Experimental characterization of short-pulse generation using switch lines

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Abstract: We report the experimental observation of the generation of short electrical pulses in a switch line, which is a transmission line periodically loaded with electronic switches. Pulse-width compression was experimentally demonstrated in the test switch line, using discrete Esaki diodes as the switches.

References

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1 Introduction

A switch line, defined as a lumped transmission line containing a series resistor, shunt capacitor, and shunt switch in each section (switch open for voltages greater than some fixed threshold; switch closed otherwise), is first discussed by Richer in 1966 [1]. We investigate the switch line for use in

high-speed electronics, particularly for the generation of ultrashort electrical pulses. The generation of an ultrashort electrical pulse with a picosecond duration is a key to achieving a breakthrough in high-speed electronics [2]. Potential applications include measurement systems with a picosecond temporal resolution, over 100 Gbit/s communication systems, and submillimeter-to-teraherz imaging systems. For use in high-speed electronics, the series inductance becomes greater than the series resistance. We investigated the quasi-steady propagation of a pulse on a switch line, where the series resistor is replaced by a series inductor to determine the properties of the switch line [3].

2 Operating principles

Figure 1 shows a circuit diagram of a switch line, where L, C, and G represent the series inductor, shunt capacitor and shunt switch of the unit section, respectively. Esaki diodes or resonant tunneling diodes (RTDs) [4] are best employed as periodically loaded switches. For simplicity, we assume that the switches have voltage-dependent conductance: $G = G_0\theta(V_{th} - V)$, where $\theta(V)$ exhibits the Heaviside function. Moreover, V_{th} is the voltage threshold of the switch, which corresponds to the peak voltage of the tunneling diodes. Hereafter, we discuss a pulse on a switch line that crosses V_{th}. We refer to the voltage range less (greater) than V_{th} as region I (II). The pulse is influenced by finite shunt conductance in region I and is completely loss-free in region II. Note that a switch line behaves as a linear dispersive line when considering regions I and II only. A linear dispersive line allows exponential waves together with sinusoidal waves. In general, exponential waves are discarded because they cannot satisfy any physically meaningful boundary conditions. However, we consider the case in which a pulse crosses V_{th}. In this case, the development of an exponential wave in region I becomes possible by combining it continuously with a sinusoidal wave in region II. By numerical evaluations, it is known that an exponential mode develops in region I, and a sinusoidal one develops in region II.

For quasi-steady pulse propagation, the phase velocity of the sinusoidal mode in region II must coincide with the exponential one in region I. Figure 2 shows the dependence of the phase velocity on the wave length. The phase
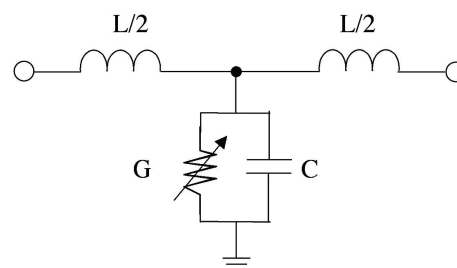

Fig. 1. Equivalent representation of a switch line. L: series inductance, C: shunt capacitance, and G: shunt conductance simulating loaded switch.
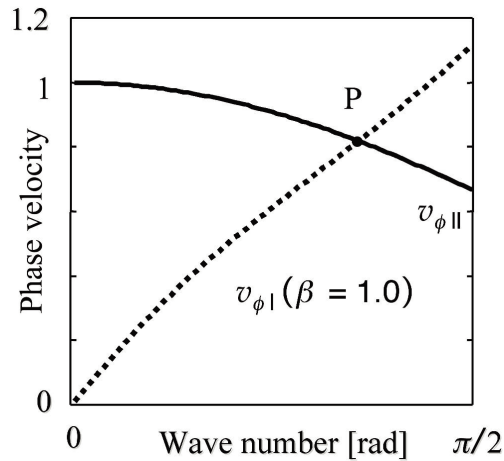
Fig. 2. Dispersion curves in regions I and II. The compressed short pulse occupies the cross point P.

velocities of a sinusoidal mode in region II ($v_{\phi II}$) and an exponential mode in region I ($v_{\phi I}$) are shown. $v_{\phi I}$ depends on the dimensionless conductance β defined as

$$\beta = G_0 \sqrt{\frac{L}{C}} \ . \tag{1}$$

In general, $v_{\phi II}$ decreases and $v_{\phi I}$ increases, as the wave number becomes large. They coincide at cross point P in Fig. 2, which occupies the range of rather large wave numbers. For coincidence of the velocities in both regions I and II, the input pulse experiences a shortening of the wavelength, i.e., the input pulse is compressed greatly. The degree of compression is estimated by the wave number at P. Moreover, the wave number becomes larger for larger β; therefore, the greater the conductance, the more is the input pulse compression. Although this discussion is based on ideal switch lines, the same properties have been determined for switch lines implemented with practical tunneling devices by SPICE- and finite-difference-time-domain-based calculations [5].

3 Experiments

Experimentally, we used a 50-section switch line whose unit section is shown in Fig. 1. The circuit is built on a standard bread board. The shunt electronic switches are NEC 1S1763 Esaki diodes. The peak current and voltage, which corresponds to V_{th} in the ideal switch model, are typically 6.0 mA and 60 mV, respectively. Moreover, the typical parasitic capacitance is 30.0 pF. Series inductances and shunt capacitances are implemented using 1.0 µH inductors (TDK SP0508) and capacitors (TDK FK24C0G1), respectively. The design parameters are estimated as $L = 1.0\,\mu$H, and $G_0 = 0.1$ S. To see the β dependence of the degree of the pulse compression, we prepared two different capacitors, one with a capacitance of 10 nF, and one with 4.7 nF. The test switch line is fed by a pulse signal generated by an Agilent 81150A function generator. A Gaussian pulse with a full-width-at-half-maximum (FWHM) of
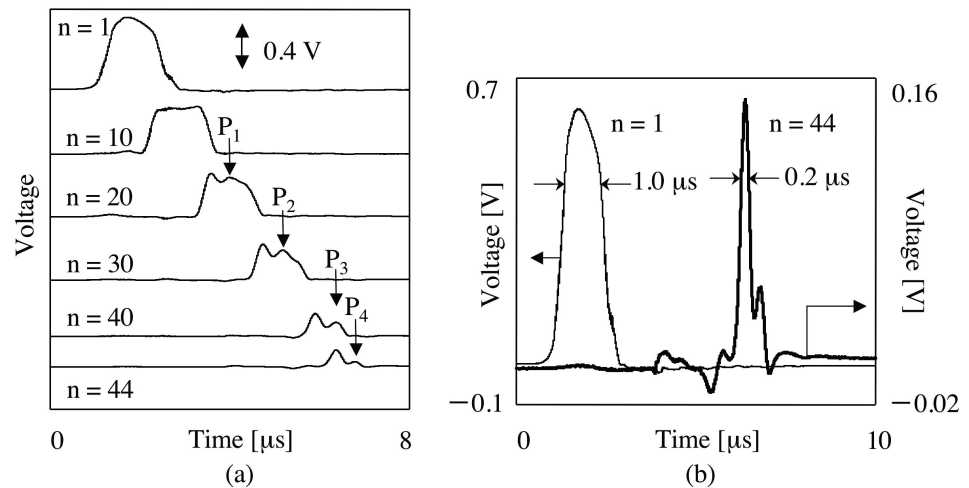
Fig. 3. Characteristics of a switch line where $\beta = 1.0$. (a) Waveforms monitored at cells $n = 1$, 10, 20, 30, 40, and 44, and (b) normalized pulses at $n = 1$ and $n = 44$.

1.0 μs is input. The generator output impedance is set as 5 Ω, and the other end of the test line is short-circuited. The signals along the test switch line are detected and monitored in the time domain using an Agilent DSO90254A oscilloscope.

Figure 3 (a) shows the voltage waveforms monitored at cells $n = 1$, 10, 20, 30, 40, and 44. The shunt capacitance is set as 10 nF, such that $\beta = 1.0$. We can see that the pulse is split into two at $n > 20$. The symbols P_i ($i = 1$, 2, 3, and 4) in Fig. 3 (a) show the positions of the second pulses developed at $n > 20$. The 1.0-μs wide pulse is compressed to give a width of 0.2 μs after propagation. The lifetime of the first pulse is greater than that of the second; therefore, a single short pulse remains at $n = 44$. To determine the degree of compression, we compared the waveform at $n = 1$ (thin solid curve) with that measured at $n = 44$ (thick solid curve) in Fig. 3 (b). The left vertical axis measures the voltage at $n = 1$, while the right-vertical axis measures the voltage at $n = 44$. Although the amplitude is attenuated, the FWHM of the compressed pulse is estimated to be 0.2 μs. The attenuated amplitude can result from the parasitic resistances of the inductors and capacitors. It is established that the finite resistive elements do not prevent the switch line from achieving pulse compression.

The results shown in Fig. 4 (a) were obtained by the same measurements performed to obtain those shown in Fig. 3, but with a shunt capacitance of 4.7 nF ($\beta = 1.45$). Figure 4 (a) shows more compression than seen in Fig. 3 (a). This result is consistent with the prediction that a pulse is compressed more for greater β. To quantify the degree of compression, the fundamental frequency of the resulting single pulse is evaluated, which should correspond to the wave number at the cross point of the dispersion curves $v_{\pi I}$ and $v_{\pi II}$ in Fig. 2. For $\beta = 1.0$, the fundamental frequency is calculated to be 2.9 MHz, while for $\beta = 1.45$, it is 4.2 MHz. This means that the pulse width
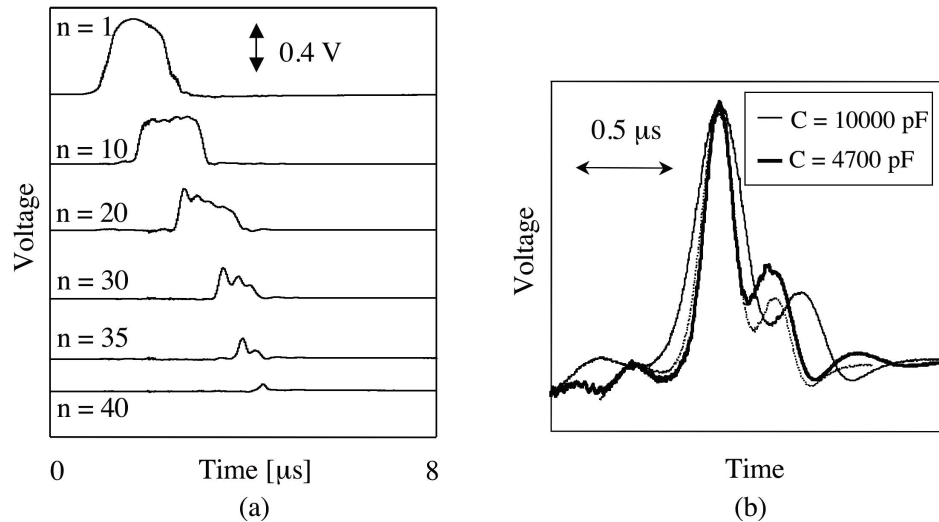
Fig. 4. Characteristics of a switch line where $\beta = 1.45$. (a) Waveforms monitored at cells $n = 1$, 10, 20, 30, 35, and 40, and (b) comparison between the compressed pulse in the switch line for $\beta = 1.0$ and $\beta = 1.45$. The thin-solid curve in Fig. 4 (b) shows the compressed pulse in the $\beta = 1.0$ line, while the thick-solid curve shows it in the $\beta = 1.45$ line.

becomes 70 percent smaller for 4.7 nF capacitors than for 10.0 nF over time. Figure 4 (b) compares the compressed pulses for both cases. The amplitudes are normalized to make them identical for clear comparison. The thin and thick pulses represent the compressed pulses for 10.0 and 4.7 nF capacitors, respectively, and the dotted pulse represents the one obtained by artificially compressing the solid pulse by 70 percent along the horizontal axis. For the first peak, the dotted pulse fits the thick-solid one well. These observations strongly suggest that compressed pulses are generated in the test switch line.

In conclusion, we successfully demonstrated pulse compression using switch lines. Our approach could also be scaled from its current MHz form into microwave, millimeter-wave, and terahertz forms, when implemented with state-of-the-art tunneling devices such as InP RTDs.