pulse has first null bandwidth of 1800 MHz, respectively.

The measured output pulse widths for 4-bit pulse generator range from 900 psec to 2400 psec with steps of 100 psec, which corresponds to bandwidth of 400 MHz to 1.1 GHz. In the Figure 12, the shortest, the longest and the other two time pulses among 16 output pulses are plotted on the same graph. Amplitude of the pulse output is around 300 mV when the applied input signal has a peak of 1.4 V at a frequency of 20 MHz. The output pulse of the generator can be easily used in and improve the performance of UWB GPR systems since most GPR systems are designed to work between 0.1 and 1.5 GHz [12, 13].

Also, one should note that the resolution of the pulse generator increases when the numbers of phase shifter sections are increased; however, this limits the frequency bandwidth since the group delays of the PIN diodes and dc blocking capacitors increase as more sections are placed into the circuitry. Therefore, there is a trade off between the frequency bandwidth and the resolution that can be obtained.

## **Conclusion**

In this paper, an UWB signal generator for an impulse type of pulse generator is described. 2-section and 4-section versions of N-Bit digitally tunable UWB pulse generator using SRD, microstrip line delay lines and PIN diodes are presented. The simulated and measured pulse widths are in agreement and the pulse width changes from 550 psec (~2 GHz bandwidth) to 1750 psec (~550 MHz bandwidth) for 2-section version and changes from 900 psec (~1.1 GHz bandwidth) to 2400 psec (~450 MHz bandwidth) for 4-section version, which can be considered as an UWB pulse. The minimum pulse width is determined by the transition time

of the employed SRD and the group delays of the PIN diodes and DC blocking capacitors changed with the number of phase shifter sections. Also, the monocycle type pulses can be easily obtained by using the similar circuitry which is used to obtain the UWB pulse. The circuitry is low-cost, can be easily used in GPR, UWB radar, UWB positioning applications.

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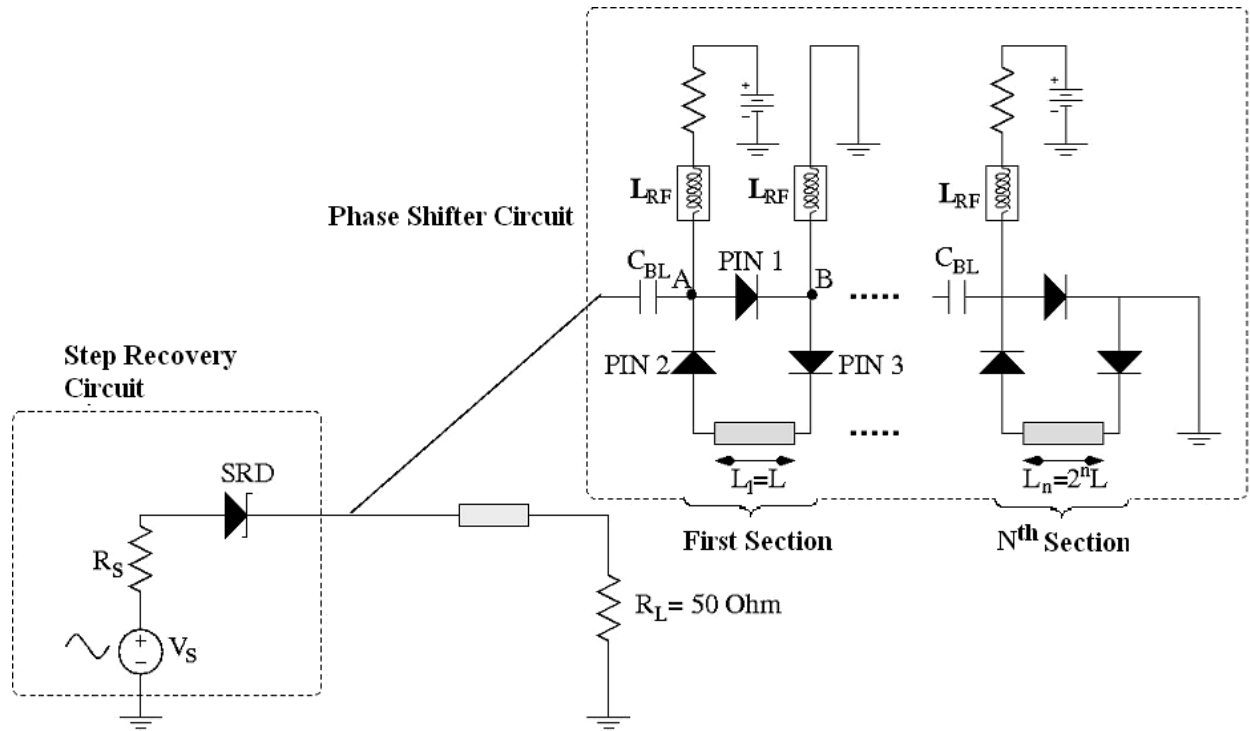
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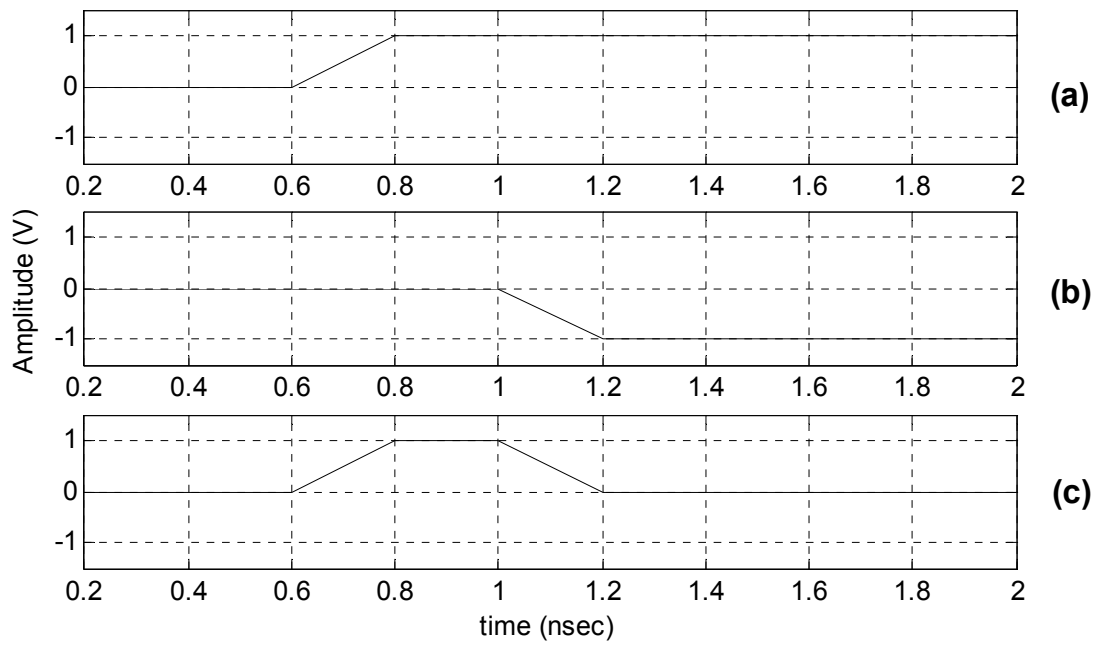
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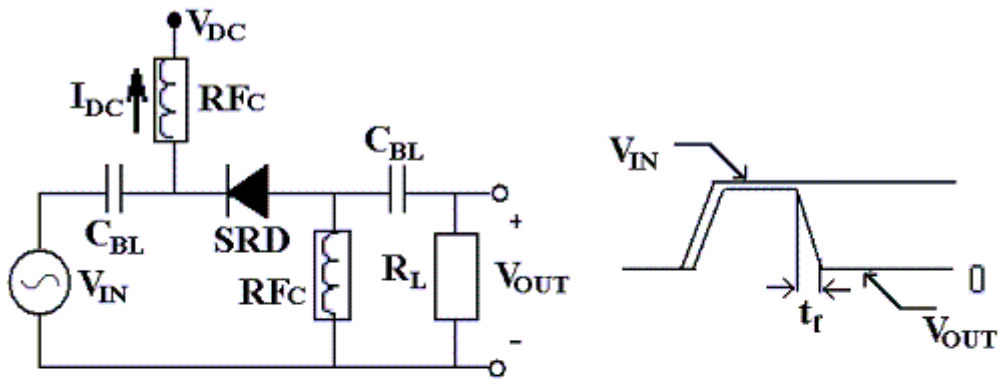


**Figure 1** Schematic of the N-Bit digitally tunable pulse generator

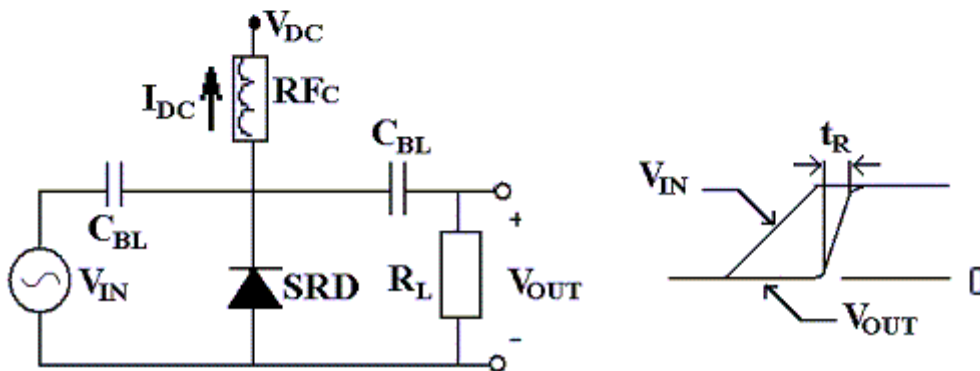


**Figure 2 (a)** A sharp edge obtained by using the SRD **(b)** the delayed version of the sharp edge with the opposite polarity **(c)** Sum of (a) and (b) to generate the desired pulse

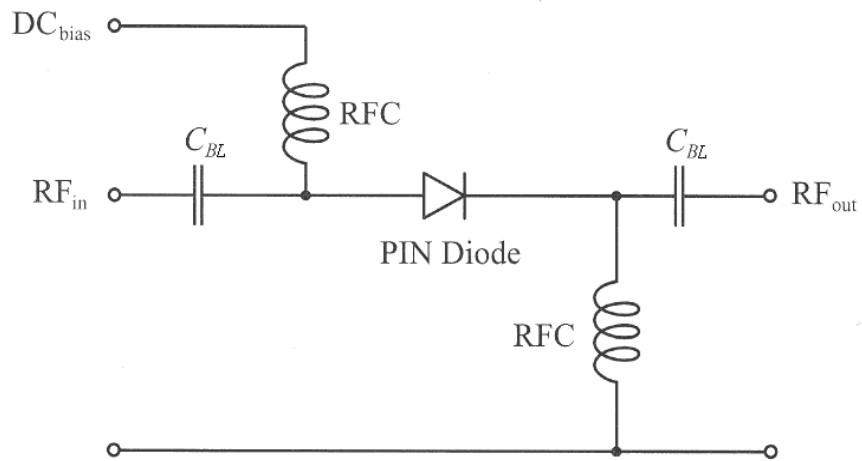
**Fall time sharpening (or pulse width control):**



**Rise time sharpening (or delay control):**

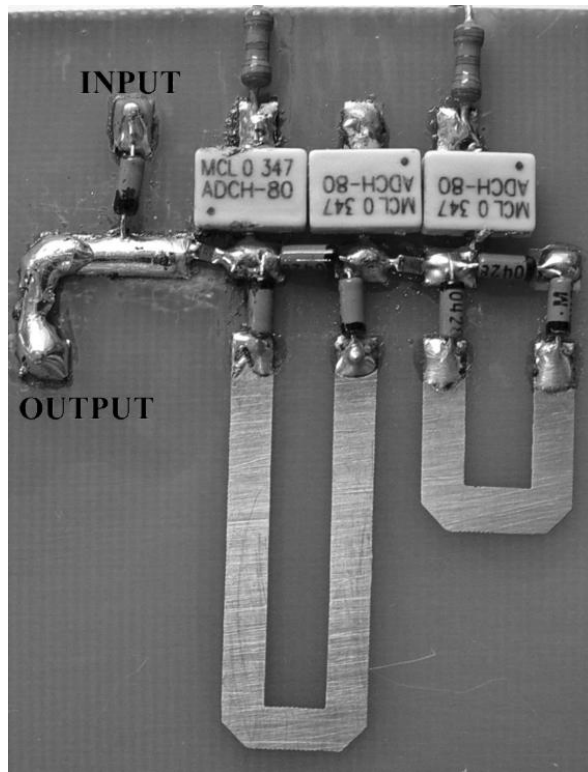


**Figure 3** Standard step recovery diode pulse sharpening circuits

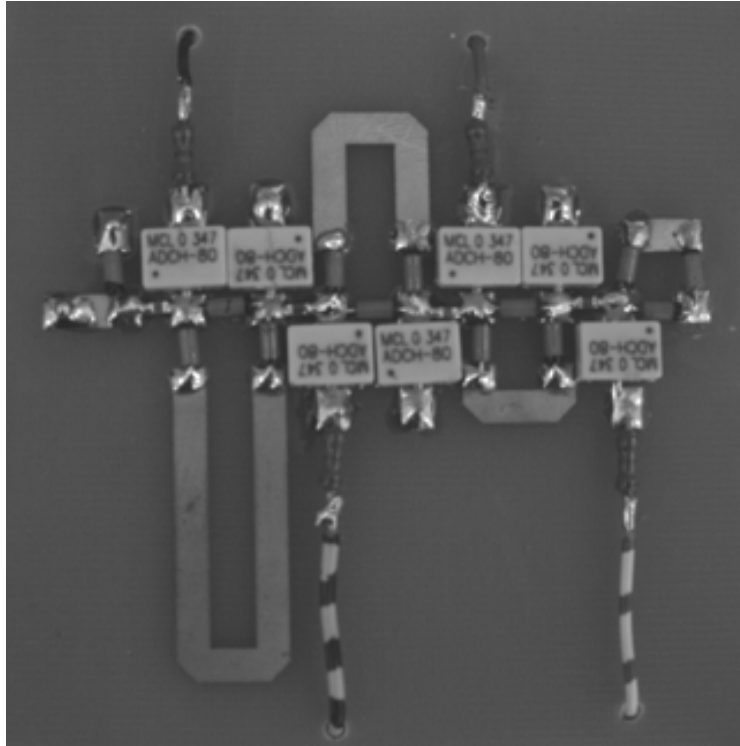


**Figure 4** Switching circuit with biased PIN diode in series configuration

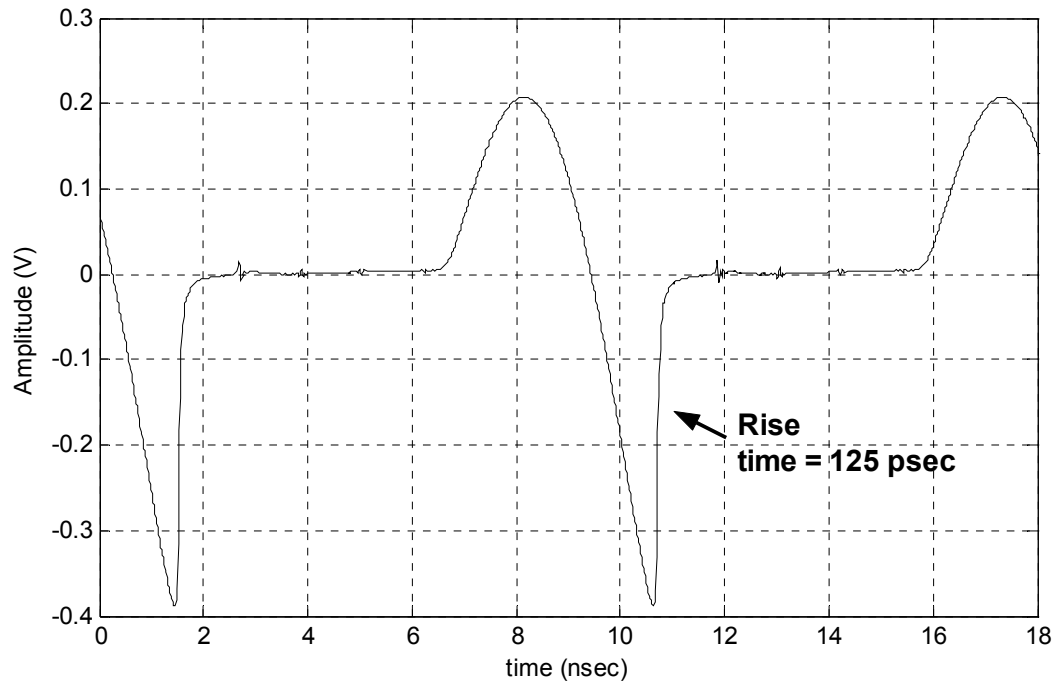




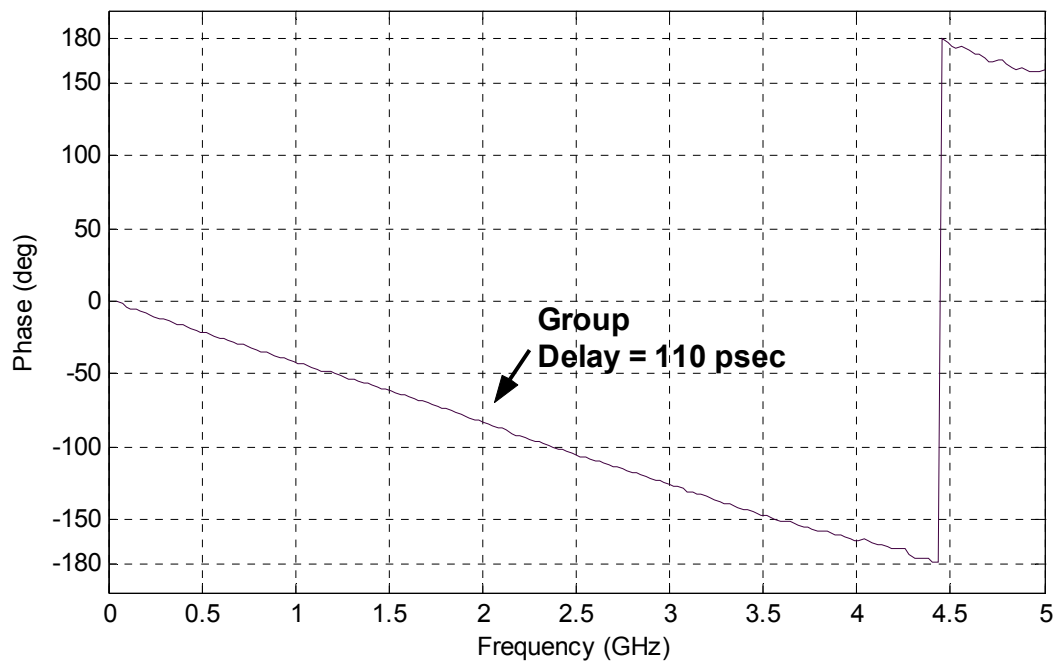
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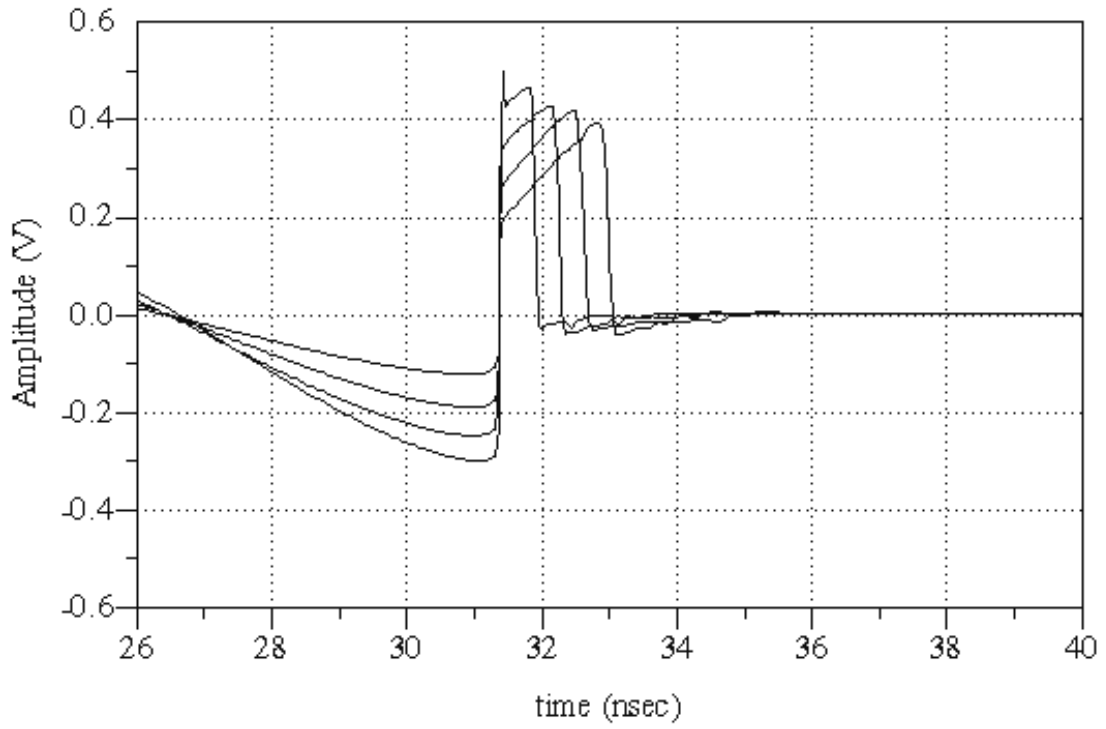
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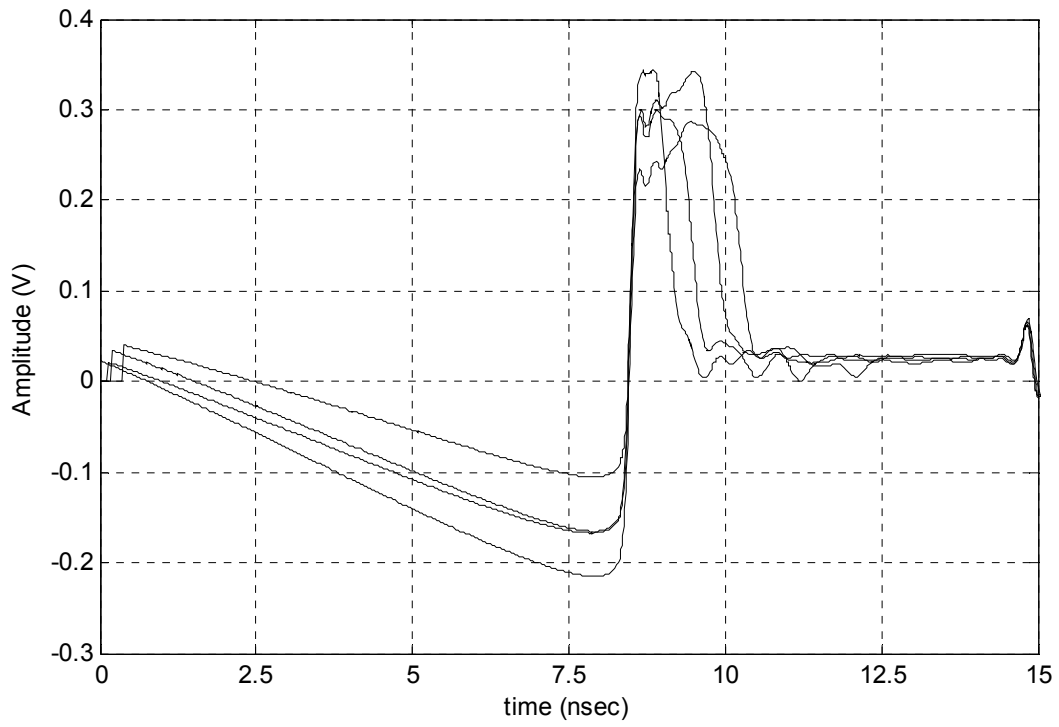
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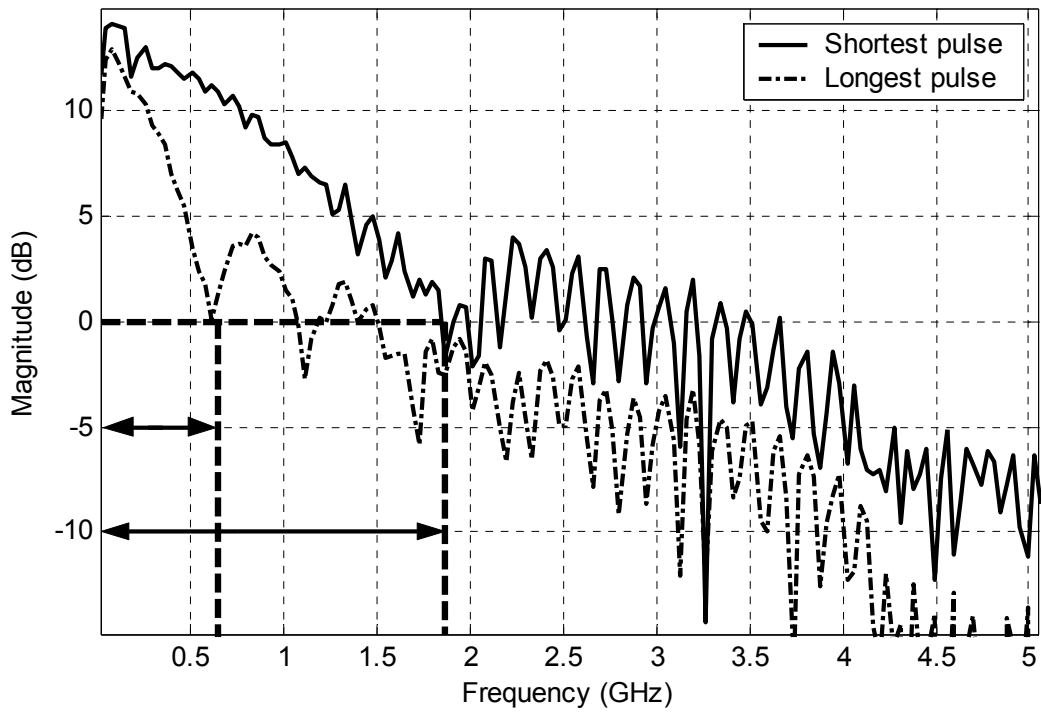
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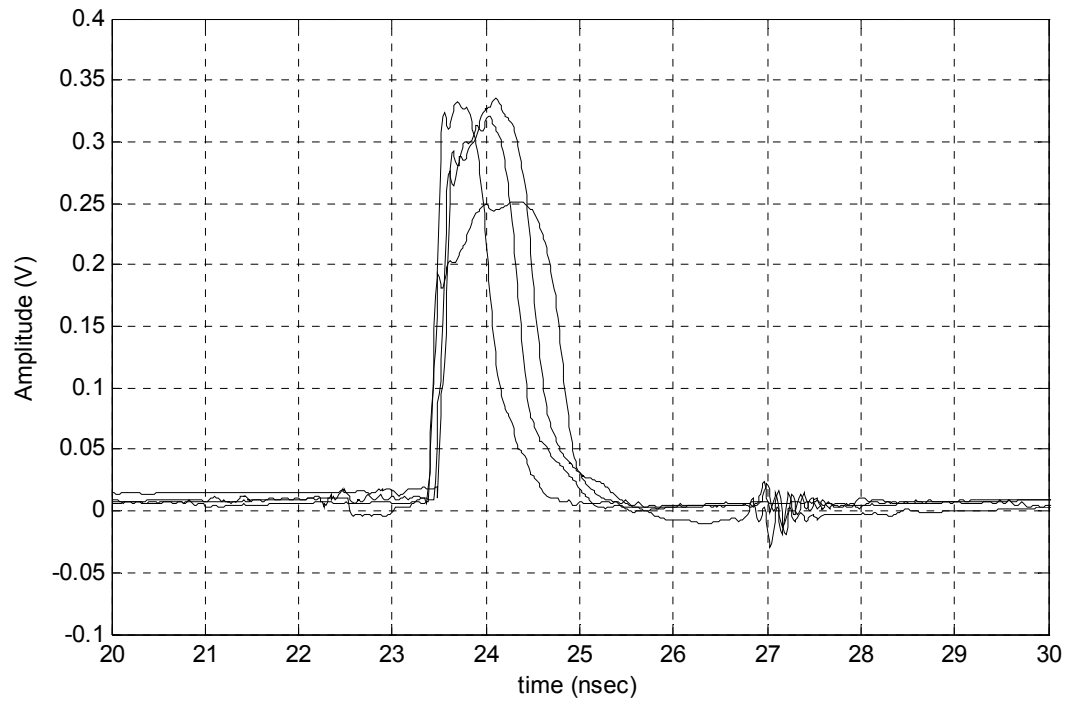
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**Figure 10** Variable width pulses generated by UWB pulse generator circuit (measured)



**Figure 11** Frequency Domain Characteristics of the longest and shortest pulses



**Figure 12** Measured output pulses generated by 4-Bit UWB pulse generator circuit



**Table 1.** Pulse durations of 2-bit digitally tunable pulse generator

<b>Code*</b>		<b>Pulse Width (psec)</b>
<b>Section 1</b>	<b>Section 2</b>	
0	0	550
0	1	950
1	0	1350
1	1	1750

- **Code 0:** the series PIN diode is forward-biased in the section
- **Code 1:** the series PIN diode is reversed-biased in the section

**Table 2.** Pulse durations of 4-bit digitally tunable pulse generator

Code*				Pulse Width (psec)
Section 1	Section 2	Section 3	Section 4	
0	0	0	0	900
0	0	0	1	1000
0	0	1	0	1100
0	0	1	1	1200
0	1	0	0	1300
0	1	0	1	1400
0	1	1	0	1500
0	1	1	1	1600
1	0	0	0	1700
1	0	0	1	1800
1	0	1	0	1900
1	0	1	1	2000
1	1	0	0	2100
1	1	0	1	2200
1	1	1	0	2300
1	1	1	1	2400