Generation of short electrical pulses using nonlinear traveling-wave field effect transistors

Koichi Narahara^{a)}

Graduate School of Science and Engineering, Yamagata University,
4–3–16 Jonan, Yonezawa, Yamagata 992–8510, Japan

a) narahara@yz.yamagata-u.ac.jp

Abstract: We investigated the properties of pulse propagation on nonlinear traveling-wave field effect transistors (TWFET) in order to develop a method for generating short electrical pulses. We considered the case where a decreasing voltage pulse is applied to the gate line and an increasing one is simultaneously applied to the drain line. By properly designing the top and bottom levels of the applied pulses, every FET simulates an electronic switch (the switch is open for voltages greater than some fixed threshold, and closed otherwise). On a line with such switches, a pulse experiences great shortening by the development of steep exponential wave; therefore, a TWFET operates as a short pulse generator.

Keywords: traveling-wave FETs, pulse generation, nonlinear waves

Classification: Microwave and millimeter wave devices, circuits, and systems

References

- [1] M. J. W. Rodwell, S. T. Allen, R. Y. Yu, M. G. Case, U. Bhattacharya, M. Reddy, E. Carman, M. Kamegawa, Y. Konishi, J. Pysl, and R. Pallela, “Active and nonlinear wave propagation devices in ultrafast electronics and optoelectronics,” *Proc. IEEE*, vol. 82, pp. 1037–1059, 1994.
- [2] G. W. McIver, “A traveling-wave transistor,” *Proc. IEEE*, vol. 53, pp. 1747–1748, 1965.
- [3] K. C. Gupta, R. Garg, and I. J. Bahl, *Microstrip Lines and Slotlines*, Artech, 1979.
- [4] K. Narahara and T. Otsuji, “Characterization of wave propagation on traveling-wave field effect transistors,” *Jpn. J. Appl. Phys.*, vol. 37, pp. 6328–6339, 1998.
- [5] K. Narahara and A. Yokota, “Experimental characterization of short-pulse generation using switch lines,” *IEICE Electron. Express*, vol. 5, pp. 973–977, 2008.
- [6] K. Narahara and S. Nakagawa, “Nonlinear traveling-wave field effect transistors for amplification of short electrical pulses,” *IEICE Electron. Express*, vol. 7, pp. 1188–1194, 2010.

1 Introduction

The generation of an ultrashort electrical pulse is one of the keys to produce a breakthrough in high-speed electronics [1]. The applications include high-resolution measurement and high-speed communication systems. We investigated traveling-wave field effect transistors (TWFETs) as a platform for generating short electrical pulses. A TWFET is a special type of FET whose electrodes are employed not only as electrical contacts but also as transmission lines [2]. We consider the case where a decreasing voltage pulse is applied to the gate line and an increasing one is simultaneously applied to the drain line. By properly designing the top and bottom levels of the applied pulses, every FET simulates an electronic switch (the switch is open for voltages greater than some fixed threshold, and closed otherwise). When a pulse crosses the threshold in a transmission line with regularly spaced switches, it is established that a sinusoidal mode supports the pulse at the voltages greater than the threshold as usual, while an exponential mode supports the pulse at the voltages smaller than the threshold. For making the velocities of both the modes coincident, the typical wave number of the exponential mode has to become very large, so that we expect significant shortening of the input pulse.

2 Short pulse generation using TWFETs

Figure 1 (a) shows the equivalent representation of a TWFET. Every source is earthed. The gate and drain lines are represented by red and blue components, respectively. The electrode lines are composed of the series inductor, series resistor, and shunt capacitor. The shunt capacitor includes FET parasitics. The gate and drain lines are coupled via the mutual capacitor, mutual inductor, and the contributions of FET, including the drain-source and drain-gate currents. To operate a TWFET as a generator of short pulses, one end of each line labeled as V_{gin} (V_{din}) is for signal applications. Figure 1 (b) shows the required pulse shapes applied at V_{gin} (V_{din}). The voltages biasing the gate and drain lines are denoted as V_{G1} and V_{D1} , respectively. The drain pulse has the opposite parity to the gate pulse. Moreover, the top and bottom voltage levels of the drain (gate) pulse are set to V_{D2} (V_{G1}) and V_{D1} (V_{G2}), respectively. At this point, V_{G2} is set below the FET threshold voltage V_{TO} , and both of V_{D1} and V_{G1} are set to approximately 0 V. Because of the presence of electromagnetic couplings between the gate and drain lines, two different propagation modes, called the c mode and the π mode [3], are developed on a TWFET. We can design a TWFET to amplify only the pulses carried by one of the two modes and attenuate the pulses carried by the other mode [4]. The red curves in Fig. 1 (c) show the typical drain current–voltage relationships for several different gate bias voltages. The uppermost and lowermost curves correspond to the relationships for V_{G1} and V_{G2} , respectively. The drain voltage and current occupy the positions A and B in Fig. 1 (c) at the pulse bottom and the peak, respectively. Assuming the simultaneous propagation of the leading edges of the gate and drain pulses,

Fig. 1. Fundamental properties of a TWFET. (a) The circuit configuration of a TWFET, (b) the pulses applied to the electrode lines of a TWFET, and (c) the dynamical current-voltage relationship on the drain line.

when the drain voltage starts to increase at the rising edge of the pulse, the drain current first increases and reaches a maximum value at $V_{din} = V_{pk}$. The current then decreases rapidly when the gate voltage reduces below V_{TO} at $V_{din} = V_{btm}$. Therefore, every FET operates as an electronic switch that is open for $V_{din} > V_{btm}$, and closed for $V_{din} < V_{pk}$.

For $V_{pk} \sim V_{btm}$, the drain current–voltage relationship is properly described by a voltage-dependent conductance: $G = G_0\theta(V_{pk} - V_{din})$, where $\theta(V)$ exhibits the Heaviside function. For convenience, we refer to the voltage range less (greater) than V_{pk} as region I (II), as been in Fig. 2 (a). The pulse is influenced by finite shunt conductance in region I and is completely loss-free in region II. Note that the drain line behaves as a linear dispersive line when only regions I and II are considered. 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_{pk} . 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 the characterizations of a test line employing a tunneling diode as a switch, it is established that an exponential mode develops in region I, and a sinusoidal mode develops in region II [5].

Fig. 2. Operating principles of short pulse generation. (a) An idealized model of current-voltage relationship of the drain line, (b) the dispersion relationships of sinusoidal and exponential waves, and (c) the mechanism of short pulse generation.

For quasi-steady pulse propagation, the velocity of the sinusoidal mode in region II must coincide with that of the exponential mode in region I. Figure 2 (b) shows the typical dependence of velocities on the wave number. The velocities in region I and II are represented by the dotted and solid curves. In contrast to sinusoidal modes, the velocity of an exponential mode increases as the wave number increases. Moreover, the two velocities generally coincide at the cross point P in Fig. 2 (b), which occupies the range of large wave numbers. Figure 2 (c) schematically explains the mechanism of short pulse generation. When a pulse of width l_{init} is input to the drain line [(1) of Fig. 2 (c)], a short wavelength sinusoidal wave develops and is supported by an exponential edge as in (2). The wave number of this sinusoidal wave is determined by the position of the cross point P in Fig. 2 (b). Because the drain line attenuates voltage waves only below V_{pk} , the small-amplitude parts of the wave disappear with the shorter propagation than the large-amplitude ones [(3) in Fig. 2 (c)]. Finally, a short pulse is obtained at the output [(4) in Fig. 2 (c)]. Note that the spatial duration of the obtained pulse l_{fin} is determined by the wavelength corresponding to the point P . As a result, the input pulse experiences great shortening when we design the line to make the wave number corresponding to P as large as possible. The temporal duration

of finally obtained short pulse is given by the inverse of cross-point frequency f_c , as far as the electron transit time through the FET channel is smaller than $1/f_c$. Roughly speaking, f_c is on the order of $1/2\pi\sqrt{L_0C_0}$, where C_0 and L_0 are the line capacitance and inductance, respectively.

3 Numerical evaluations

For calculations, we employ a model shown in Fig. 3(a). The per-unit-cell series inductance and shunt capacitance of the gate (drain) line are denoted by L_g (L_d) and C_g (C_d), respectively. The reactive coupling between the gate and drain lines is represented by the gate-drain capacitance, C_m and the mutual inductance, L_m . The contributions of an FET are represented by the gate-source, gate-drain, and drain-source currents, denoted as I_{gs} , I_{gd} , and I_{ds} , respectively. Both $I_{gs}(V)$ and $I_{gd}(V)$ are modeled as an ordinary diode current and are given by $I_0(\exp(qV/k_BT) - 1)$, where q , k_B , and T are the elemental charge, the Boltzmann constant, and the temperature, respectively. On the other hand, I_{ds} is given by the following function of the gate-source voltage, V_{gs} and the drain-source voltage, V_{ds} :

$$I_{ds}(V_{gs}, V_{ds}) = \beta(V_{gs} - V_{TO})^2 \tanh(2V_{ds}), \quad (1)$$

for $V_{gs} > V_{TO}$, and $I_{ds} = 0$ otherwise. The parasitic capacitances of an FET are included in $C_{g,d,m}$ and their dependence on the terminal voltages is neglected. Then, the transmission equations of a TWFET are given by

$$L_g \frac{dI_n}{dt} + L_m \frac{dJ_n}{dt} = V_{n-1} - V_n - R_g I_n, \quad (2)$$

$$L_d \frac{dJ_n}{dt} + L_m \frac{dI_n}{dt} = W_{n-1} - W_n - R_d J_n, \quad (3)$$

$$(C_m + C_g) \frac{dV_n}{dt} - C_m \frac{dW_n}{dt} = I_n - I_{n+1} - I_{gs}(V_n) - I_{gd}(V_n - W_n), \quad (4)$$

$$(C_m + C_d) \frac{dW_n}{dt} - C_m \frac{dV_n}{dt} = J_n - J_{n+1} - I_{ds}(V_n) + I_{gd}(V_n - W_n), \quad (5)$$

where the line voltages of the gate and drain lines at the n th cell are denoted by V_n and W_n , respectively, and the line currents of the gate and drain lines at the n th cell are denoted by I_n and J_n , respectively.

We numerically solve Eqs. (2)–(5) using a standard finite-difference time-domain method. The total number of cells is 500. We set β , V_{TO} , L_g , L_d , L_m , R_g , R_d , C_g , C_d , and C_m to 0.6 mA/V², -1.5 V, 2.0 μ H, 2.0 μ H, 0.0 μ H, 1.0 Ω , 1.0 Ω , 5.0 pF, and 5.0 pF, 5.0 pF, respectively. Here, the parameters of a Toshiba 2SK30A junction FET are used. Moreover, V_{G1} , V_{G2} , V_{D1} , and V_{D2} are set to 0.0, -2.0 , 0.0, and 2.0 V, respectively. On the basis of the design theory developed in [6], the decay rates of the fast and slow mode, which are calculated to be 8.7×10^7 s⁻¹ and -2.7×10^7 s⁻¹, respectively. Note that the negative decay rate means that the corresponding mode is amplified. Thus, only the slow mode is amplified for the present line parameters. As a result, it is guaranteed that the edge of the drain pulse is always co-traveling with the edge of the gate pulse. Figure 3(b) shows the calculated waveforms of the drain pulse monitored at $n = 1, 50, 100, 150, 200, 250, 300$, and 350. The

Fig. 3. Numerical evaluations. (a) The numerical model of a TWFET, and (b) the pulse shortening observed in the drain line.

input waveform has the shape of a squared hyperbolic secant with duration of $0.3 \mu\text{s}$ as shown by the blue waveform in Fig. 3 (b). Until the pulse reaches the 50th cell, its leading edge becomes steep due to the development of the short wavelength exponential mode in region I. Passing the 50th cell, the top of the pulse exhibits oscillation resulting from the development of a short wavelength sinusoidal wave in region II. The second peaks of the oscillatory waveforms are emphasized by arrows. It decays gradually up to the 300th cell and disappears by the subsequent rapid decay. During this, the first pulse still survives. It is established that the smaller pulses decay more quickly than the larger ones. Finally, we obtain a very short pulse at the 350th cell, as shown by the red waveform in Fig. 3 (b). The temporal duration of finally obtained pulse is estimated to be 13.9 ns ; therefore, the cross-point frequency f_c is calculated to be 36 MHz . On the other hand, f_c is analytically calculated to be 40 MHz . The numerical value of f_c is well characterized analytically. Moreover, the pulse becomes shortened, such that the inverse of the pulse width is close to the line's cutoff frequency.