HIGH SPEED PULSE AND DIGITAL TECHNIQUES

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PREFACE

The rapid advances in semiconductor technology have led to an increasing variety, improving performance, decreasing cost, and expanding application of high speed digital integrated circuits.

In addition to conventional circuit design, the efficient utilization of these circuits also requires the use of high speed pulse and digital techniques that up to now could be found only scattered among many books on circuit theory, pulse circuits, and computer-aided circuit design, and in various catalogs and journals. This book presents such techniques in one volume and in a form oriented toward the user of high speed digital circuits. It is based on the author's 25 years of experience in high speed pulse and digital techniques.

A complete treatment of the subject requires the use of calculus and complex variables. Nevertheless, a prior knowledge in these fields is not needed for this book, except for footnotes and some optional problems. However, some elementary features of calculus are introduced and used in the text. The presentation is liberally interspersed with worked examples that support the introduction of new concepts. The problems at the end of the chapters enable the reader to broaden and test his understanding of the material; answers to selected problems are given at the end of the book.

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Palo Alto, California
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†Optional material is denoted by †.

CHAPTER 1

OVERVIEW

This book describes pulse and digital techniques that are applicable to the use of today's high speed digital integrated circuits with operating speeds of 1 to 10 nanoseconds. Perhaps not too surprisingly the use of such circuits presents more problems in interconnections and the associated time constraints than slower circuitry. For this reason a substantial part of the book deals with passive R–C, R–L, R–L–C, and transmission line circuits. However, many of these considerations are strongly related to the internal structure of the integrated circuits, hence a treatment of the high speed properties of diodes and bipolar transistors is also included. Further, properties of the two fastest digital integrated circuit families, the ECL and the Schottky-diode-clamped TTL, are also discussed.

Chapter 2 reviews basic results of linear circuit theory. However, in addition to the traditional treatment emphasizing wideband amplifiers, the chapter also presents material that is oriented toward problems arising from grounding and crosstalk in digital systems.

Chapter 3 provides a treatment of diode circuits. Properties of junction diodes are discussed in detail, as they are basic to the understanding of transistor operation. Computer-aided design methods are introduced and applied to dc and transient analysis in diode circuits—these methods are also applicable to transistor circuits. A brief discussion on tunnel diodes and tunnel-diode circuits is also included.

Chapter 4 treats bipolar (junction) transistors and circuits using them. A complete description of a high speed bipolar transistor would require a model using about 26 parameters. However, the treatment here is restricted to simple models focusing on properties that are of principal importance in high speed pulse and digital circuits. The chapter also includes a discussion on emitter follower stability, a description of Schottky-diode-clamped TTL circuits, and an analysis of propagation delays and transition times in emitter-coupled logic (ECL) circuits.

Chapter 5 provides a description of transmission lines and their use in digital systems. It treats propagation delay, capacitance, and inductance, and describes coaxial, stripline, and various other transmission line configurations that are used in digital systems. Transients in transmission lines are analyzed for linear resistive and capacitive terminations, as well as for nonlinear resistive termination encountered in use with TTL circuits. A brief discussion of losses in transmission lines is also included.

CHAPTER 2

LINEAR CIRCUITS

This chapter describes basic properties of linear components and circuits with emphasis on characteristics that are utilized in high speed digital circuits. Time-domain properties of resistors, capacitors, inductors, and voltage and current sources are described, followed by the introduction of the unit step, the exponential, and the logarithmic functions.

Transient responses of R–C circuits are described for step, pulse, and ramp inputs, and the Elmore delay and the Elmore risetime are introduced as characteristics of the frequency response. Transient responses of R–L–C circuits are presented including applications to crosstalk on ground returns; delay, risetime, overshoot, and frequency response are also discussed, and relationships are established between the transient response and the Elmore delay and the Elmore risetime.

The chapter also includes brief discussions of R–L circuits and pulse transformers and concludes by a treatment of cascaded R–C and R–L–C circuits. Transmission lines are not discussed, since they are the subject of Chapter 5.

2.1 RESISTORS

The simplest linear component is the *resistor*,* shown in Figure 2.1*a*. When the applied *voltage* V_R (measured in volts, V) and the *resistance* R (measured in ohms, Ω) are given, the *current* I_R (measured in amperes, A) can be found from *Ohm's law*:

*Terms are introduced by italics.

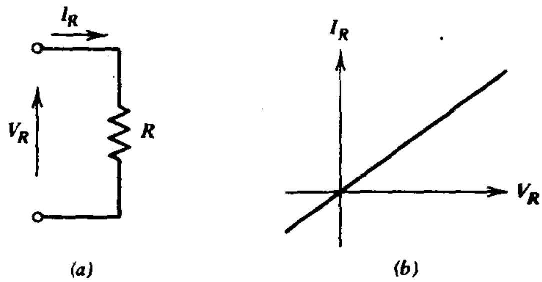

Figure 2.1 The resistor. (*a*) Symbol; (*b*) I_R versus V_R characteristic.

$$I_R = \frac{V_R}{R} \tag{2.1}$$

illustrated in Figure 2.1*b*.

The *power* P_R (measured in watts, W) dissipated in a resistor is

$$P_R = V_R I_R \tag{2.2a}$$

which can be also written as

$$P_R = I_R^2 R, \tag{2.2b}$$

or as

$$P_R = \frac{V_R^2}{R}. \tag{2.2c}$$

The resistance of a bar of material is given by

$$R = \rho \frac{l}{A} \tag{2.3}$$

where ρ is the *resistivity* (for copper $\rho \approx 1.7 \times 10^{-8}$ Ωm), l is the length of the bar in meters, and A is its cross-sectional area in square meters (m^2).

Example 2.1 Calculate the resistance of 100 feet of #20 copper wire. The length is $l = 100$ feet ≈ 30 m. The diameter is given by wire tables as 0.032 in. = 0.81 mm = 0.81×10^{-3} m. Thus the cross-sectional area

$$A = 0.81^2 \times 10^{-6}\,\text{m}^2\,\frac{\pi}{4} = 0.52 \times 10^{-6}\,\text{m}^2.$$

Hence

$$R = \rho\frac{l}{A} = 1.7 \times 10^{-8}\,\Omega\text{m}\,\frac{30\text{ m}}{0.52 \times 10^{-6}\,\text{m}^2} = 1.04\,\Omega.$$

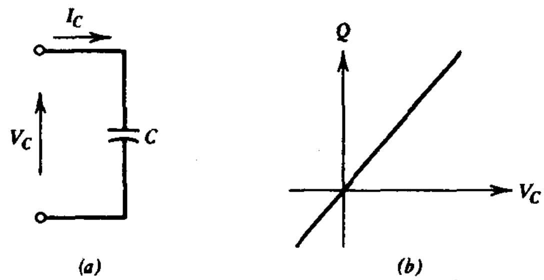

Figure 2.2 The capacitor. (*a*) Symbol; (*b*) Q versus V_C characteristic.

2.2 CAPACITORS

A *capacitor* (Figure 2.2*a*) is capable of storing *charge*. For a given voltage V_C and *capacitance* C (measured in farads, F: 1 farad = 1 second/ohm), the stored charge Q (measured in coulombs: 1 coulomb = 1 ampere X second) is given by

$$Q = CV_C \tag{2.4}$$

as illustrated in Figure 2.2*b*. The stored charge is, however, the accumulation of current. Hence, when the current is I_C, in a time interval with a duration dt the charge changes by an amount dQ given by

$$dQ = I_C\,dt; \tag{2.5a}$$

also, the current I_C equals the *rate of change* of Q, which is dQ/dt:

$$I_C = \frac{dQ}{dt}. \tag{2.5b}$$

For a voltage change of dV, according to eq. (2.4), the charge changes by an amount of

$$dQ = C\,dV_C. \tag{2.6}$$

Combination of eqs. (2.5*b*) and (2.6) leads to

$$I_C = C\frac{dV_C}{dt}. \tag{2.7}$$

Example 2.2 A capacitor that has a capacitance of $C = 0.5$ farad is connected to a current source that delivers the current I_C shown in the upper graph of Figure 2.3. The charge Q of the capacitor and the voltage V_C across it are shown in the lower graph for an arbitrarily chosen initial charge of $Q_{t=0} = 0.25$ coulomb. The quantities I_C, Q, and V_C are related by eqs. (2.4) through (2.7).

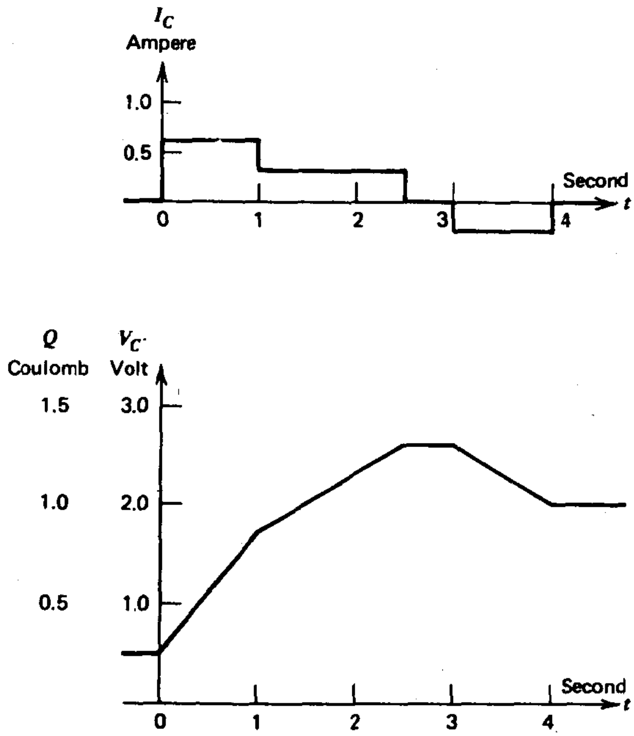

Figure 2.3 Current I_C flowing into a capacitor with a capacitance of 0.5 farad (upper graph), and the voltage V_C and the charge Q of the capacitor with an arbitrary initial charge of 0.25 coulomb (lower graph).

In Figure 2.3 the graph of the current flowing into the capacitor is composed of constant-current segments. As a result, the charge accumulated in a time interval during which the current is constant can be computed as the current multiplied by the duration of the time interval. In general, the change of charge is given by the area under the graph of the current; the area is counted negative when the current is negative.

Example 2.3 A current I_C flowing into a capacitor and the resulting charge are shown in Figure 2.4 where we assumed zero initial charge. The area under the graph of the current during the time interval of $t = 0$ to $t = 2$ seconds is given by the area of the triangle as $I_C t/2$; thus, for example, at $t = 1$ second the area is 0.5 ampere × 1 second/2 = 0.25 ampere × second = 0.25 coulomb, as shown in the graph of Q. The charge can be found in a similar manner at any time between $t = 0$ and $t = 2$ seconds.

Between $t = 2$ seconds and $t = 3$ seconds $I_C = 0$, hence Q remains unchanged. Between times $t = 3$ seconds and $t = 5$ seconds $I_C = -1$ ampere, thus Q changes linearly. The charge accumulated during this interval is $dQ = -1$ ampere × (5 seconds - 3 seconds) = -2 coulombs resulting in a change from the $Q = 1$ coulomb at $t = 3$ seconds to $Q = -1$ coulomb *at* $t = 5$ seconds.

Between $t = 5$ seconds and $t = 6$ seconds $I_C = 0$, thus Q remains -1 coulomb. Between $t = 6$ seconds and, for example, $t = 7$ seconds the change of charge is given by the area of the trapezoid: (7 seconds - 6 seconds) × (1 ampere + 0.5 ampere)/2 = 0.75 coulomb. By adding this to the -1 coulomb charge that is present at $t = 6$ seconds, we get a $Q = -0.25$ coulomb at $t = 7$ seconds. The charge can be similarly found at any time between $t = 6$ seconds and $t = 8$ seconds.

Note that Figure 2.4 does not assume any specific value of capacitance C, and the voltage V_C across the capacitor is not given. However, once the charge Q as function of time is determined, the voltage as function of time can be found by use of eq. (2.4) as $V_C = Q/C$.

The charge Q in Figure 2.4 is computed as the area under the graph of I_C by use of formulae for the areas of the triangle and the trapezoid. This procedure is applicable whenever such a formula is available for the given current

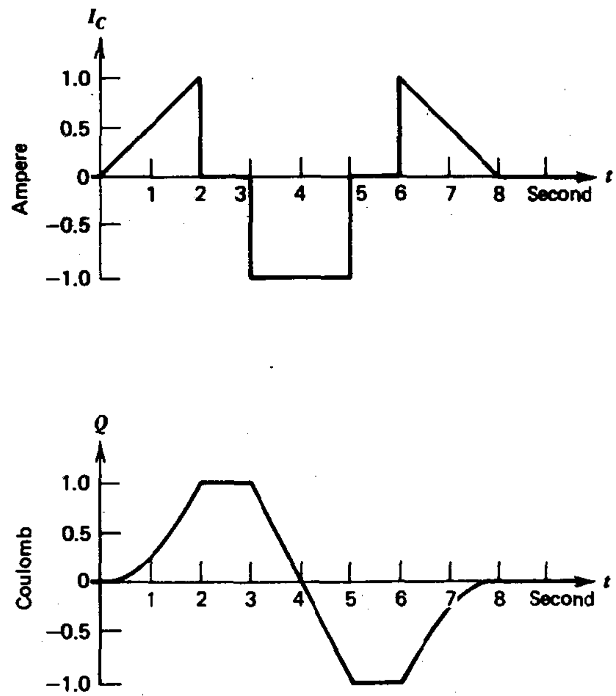

Figure 2.4 Current I_C flowing into a capacitor (upper graph) and the charge Q of the capacitor with zero initial charge (lower graph).

shape. When this is not the case the area can still be found by counting the number of squares under the graph of I_C plotted on a graph paper with a square grid.†

Thus far we assumed that the current I_C as function of time was given, and we sought charge Q and voltage V_C as functions of time. When the opposite holds, current I_C can be found as the rate of change of charge Q.

Example 2.4 In the lower graph of Figure 2.3, between $t = 1$ second and $t = 2.5$ seconds the charge changes by $dQ = 1.3$ coulomb − 0.85 coulomb = 0.45 coulomb. According to eq. (2.5*b*), the current is given as the change in charge, dQ, divided by the duration of the time interval which is dt = 2.5 seconds − 1 second = 1.5 second. Thus, $I_C = dQ/dt = 0.45$ coulomb/1.5 second = 0.3 ampere, in agreement with the upper graph of Figure 2.3.

In general, the rate of change *at* any time t can be found as the slope of the tangent drawn to the graph of Q at time t—in agreement with Figure 2.4.‡

A capacitor can not dissipate power, however, it can store energy. The energy E (measured in joules, J : 1 joule = 1 watt × second) stored in a capacitor with a capacitance of C is given as

$$E = \tfrac{1}{2} C V_C^2 \tag{2.8a}$$

or as

$$E = \tfrac{1}{2} Q V_C. \tag{2.8b}$$

The capacitance of two parallel plates that have opposing areas of A each and that are separated by a distance d can be approximated as

$$C = \epsilon_0 \epsilon_r \frac{A}{d}. \tag{2.9}$$

In eq. (2.9), $\epsilon_0 = 8.85 \times 10^{-12}$ farad/m, ϵ_r is the relative *dielectric constant* ($\epsilon_r \approx 1$ in vacuum or in air); it is also assumed that each dimension of A is much larger than d.

Example 2.5 Calculate the capacitance between two opposing dimes spaced $d = 0.1$ in. = 2.54 mm apart in air. The diameter of a dime is 0.7 in. = 17.5 mm = 1.75×10^{-2} m. The area is thus $(1.75 \times 10^{-2}\ \text{m})^2 \times \pi/4 = 2.4 \times 10^{-4}\ \text{m}^2$. The capacitance

†This is, in fact, a graphical integration. In general, the charge $Q = CV_C$ is given by the integral $\int I_C\, dt$ and graphical (or numerical) integration can be avoided whenever $\int I_C\, dt$ is available from a table of integrals.

‡Analytically, the current is given by the derivatives $I_C = dQ/dt = C\, dV_C/dt$.

$$C = \epsilon_0 \epsilon_r \frac{A}{d} = 8.85 \times 10^{-12} \frac{\text{F}}{\text{m}} \frac{2.4 \times 10^{-4}\,\text{m}^2}{2.54 \times 10^{-3}\,\text{m}}$$

$$= 0.84 \times 10^{-12}\ \text{F} = 0.84\ \text{pF (picofarad)}.$$

2.3 INDUCTORS

An *inductor* (Figure 2.5*a*) is capable of storing magnetic *flux*. For a given current I_L and *inductance* L (measured in henrys, H: 1 henry = 1 ohm × second), the stored *flux*, Φ (measured in webers: 1 weber = 1 volt × second) is given by

$$\Phi = LI_L \tag{2.10}$$

as illustrated in Figure 2.5*b*. When the voltage across the inductor is V_L, in a time interval with a duration of dt its flux changes by an amount $d\Phi$ given as

$$d\Phi = V_L\, dt; \tag{2.11a}$$

also, the voltage V_L equals the rate of change of the flux, which is $d\Phi/dt$:

$$V_L = \frac{d\Phi}{dt}. \tag{2.11b}$$

For a current change of dI_L, according to eq. (2.10), the flux changes by an amount of

$$d\Phi = L\, dI_L. \tag{2.12}$$

Combination of eqs. (2.11*b*) and (2.12) leads to

$$V_L = L\frac{dI_L}{dt}. \tag{2.13}$$

An inductor can not dissipate power, but it can store energy. The energy E stored in an inductor with an inductance of L is given as

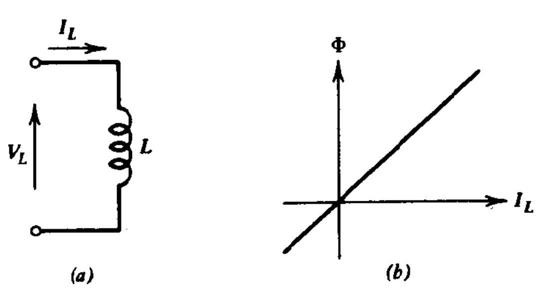

Figure 2.5 The inductor. (*a*) Symbol; (*b*) Φ versus I_L characteristic.