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DESIGN NOTE

Generation of kilovolt–subnanosecond pulses using a nonlinear transmission line

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Abstract. A nonlinear transmission line (NLTL) is used to speed up the risetime of high voltage (>1 kV) pulses. The theory of the NLTL is reviewed and practical implementations and limitations are discussed. An NLTL is used to generate a 1.5 kV pulse with a risetime of 500 ps. The note concludes with a discussion of generating pulses with amplitudes greater than 3.5 kV and risetimes less than 200 ps.

1. Introduction

There are many applications which require pulses with amplitudes greater than several hundred volts and risetimes in the picosecond regime. However, many instruments are limited in their measuring capabilities by the speed of the gating or sampling pulse used. This paper presents a technique by which nanosecond risetimes can be changed into picosecond risetimes while maintaining the general shape of the pulse. This will increase the bandwidth of measuring systems by allowing shorter gating and faster turn-on times.

Pulses with risetimes less than 5 ns and with amplitudes greater than 4 kV can be generated using power MOSFETS [1–3]. The output of the power MOSFET pulse generator is then fed to a nonlinear transmission line (NLTL) [4–7] and sharpened to the desired risetime.

2. Review of nonlinear transmission line operation

The basic idea behind a NLTL [4] is that the velocity of propagation at a point on the NLTL depends on the voltage at that point. Referring to Figure 1, if the velocity of the wave at the 10% voltage point is slower than the velocity at the 90% point, where the risetime is the time difference between these points, the 90% point 'catches up' with the 10% point, in effect speeding up the rising edge of the pulse.

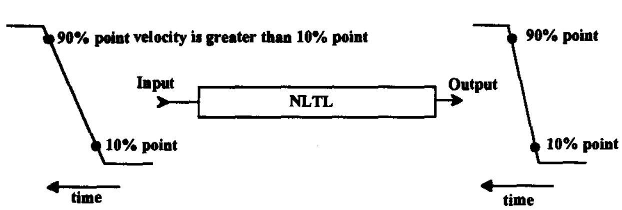

Figure 1. Shows that if the velocity of the wave at the 90% point is greater than the velocity at the 10% point the output risetime will decrease.

The velocity of propagation along a transmission line is $1/\sqrt{LC}$ where L and C are the inductance and capacitance per unit length of transmission line. Consider the circuit shown in Figure 2(a) and its equivalent circuit shown in Figure 2(b). The diodes are always reverse biased. The capacitance of a diode is a function of the reverse potential across it and for an abrupt junction is given by

$$C_d = \frac{C_{jo}}{\sqrt{1 + V_d/\varphi}}$$

where C_{jo} is the zero bias depletion capacitance, V_d is the magnitude of the reverse voltage across the diode and φ is the junction potential. The capacitance of the diode at the 10% and 90% voltage points will be called

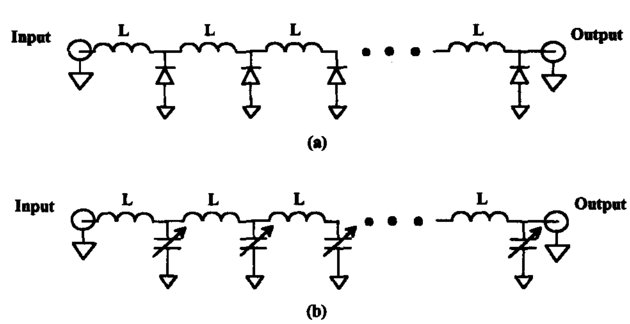

Figure 2. (a) Circuit diagram of the nonlinear transmission line and (b) equivalent circuit when the diode behaves like a variable capacitor.

C_{d10} and C_{d90} respectively. Therefore the velocity of the pulse at the 10% point is $1/\sqrt{LC_{d10}}$ and at the 90% point $1/\sqrt{LC_{d90}}$. Similarly the decrease in risetime per section (DRPS) is equal to the delay difference at the 10% and 90% points or $\sqrt{LC_{d90}}-\sqrt{LC_{d10}}$. Note that if this were a normal transmission line where the capacitance and inductance per section were constant the DRPS would be zero. If the delay is 20 ps per section (one section consisting of a single inductor and diode) and it is desired to change a 1 ns risetime pulse into a 500 ps risetime, then 25 sections are needed. The DRPS can be increased by using larger value inductors or selecting a diode with a large $C_{d10}-C_{d90}$.

This periodic structure has a Bragg cut-off frequency [5–7] f_c given by $1/\pi\sqrt{LC_{jo}}$. This cut-off frequency puts an upper limit on the DRPS. The minimum risetime is $t_{rm}=0.35/f_c$ at the Bragg cut-off frequency, and there will be significant ringing in the output pulse. When generating an impulse this ringing can be used to generate larger amplitude signals than would be achieved if f_c were not the dominant effect. In general, for clean pulses, the output risetime should be at least twice as long as t_{rm}.

Another concern is the diode series resistance and junction capacitance time constant. The diode series resistance consists of the ohmic contact resistance and the resistance of the lightly doped region between the p- and n-type semiconductors. The contact resistance is typically less than 0.3 Ω while the resistance of the lightly doped region is typically 10 Ω. When the diode capacitance is 20 pF a small signal time constant of 200 ps is introduced. In practice the diode cut-off frequency has little effect when sharpening high-voltage signals owing to the small value of junction capacitance (of the order of 1 pF) at the 10% voltage point of the pulse. Because the resistance of the lightly doped region will decrease with increasing reverse potential, the practical time constant of the diode is 20 ps.

3. An example

As an example consider a NLTL which takes a 1.5 kV, 2 ns risetime pulse and generates a 1.5 kV, 500 ps risetime output pulse. The immediate requirement on the diodes is that they have a breakdown voltage greater than 1.5 kV. The 1N4007 diode chosen for this example has a breakdown voltage greater than 1.6 kV. The C_{jo} of the 1N4007 is typically 13 pF. The series inductance internal to the diode package is 2.5 nH. The diode will become series resonant at a frequency of $1/2\pi\sqrt{2.5\ \text{nH}\cdot 13\ \text{pF}}$ or 883 MHz. This corresponds to a risetime of 400 ps. Because the inductance will begin to offset the diode capacitance before the resonant frequency, the resonant limited risetime is lower than what will be obtained in practice.

To ensure that the diodes limit the risetime rather than the periodic structure, a small inductance between stages and a large number of sections were selected. It would be more economical to vary the inductor value by using large value inductors at the beginning of the NLTL and small values at the end. This would avoid the Bragg cut-off frequency and minimize the number of diodes required.

For this design 3 nH is used between stages. The inductor is constructed using a 0.5 cm piece of 20 AWG wire. The anodes of the diodes are soldered to a copper ground plane while the cathode is elevated to reduce stray capacitance. The Bragg frequency of this structure is $1/\pi\sqrt{3\ \text{nH}\cdot 13\ \text{pF}}$ or 1.6 GHz which corresponds to a risetime of 217 ps, a factor of two below the diode resonant risetime. Assuming $\varphi=1$ the capacitance of the diodes is $C_{d10}=13\ \text{pF}/\sqrt{150}=1.06\ \text{pF}$ and $C_{d90}=13\ \text{pF}/\sqrt{1350}=0.35\ \text{pF}$. This corresponds to a DRPS of $\sqrt{3\ \text{nH}\cdot 1.06\ \text{pF}}-\sqrt{3\ \text{nH}\cdot 0.35\ \text{pF}}=24\ \text{ps}$. Because of a stray capacitance per section of approximately 0.2 pF, the actual DRPS is approximately 20 ps.

Figure 3 shows the input pulse (trace A) and the output pulses (traces B and C) using 50 sections and 100 sections respectively. The risetime of our measuring system was 850 ps, determined using a 25 ps risetime pulse generated with a tunnel diode. Trace B for 50 sections shows a measured risetime of 1.26 ns. The actual risetime of trace B is $\sqrt{(1.26n)^2-(0.85n)^2}=930$ ps. This corresponds very closely to the estimated risetime, namely (1.9 ns − 50 × 20 ps) or 900 ps. When we add 50 more sections we encounter the diode limited risetime with a measured risetime of 500 ps. Adding additional sections did not decrease the risetime confirming that the diodes are indeed the limiting factor.

4. Discussion

The diode breakdown voltage and series inductance are the limiting factors in achieving higher amplitude and

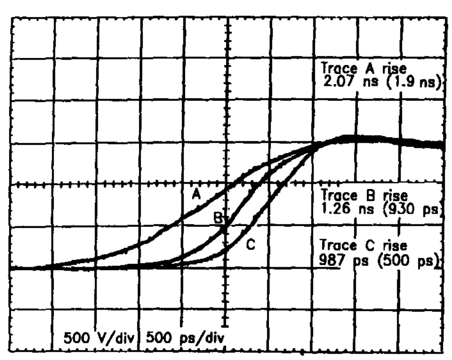

Figure 3. Trace A is the input to the NLTL and has a risetime, after removing the scope risetime, of 1.9 ns. The risetimes of traces B and C are 930 ps and 500 ps respectively. Trace B corresponds to 50 diodes while trace C corresponds to 100 diodes. The vertical scale corresponds to 500 V per division while the horizontal scale is 500 ps per division.

faster risetime pulses. The breakdown voltage of the diodes can be increased by using glass passivation.†

If the diodes cannot be removed from their package then risetime performance is limited by the series inductance. A simple but effective method to increase both the diode series resonant frequency and the Bragg cut-off frequency is to apply a small positive DC voltage to the line. For example, if 15 V is applied to the line, the initial capacitance of each diode will decrease by a factor of four, increasing the resonant limited frequencies by two (causing the resonant limited risetime in the example presented to become 200 ps). The cost for this improvement is a small decrease in the DRPS.

† General Instruments manufactures glass passivated rectifiers with breakdown voltages in excess of 3.5 kV. One supplier is Newark Electronics, Chicago, IL 60640, USA.

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