Signal integrity analysis on discontinuous microstrip line

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Abstract. In high speed PCB design, microstrip lines were used to control the impedance, however, the discontinuous microstrip line can cause signal integrity problems. In this paper, we use the transmission line theory to study the characteristics of microstrip lines. Research results indicate that the discontinuity such as truncation, gap and size change result in the problems such as radiation, reflection, delay and ground bounce. We change the discontinuities to distributed parameter circuits, analysed the steady-state response and transient response and the phase delay. The transient response cause radiation and voltage jump.

1. Introduction

In PCB design, transmission lines are used to transmit the signal from one side to the other side. But it has become more difficult to keep the signal integrity (SI) during transmission as the clock frequency get faster and signal rising time became shorter. The good SI requires the signal to reach the correct voltage within required time. When the signal in transmission line encounter a change of transient impedance, part of the signal will be reflected and distorted. This is the common reason of bad signal integrity.

The transient impedance of the signal propagated along the transmission line is named as characteristic impedance. The characteristic impedance is the inherent properties of transmission line which is only related to the material properties, dielectric constant, the unit length capacitance, and the length of the transmission line, and it is a key factor for SI in transmission line circuit. Therefore, it is very important to study the relationship between the characteristic impedance and the SI.

Microstrip line is consisted of the dielectric substrate, the conductor and the return path. The two most important parameters of microstrip lines are characteristic impedance and phase velocity. The former one related to the impedance matching, while the latter determines its electrical length and geometric length. Characteristic impedance means the ratio of the voltage travelling wave to the current travelling wave transmitted on the transmission line, or the ratio of the incident voltage wave to the current [1]. And the phase velocity represents the moving speed of electromagnetic waves in transmission lines. The characteristic impedance and phase velocity are just effective for a specific wave. The microstrip lines are developed from the parallel two-lane with the dielectric substrate was added between the conductors, which make the analysis more complex. In the dielectric region, the phase velocity of the TEM is \( C/\varepsilon_r^{0.5} \) and \( \varepsilon_r \) is the relative permittivity. While in the air, the phase velocity of the TEM is \( c \). Thus, between the interface of the air and the dielectric, the TEM wave can not reach a phase matching [2]. In most practical applications, dielectric substrate is so thin that the

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field can be regarded as quasi TEM field. The equation of the characteristic impedance and the phase velocity are as follows:

\[
Z_0 = \begin{cases} 
60 \ln \left( \frac{8H}{W} + \frac{W}{H} \right) \Omega & \text{if } W/H \leq 1 \\
\frac{120\pi}{W/H + 2.42 - 0.44H/W + (1 - H/W)\Omega} & \text{if } W/H \geq 1
\end{cases}
\]

(1)

When W/H is really large, all power lines can be considered as within the media region.

The current of the return path concentrated below the signal path. The current becomes more centralized with the frequency become higher [3]. The current distribution always tends to reduce the circuit impedance. The return current must flow through this impedance. A voltage drop on the return path has been generated [4].

When there is a continuous microstrip line, a large plane capacitance was generated between the signal path and return path. So the return path is a low inductor signal path. It is known that the signal is propagated along the lowest inductor path, and a complete return path can effectively reduce the signal propagation delay.

![Image](image.png)

**Figure 1.** The model of a microstrip line.

2. The influence of discontinuity

In the process of signal transmission, when the signal has an electric transition, will cause a path discontinuity inevitably. The discontinuity can be equalled to a circuit in some way.

Micorstrip circuits invariably incorporate transmission line discontinuities of one type or another. Some of the most common forms of microstrip discontinuities are open ends, gaps, steps in width, right-angled bends, T junctions, and cross junctions. Since discontinuity dimensions are usually much smaller than the wavelength in microstrip, they may be modeled by lumped element equivalent circuits.

Signal distortion caused by discontinuities was affect by two parameters: the rise time and the impedance mutation. The transient impedance on capacitor and inductor is determined by the change rate of voltage and current.

A discontinuity in a microstrip is caused by an abrupt change in the geometry of the strip conductor. Therefore, electric and magnetic field distributions are modified near the discontinuity. The altered electric field distribution gives rise to a change in a capacitance, and the changed magnetic field distribution can be expressed in terms of an equivalent inductance. The analysis of a microstrip discontinuity involves the evaluation of these capacitances and inductances and can either be based on quasi-static considerations or carried out more rigorously by full wave analysis [5].

2.1. Open end

Near the open end, the distribution of the electric field changed, the power line extended out of the open end. So the energy is deposited in this region. In figure 2, microstrip open end is not just an open
end, so we can assume that there is a capacitor. For a very short ideal open line is equivalent to a capacitor. As the result of the spread of the electric field to the free space outside the microstrip open end, a surface wave was generated on the surface of the dielectric plane, and a wave radiated to the free space. If the dielectric thickness of the plate reaches a certain level, a high mode wave has been generated in the microstrip line transmitted on the reverse direction. Consider the characteristic impedance, couple with the \( c_{oc} \), they form an RC circuit. In the rising, there is a damped oscillation to form the signal ringing [4, 6].

\[
u(t) = \frac{1}{C} \int_0^t i(x)dx + u_{0-}
\]

\[
Z_{oc} = \int_0^t u(t)^2 dt / c_{oc}
\]

In equation 2, we know that \( u(t) \) is relation to the previous state, and it have an integration time \( t \). For the voltage between capacitance can’t jump, the transient response was disturbed. For example, if there is no capacitance, \( u(0) = 1 \) v, at \( u(0+) \), the voltage should be 0 v, if we have a excitation \( \delta \), at \( 0+ \), the voltage \( u(\delta) = 0 \) v. While if there this a \( c_{oc} \), \( u(0+) = 1 \) v, we make a integration with \( \delta \), \( u(\delta) = 1 \) v, so at \( 0+ \), \( u(t) = 1+1 = 2 \) v, the response has been seriously damaged. In a 2.5 v LVTTL circuit, \( V_{OH} \geq 2.0 \) v, \( V_{HI} \geq 1.7 \) v. In the circuit, thus a logic error was generated. The circuit also has a buildup time, during this time, the circuit has an oscillation state, sometimes it can cause a logic error either, thus in the building time, a phase delay was generated. So, signal integrity problems were generated.

\[\text{Figure 2. Open end and equivalent circuit.}\]

2.2. Gaps in a microstrip line

When there is a gap in a microstrip line, we can get the equivalent circuit as figure 3, in the circuit, two lines were linked by a series capacitor. At the open end of the two lines, two capacitors in a parallel connection [6]. So, the gap can equivalent to a \( \| \) Capacitor network. The equation circuit consists of parallel capacitor \( C_{p1}, C_{p2} \), and a series capacitor \( C_g \).

\[\text{Figure 3. Gap and equivalent circuit.}\]

We can’t calculate the circuit with Kirchhoff theorem because this circuit is consists of capacitors without other elements. If this circuit works at a high frequency, we assume all the capacitors were short-circuit with a building time. During this time, the capacitors involve in a charging and discharging process, and the circuit works in an unknown state. In some cases, the circuit would works
in a self-excited oscillation state. When \( C_g \) is so tiny that we can ignore it, the electric field \( E_{p1} \) energy storage in \( C_{p1} \), on \( C_{p2} \), an induced electric field \( E_{p2} \) was formed. For \( E_{p1} \neq E_{p2} \), between \( E_{p1} \) and \( E_{p2} \), there is a voltage jump. So, near the gap, there is radiation, voltage jump and unknown states.

2.3. Step in width
Steps in width exist a junction of two microstrip lines that have different impedances. In the cut off area, the electric charge is decreased. The configurations of a step discontinuity and its equivalent circuit are shown in figure 4. In terms of distributed elements, the discontinuity capacitance \( C_s \) has the effect of an increase in the wide line’s length and an equal decrease in the narrow line’s length. The series inductor shows that the magnetic energy increase considerable while the electricity decreased [4, 6]. With the energy exchange from the inductor to the capacitor, the energy is exchanged between the electric field and the magnetic field, electromagnetic waves were generated and radiate to the open area, the EMI emerged.

When the bend has a load \( Z \), the

\[
VSWR = C + \left(C^2 - 1\right)^{1/2}
\]

(4)

The reflection coefficient

\[
\Gamma = \frac{VSWR - 1}{VSWR + 1} = \frac{C - 1 + \left(C^2 - 1\right)^{1/2}}{C + 1 + \left(C^2 - 1\right)^{1/2}}
\]

(5)

\( \Gamma \) is depending on \( C \), when \( C \) changes, \( \Gamma \) is changed.

We assume there is a voltage source \( U_s \) in this circuit, we can get a 3 order equation:

\[
U_s - L_i \left\{ di_{L1} \right\} / dt + R_{i2} + L_{i2} (d^2 i_{L2} / dt^2) / dt - L_{i2} / dt - R_{i2} i_{L2} = 0
\]

(6)

\[
U_s - L_i C_i L_{i2} i_{L2} - L_i C_i R_{i2} i_{L2} - L_{i2} / dt - R_{i2} i_{L2} = 0
\]

(7)

When \( U_s = 0 \), the response:

\[
i_{L2} = 1 + \left(A_1 + A_2 t + A_3 t^2\right) e^{-t}
\]

(8)

\( I_2 \) have a constant 1, an index, thus this will works in an oscillation state. In some cases, this circuit works in an over damping state, and the steady state is damaged.

![Figure 4. Step in width and equivalent circuit.](image)

2.4. Bends
The current line of right angle bend shown in figure 5: Around the corner there is a parallel capacitor, the extend length just as two serious inductors [4, 6]. We can convert the microstrip bend to a uniform bend. Then use the duality theorem transform to a duality waveguide, we got the equivalent circuit as figure 5. For the circuit is similar with figure 4, the analysis is similar with the former situation.
3. Conclusion
The microstrip discontinuity generates lots of electromagnetic effects, and cause signal integrity problems. Near the open end, the impedance has changed, and a reflection wave was generated, as well as time delay. Near the gap, there is a time delay and a voltage transition, the signal integrity problem comes. Step in width in microstrip lines cause signal integrity problems such as radiation, delay, ringing and reflection.

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