New Research on High-Frequency Circuits and Electromagnetic Radiation

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[Abstract] In this paper, capacitors are divided into radiant capacitors and energy storage capacitors, and inductors are divided into radiation inductors and energy storage inductors. The distributed capacitance and distributed inductance that exist in high-frequency circuits are mainly distributed radiant capacitance and distributed radiated inductance. Furthermore, it is pointed out that the capacitors and inductors in LC resonance must be energy storage capacitors and energy storage inductors. Based on these new concepts, it is revealed that the existing Transmission line equations are not valid, and the new Transmission line equations are proposed. This paper provides a new theoretical basis for electromagnetic compatibility, transmission line theory and antenna design.

[Keywords] High-frequency circuits; Distributed parameters; Distributed radiation capacitor; Distributed radiation inductor; Energy storage capacitor; Energy storage inductor; LC resonance; Transmission line equations; Electromagnetic radiation; Kirchhoff's Law.

1. Introduction

The passive elements in high-frequency circuits can be categorized into two types: lumped elements and distributed elements. Lumped passive elements are mainly resistors, capacitors (plate capacitors), inductors (inductance coils) and connecting wires. An actual resistor, capacitor, or inductor is characterized by resistance, capacitance, or inductance at low-frequency. For example, the electrical property of a resistor is its resistance value R, the electrical property of a capacitor is its capacitance value C, and the electrical property of a capacitor is its inductance value L. At low-frequency, the resistance, capacitance, and inductance of a connecting wire are zero. However, at high-frequency, electrical properties of lumped elements change. These characteristics, which are reflected by the distribution parameters, These distributed parameters that affect the electrical characteristics of passive elements are mainly loss resistance, distributed capacitance and distributed inductance.

Over the past half-century, high-frequency circuits have evolved from radio frequency (RF) and microwave technologies to the terahertz range, with signal wavelengths reducing from meters and centimeters to millimeters. However, in the application of high-frequency technology, existing theories often fall short in adequately explaining specific engineering challenges. In many areas involving high-frequency circuits and electromagnetic radiation, such as electromagnetic compatibility, transmission line theory, and antenna design [5] [6] [7] [8] [9], classical electromagnetic theory no longer fully meets the demands of modern technical applications.

2. High frequency circuits

2.1 Capacitance

Capacitance is the ability of a conductor to store charge. The capacitance of a conductor is defined as the ratio of the charge to the potential.

$$C = q / u$$

The unit of capacitance is F, which is a very large unit, and the Earth's capacitance is about 710 μF.

A conductor with an electric charge that generates an electric field and electric flux around it.

2.1.1 Isolated capacitance/radiation capacitance

When a single conductor is surrounded by free space and is far from other objects, such a conductor is an isolated conductor. The capacitance of an isolated conductor is related only to its shape and size, and is an intrinsic property of the isolated conductor, independent of charge and potential.

The capacitance of an isolated conducting sphere of radius R:

$$C = 4\pi \varepsilon_0 R$$

Shown in Fig. 1, is a sphere of insulated conductors, and let its radius R = 0.1 m. The capacitance C = 10 pF of the isolated conductor sphere.

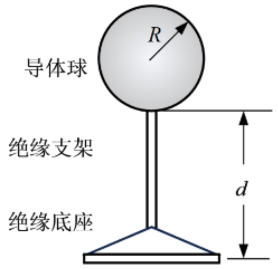


Fig. 1 Insulated conductor sphere

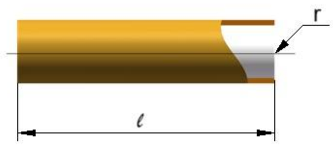


Fig. 2 Isolated conducting cylinder

As shown in Fig. 2, an isolated conducting cylinder of radius r and length l. Let the charge be distributed only on the surface of the cylinder, the capacitance of the isolated conducting cylinder:

$$C = 2\pi \varepsilon_0 (2 r \ell)^{1/2} \qquad (2\text{-}1)$$

The electric field generated by an isolated conductor is distributed in the open free space around it, and when the charge q(t) on the isolated conductor is time-varying, the isolated conductor will radiate electric field waves to the free space around it, so the isolated capacitance is also known as open-radiation capacitance, or radiation capacitance.

2.1.2 Capacitors/storage capacitors

Two conductors that are close to each other with a layer of non-conductive insulating medium sandwiched between, form a capacitor. Capacitors are components that store electricity and energy, playing an important role in circuits such as tuning, bypassing, coupling, and filtering.

$$C = \frac{Q}{U_A - U_B} = \frac{\varepsilon_r S}{4\pi k d}$$

The most common type of capacitor is the parallel plate capacitor, which consists of two metal conductor pole plates parallel to each other, separated by a dielectric material. Formula for calculating the capacitance of a parallel plate capacitor:

Where U_A - U_B is voltage between the two parallel plates, ε_r is relative dielectric constant, k is electrostatic force constant, S is the area directly opposite the two plates, and d is the distance between the two plates. The electric field between two parallel plates of a parallel plate capacitor is a uniform electric field with electric field strength E = U / d.

Parallel plate capacitor is a storage of power and electrical energy components, generally considered to have its electric field energy closed, concentrated between the two metal parallel plates, do not radiate electric field energy to free space. Capacitors are also known as enclosed energy storage capacitors, energy storage capacitors or capacitors.

In summary, capacitors are categorized into radiation capacitors and energy storage capacitors. In LC resonant circuits, capacitor C is also an energy storage capacitor, and the electric field energy stored in capacitor C and the magnetic field energy stored in inductor L are converted to each other. In high-frequency circuits, there is a non-negligible radiation capacitance in the lines of the PCB board, and even for capacitors, there is also a non-negligible radiation capacitance in their pins. In high-frequency circuits, EMC electromagnetic compatibility, transmission line and antenna design and application, lead distribution capacitance, in consideration of the energy storage distribution capacitance at the same time, must consider the impact of radiation distribution capacitance; especially for antennas, distribution capacitance is mainly manifested as radiation distribution capacitance.

Figure 2A shows the identification of the storage capacitor in the circuit and Figure 2B shows the identification of the radiation capacitor.

Fig. 2A Energy storage capacitance

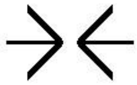


Fig. 2B Radiation capacitance

2.2 Inductance

When a metal wire is passed through an electric current, a magnetic field and magnetic flux are created around it. The inductance of a wire is defined as the ratio of magnetic flux to current.

$$L = \Phi / I$$

The unit of inductance is H (Henry).

2.2.1 Isolated inductance/radiation inductance

When a long metallic straight wire is surrounded by free space and is located away from other objects, such a wire is an isolated wire. This is shown in Figure 3.

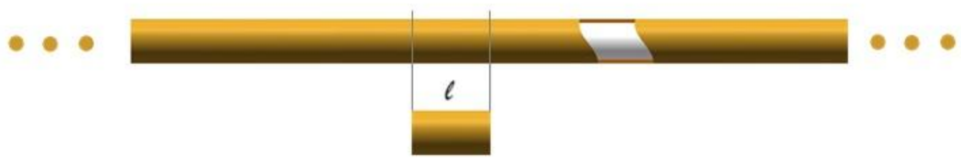


Fig. 3 Inductance of an isolated wire

In the metal long straight wire to take the length of l a section of the wire, then the section of the isolated wire, the isolated inductance of the approximate formula:

$$L = \mu_0 l /2 \qquad (2\text{-}2)$$

An isolated inductor produces a magnetic field that is distributed in the open free space around it. When the current in the isolated inductor is time-varying, the isolated inductor will generate an alternating magnetic field and radiate magnetic field waves into free space, so the isolated inductor is also called an open radiation inductor, or radiation inductor.

2.2.2 Inductors/Storage Inductors

An inductor is a component that converts electrical energy into magnetic energy and stores it. The most common type of inductor is a metal wire coil, which is generally made of enameled wire, and the inductance of the coil is proportional to its number of turns. The inductance of a coil is simply a parameter related to the number of turns, size and shape of the coil and the dielectric; it is an intrinsic characteristic of the coil independent of the applied current.

Inductors are capable of converting electrical energy into magnetic energy and storing it as a component, and are generally considered to have their magnetic energy enclosed and concentrated inside the center of the coil, without radiating magnetic energy to the outside free space. Inductors are also known as closed energy storage inductors, energy storage inductors or inductors.

In summary, inductors are categorized into radiation inductors and energy storage inductors. In LC resonant circuits, inductor L is an energy storage inductor, and the magnetic field energy stored in inductor L and the electric field energy stored in capacitor C are converted to each other. In high-frequency circuits, there is a non-negligible radiation inductance in the lines of the PCB board. In high-frequency circuits, EMC electromagnetic compatibility, transmission line and antenna design and application, the introduction of the aggregate parameter and the distribution parameter inductance, in the consideration of the energy storage inductance at the same time, it is necessary to consider the impact of radiation inductance; especially for antennas, the radiation inductance is the main conversion of energy of its magnetic field energy.

FIG. 4A shows the identification of the storage inductor in the circuit and FIG. 4B shows the identification of the radiation inductor in the circuit.

Fig. 4A Energy storage inductor

Fig. 4B Radiation inductor

2.3 Connecting Wires

Connection wires are often referred to as transmission lines in RF circuits and are used to transmit electrical energy and electrical signals. At low frequencies, the resistance, capacitance and inductance of a connecting line are zero. However, at high frequencies, the connection line must be considered for its distributed resistance, distributed capacitance and distributed inductance. Distributed resistance of the connecting line produces heat loss, distributed capacitance and distributed inductance of the connecting line is mainly manifested in the distribution of radiation capacitance and distribution of radiation inductance, which produces radiated electric field and radiated magnetic field, i.e., radiation loss. For a single conductor connection line, its distributed radiation capacitance is approximated by the formula (2-1), and the distributed radiation inductance is approximated by the formula (2-2).

In order to reduce the loss of the connecting line radiated electric field and radiated magnetic field, RF circuits are often used in parallel dual conductor, parallel multi-conductor, coaxial, strip line, etc., so that the distribution capacitance of the transmission line and the distribution of inductance is more often manifested as a distribution of energy storage capacitance and distribution of energy storage inductance.

2.4 Resonant Circuits

A passive one-port network containing capacitive, inductive, and resistive elements, the circuit is in resonance when the port equivalent impedance is resistive. Common resonant circuits are RLC series resonant circuits and parallel resonant circuits. Figure 5 shows an RLC series resonant circuit.

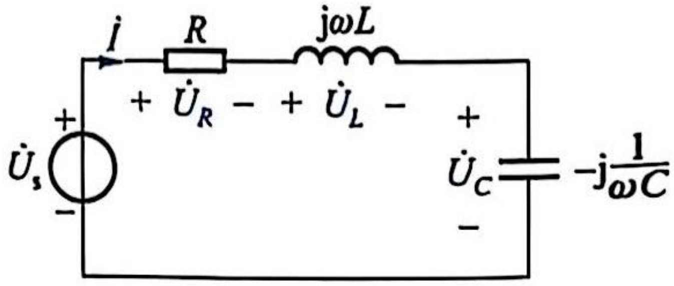


Fig. 5 RLC series resonant circuit

Its equivalent impedance at the power supply side:

$$Z(\omega) = R + j\,(\omega L - 1/\omega C)$$

When $(\omega L - 1/\omega C) = 0$, the circuit is in resonance. The angular frequency at this point is called the resonant angular frequency:

$$\omega_0 = (LC)^{1/2}$$

When the circuit is in resonance, it has the following characteristics:

(1) At resonance the port impedance is resistive and the amplitude of the port current is maximized. The electric field energy of the capacitor forms a periodic oscillation with the magnetic field energy of the inductor.

$$\dot{U}_L(\omega_0) + \dot{U}_C(\omega_0) = 0$$

(2) The total series voltage of the inductor and capacitor at resonance is equal to zero, which is equivalent to a short circuit.

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

(3) Overvoltage may occur on the inductor and capacitor at resonance, such that

Q is the quality factor of the circuit. When $Q \gg 1$, then $U_L(\omega_0) = U_C(\omega_0) \gg U_S$, the voltage of the inductor and capacitor is much higher than the supply voltage, which is known as an overvoltage phenomenon in power systems, and poses an overvoltage hazard to power system equipment. However, in communication systems, series resonance amplifies weak signals.

In summary, the essence of LCR circuit resonance is that the electric field energy in the capacitor and the magnetic field energy in the inductor is converted to each other, increasing and decreasing, and fully compensated. The sum of the electric field energy and magnetic field energy remains constant at any moment. Therefore, the capacitance and inductance in the above resonant circuit must be energy storage capacitance and energy storage inductance, and the radiation capacitance and radiation inductance are not applicable to the above resonant circuit analysis.

3. A New Perspective on Transmission Line Equations

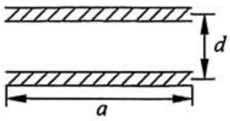
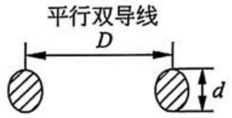
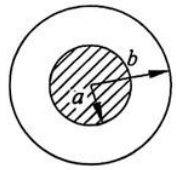
3.1 Transmission Line Equations

Transmission line means a connector capable of transmitting electrical energy and electrical signals. In low-frequency circuits, the transmission line serves only to connect the electrical components. The distribution parameters of the transmission line itself are negligible. For example, a table lamp power line is 2 meters long, the operating frequency of its power supply is 50Hz, and the wavelength is 6000 kilometers. This power line is very short in relation to the wavelength and the effect of the wavelength does not need to be considered.

In the case of high-frequency circuits, where the signal wavelength and the dimensions of the connecting line can be compared with each other, there is already a significant fluctuation effect on the connecting line. The current and voltage on the transmission line are not only a function of time, but also of spatial position. At this point the distributed parameter effects of the parameter lines themselves must be considered.

According to the existing transmission line theory: the wire flows through the current, around the high frequency magnetic field will be generated, and thus the points along the wire will exist in series distribution inductance L; between the two wires plus the voltage, there is a high-frequency electric field between the wires, so the line between the distribution of capacitance will be generated in parallel C; conductor through the current will be heated, and the high frequency due to the skin effect of the resistance will be increased, this is the distribution of resistance R; conductor current leakage, this These distribution parameters can be ignored at low frequencies, but the high frequency caused by the voltage along the line, the current amplitude changes, as well as phase lag, which is known as the distribution parameter effect. Table 3-1 shows the distribution parameters of parallel plates, parallel twin conductors and coaxial lines.

Table 3-1 Distribution parameters of common transmission lines

传输线的横截面 单位长度的分布参数	平行板 	平行双导线 	同轴线 
$R/(\Omega\cdot m^{-1})$	$\frac{2}{a}\sqrt{\frac{\pi f\mu_0}{\sigma_0}}$	$\frac{2}{\pi d}\sqrt{\frac{\omega\mu_0}{\sigma_0}}$	$\sqrt{\frac{f\mu_0}{4\pi\sigma_1}}\left(\frac{1}{a}+\frac{1}{b}\right)$
$G/(S\cdot m^{-1})$	$\frac{\sigma a}{d}$	$\frac{\pi\sigma}{\ln\frac{D+\sqrt{D^2-d^2}}{d}}$	$\frac{2\pi\sigma}{\ln\frac{b}{a}}$
$L/(H\cdot m^{-1})$	$\frac{\mu_0 d}{a}$	$\frac{\mu_0}{\pi}\ln\frac{D+\sqrt{D^2-d^2}}{d}$	$\frac{\mu_0}{2\pi}\ln\frac{b}{a}$
$C/(F\cdot m^{-1})$	$\frac{\varepsilon d}{a}$	$\frac{\pi\varepsilon}{\ln\frac{D+\sqrt{D^2-d^2}}{d}}$	$\frac{2\pi\varepsilon}{\ln\frac{b}{a}}$

In the table, ε and σ are the dielectric constant and conductivity of the medium between the conductors, respectively; σ_1 is the conductivity of the conductor, and μ_0 is the magnetic permeability of the conductor and the medium.

The following transmission line equations are derived from the parallel twin conductor. A microelement of length Δz is intercepted on the parallel twin conductor, and the equivalent circuit of the distributed parameters of this microelement segment is shown in Fig. 6. Where the voltages and currents at the two ends of the equivalent circuit are u(z, t), i(z, t), u(z+Δz, t), i(z+Δz, t), respectively. It has a resistance RΔz (in c/m), a distributed inductance LΔz (in H/m), a distributed capacitance CΔz (in F/m) and a leakage conductance GΔz (in S/m).

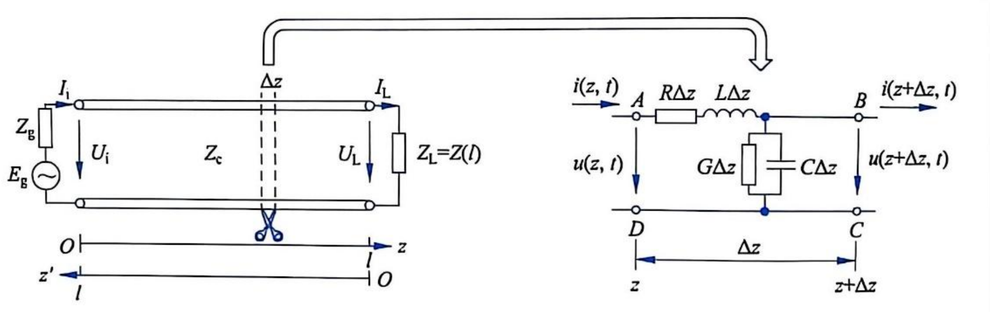


Fig. 6 Equivalent circuit for length Δz parallel twin conductors with distributed parameters

From Fig. 6, the equations below can be obtained from Kirchhoff's voltage and current laws:

$$
\begin{aligned}
&u(z,t) - R\Delta z i(z,t) - L\Delta z \frac{\partial i(z,t)}{\partial t} - u(z+\Delta z,t) = 0 \\
&i(z,t) - G\Delta z u(z+\Delta z,t) - C\Delta z \frac{\partial u(z+\Delta z,t)}{\partial t} - i(z+\Delta z,t) = 0
\end{aligned}
\quad (3\text{-}1)
$$

From Eq. (3-1), let Δz trends to 0 and further partial derivation of z, the equations below can be obtained:

$$
\begin{aligned}
&\frac{\partial u(z,t)}{\partial z} = -Ri(z,t) - L\frac{\partial i(z,t)}{\partial t} \quad (a) \\
&\frac{\partial i(z,t)}{\partial z} = -Gu(z,t) - C\frac{\partial u(z,t)}{\partial t} \quad (b)
\end{aligned}
\quad (3\text{-}2)
$$

From Eq. (3-2), let the voltage and current at point z are U(z), I(z), and Z = R + jωL, Y = G + jωC, the equations below can be obtained:

$$
\begin{aligned}
&\frac{d^2U(z)}{dz^2} - ZYU(z) = 0 \quad (a) \\
&\frac{d^2I(z)}{dz^2} - ZYI(z) = 0 \quad (b)
\end{aligned}
\quad (3\text{-}3)
$$

Eq. (3-3) are the well-known Transmission line equations, which are "second-order chi-squared ordinary differential equations".

3.2 A New Perspective on Transmission Line Equations

In the derivation of equation (3-3) transmission line equation, the distributed capacitance and distributed inductance are energy storage capacitor and energy storage inductor. In fact, parallel twin conductors flow through the current, the resulting high-frequency magnetic field, almost all radiated to the space around it, stored in the parallel twin conductors between the magnetic energy is approximated to be 0, that is, the parallel twin conductors of the distribution of inductance for the distribution of radiation inductance. Similarly, the distributed capacitance of the parallel twin conductor is mainly manifested as the distributed radiation capacitance.

In addition, Kirchhoff's laws apply to linear DC circuits. In low and medium frequency AC circuits, Kirchhoff's law can be used as an engineering approximation; in high frequency circuits, especially when the transmission line distribution parameters cannot be neglected, Kirchhoff's law no longer holds (see Appendix A). Therefore, the transmission line equation of Eq. (3-3) is not valid.

In parallel twin conductors, the transmission line distribution parameters are almost entirely distributed radiation capacitance and distributed radiation inductance, and the distributed energy storage capacitance and distributed energy storage inductance can be ignored. High-frequency signals in the parallel twin conductor transmission process, radiation loss is larger. Coaxial line there is a large distributed energy storage capacitance, high-frequency signal in the coaxial line transmission process, the radiation loss is relatively small. The transmission line equation of coaxial line must consider the distributed radiation capacitance, distributed radiation inductance and distributed energy storage capacitance.

The transmission characteristics of a high-frequency signal in an independent single conductor are analyzed below. A microelement of length Δz is intercepted in the independent conductor, and the equivalent circuit of the distribution parameters of this microelement segment is shown in Fig. 7. Where the instantaneous voltages and currents at both ends of the equivalent circuit are u(z, t), i(z, t), u(z+Δz, t), i(z+Δz, t), respectively. It has a resistance RΔz (in c/m), a distributed radiation inductance LΔz (in H/m), and a distributed radiation capacitance CΔz (in F/m).

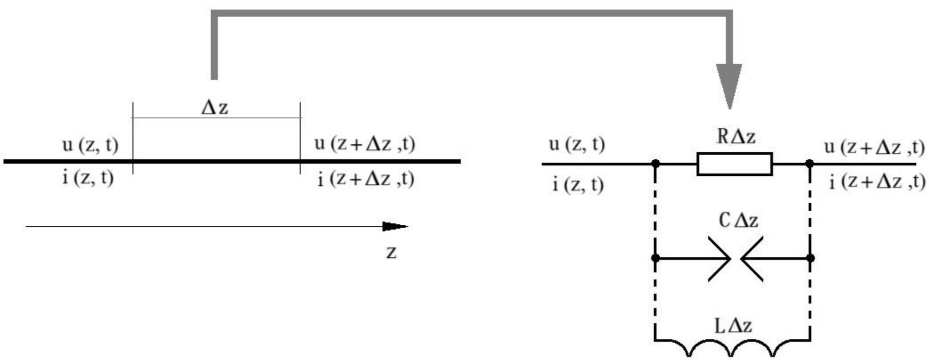


Fig. 7 Equivalent circuit of the wire Δz with distributed parameters

Let the effective values of u(z, t), i(z, t), u(z+Δz, t), i(z+Δz, t) be U(z), I(z), U(z+Δz), I(z+Δz), respectively; The phase difference between U(z) and I(z) is φ, while the phase difference between U(z+ Δz) and I(z+ Δz) is φ+Δφ. The thermal loss power in the resistor RΔz is denoted by P_R; the electric field radiation loss power in the distributed capacitance CΔz is P_C; and the magnetic field radiation loss power in the distributed inductance LΔz is P_L. According to the principle of energy conservation, the following equation holds:

$$U(z)\, I(z) \cos\varphi - U(z+\Delta z)\, I(z+\Delta z) \cos(\varphi+\Delta\varphi) = P_R + P_C + P_L. \qquad (3\text{-}4)$$

In Eq. (3-4), the loss components, P_R, P_C, and P_L, are distinct and cannot be transformed into one another. Δφ is determined by RΔz, LΔz and CΔz, but it should be pointed out that LΔz and CΔz are radiation inductance and radiation capacitance, not energy storage inductance and energy storage capacitance, and the calculation of Δφ cannot be calculated using the existing formula. Let the load impedance of the line at z be Z(z), then the relationship between voltage U(z) and current I(z):

$$U(z) = I(z)\, Z(z) \qquad (3\text{-}5)$$

Eq. (3-4) and (3-5) form the new Transmission line equations for independent lines. Eq. (3-4) shows that due to the loss components of P_R, P_C, and P_L, the RMS (or peak) values of current and potential decrease with the lengthening of the transmission line. Fig. 8 shows the loss attenuation line of the high-frequency signals on a transmission line, which is typically an exponential curve.

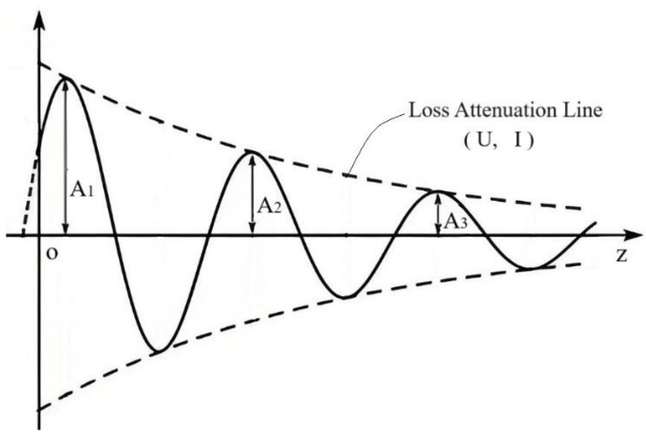


Fig. 8 Loss attenuation line on a transmission line

The purpose of the antenna is to radiate electric and magnetic field waves into free space, and the distributed parameters on the antenna are mainly the distributed radiation inductance and distributed radiation capacitance, which can be completely ignored for the distributed energy storage capacitance and distributed energy storage inductance.

Eq. (3-4) considers only the incident wave on the transmission line, not the reflected wave.