Progress In Electromagnetics Research Letters, Vol. 92, 133–138, 2020

Addition of Interdigital Capacitor to Reduce Crosstalk between Non-Parallel Microstrip Lines

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Abstract—Non-parallel microstrip lines are a layout often used in high-speed interconnections. This study initiates crosstalk reduction by interdigital capacitor for the non-parallel microstrip lines. This method reduces the far-end crosstalk by adding capacitive coupling to cancel inductive coupling after an interdigital capacitor is added at the near end of the non-parallel microstrip lines. Software simulation and actual measurement results show that the proposed method can effectively reduce the far-end crosstalk in non-parallel microstrip lines. The method is also easy to implement and in low cost.

1. INTRODUCTION

With the intelligent development of electronic products, the wiring density and operating speed of integrated circuits and PCB (printed circuit board) are continuously increasing. Moreover, the problem of crosstalk caused by signal interconnections is becoming more and more prominent, which seriously inhibits the development of high-speed circuits for a long time. Crosstalk is one of the four types of signal integrity problems. In high-speed interconnections, crosstalk seriously affects the signal transmission performance in the signal channel [1, 2].

Microstrip line is one of the most popular planar transmission lines, which is widely used in microwave circuits. The coupling between microstrip lines exists in high-speed interconnections, antenna systems [3, 4], etc. Capacitive and inductive couplings between the aggressor line and the victim line are the physical causes of crosstalk. When transmission lines work at high frequency, i.e., when the signal transmission rate is very high, the increasing and decreasing times of the signal become shorter, and the resulting instantaneous voltage conversion leads to serious crosstalk. When the two transmission lines come closer to each other in the wiring space, the increased mutual inductance and mutual capacitance produce greater crosstalk between the two transmission lines.

At present, scholars are conducting extensive research on crosstalk reduction [5–8]. For example, crosstalk can be reduced by protective wiring, serpentine microstrip lines, step-shaped transmission lines, and other methods. The research objects of these methods are the most common parallel microstrip lines. However, in practical applications, the circuit design causes the transmission line layout to be more complicated. Non-parallel microstrip lines are also a layout often used in high-speed interconnections. Therefore, the reduction of crosstalk between non-parallel microstrip lines must be studied.

A method is proposed to reduce crosstalk between parallel microstrip lines through decoupling capacitor [9]. However, decoupling capacitor inserted by this method will be limited by factors such as the spacing of lines. In the current study, the use of an interdigital capacitor is proposed to reduce crosstalk between non-parallel microstrip lines on the basis of reducing crosstalk between two parallel microstrip lines by an interdigital capacitor [10]. Crosstalk is reduced by adding an interdigital capacitor

Received 2 May 2020, Accepted 14 July 2020, Scheduled 27 July 2020

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at the near end of non-parallel microstrip lines through coupling compensation. To obtain the coupling parameters, the non-parallel microstrip lines can be spatially discretized, and each discrete segment can be approximated as a parallel microstrip line before processing to obtain the capacitance value that must be compensated.

HFSS (High Frequency Structure Simulator) software simulation and VNA (Vector Network Analyzer) actual measurement results show that crosstalk at the far end in non-parallel microstrip lines can be effectively reduced by the proposed method. In addition, the method is free from limitations such as line spacing and is easy to implement and in low cost. The crosstalk cancelation scheme can be applied to high-speed interconnections.

2. PRINCIPLE OF COUPLING COMPENSATION

Crosstalk between microstrip lines is caused by electromagnetic coupling (Figure 1). Under weak coupling, when port 3 shows no excitation signal, the coupling output of the input signal of port 1 at port 4 is the crosstalk of the aggressor line to the victim line. The far-end crosstalk of the parallel coupled microstrip lines can be modeled as [11]

$$v_d = \frac{1}{2} l \left(Z_o c_m - \frac{m}{Z_o} \right) \frac{\mathrm{d}v_a}{\mathrm{d}t} \tag{1}$$

where v_a is the excitation signal on the aggressor line, Z_o the characteristic impedance of the microstrip line, c_m the coupling capacity between microstrip lines per unit length, m the coupling inductance between microstrip lines per unit length, and l the coupling length of the microstrip lines.

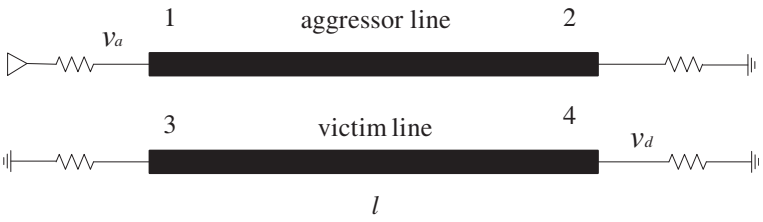

Figure 1. Crosstalk between parallel microstrip lines.

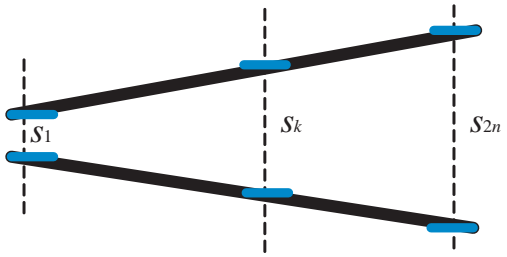

Figure 2. Discrete model of non-parallel microstrip lines.

Equation (1) shows that the far-end crosstalk noise due to capacitive coupling and the far-end crosstalk noise due to inductive coupling have opposite polarities. Thus, they will be canceled by each other but not to zero, and the far-end crosstalk always exists. If $Z_o c_m - \frac{m}{Z_o} = 0$ is set, then the far-end crosstalk will disappear. To achieve this goal, capacitive coupling can be added to compensate the inductive coupling. Assuming that the added coupling capacitance per unit length c_o makes the far-end crosstalk noise caused by capacitive coupling equal to the far-end crosstalk caused by inductive coupling, it can be set that

$$Z_o \left(c_m + c_o \right) - \frac{m}{Z_o} = 0 \tag{2}$$

That is,

$$c_o = \frac{m}{Z_o^2} - c_m \tag{3}$$

The total capacitance to be compensated between parallel microstrip lines at the coupling length l is therefore

$$c = l \left(\frac{m}{Z_o^2} - c_m \right) \tag{4}$$

In Eq. (4), Z_o, c_m, and m can be obtained from the equation in [12].

Based on the calculation of the coupling compensation capacitance between parallel microstrip lines, the coupling compensation capacitance between non-parallel microstrip lines can be calculated. The crosstalk between non-parallel microstrip lines is also the result of capacitive coupling and inductive coupling. However, the coupling parameters between non-parallel microstrip lines will change along with the position of the microstrip line. Therefore, the crosstalk calculation formula between parallel coupled microstrip lines cannot be followed to calculate the crosstalk between non-parallel microstrip lines. To obtain the coupling parameters between non-parallel microstrip lines, the non-parallel microstrip lines can be spatially discretized, and each discrete segment can be approximated as parallel microstrip lines before processing to obtain the capacitance value that must be compensated. The discrete model of non-parallel microstrip lines is shown in Figure 2. The non-parallel microstrip lines are spatially dispersed according to the direction of signal propagation. These lines are dispersed in $2n$ segments in total. Assuming that S_1 is the coupling distance of the initial discrete segment in the non-parallel microstrip lines, and S_{2n} is the coupling distance of the terminal discrete segment, the coupling distance S_k of the kth discrete segment is [13]

$$S_k = S_1 + \frac{k}{2n}(S_{2n} - S_1) \tag{5}$$

Each segment of the non-parallel microstrip lines can be approximated as parallel microstrip lines. Assuming that the capacitance to be compensated for each segment is c_k, the total capacitance value c to be compensated is

$$c = \sum_{k=1}^{2n} c_k \tag{6}$$

3. ADDITION OF INTERDIGITAL CAPACITOR TO REDUCE CROSSTALK

According to the analysis in the previous section, to suppress the far-end crosstalk between non-parallel microstrip lines, a compensation capacitor can be added. In the circuit with high-speed and high-density, due to the higher-operating frequency of the microstrip line and large wiring density, the added compensation capacitor needs to overcome the limitations of parasitic effects and line spacing. Therefore, the adoption of an interdigital capacitor is initiated to achieve the goal. This interdigital capacitor can be used as lumped circuit elements in microwave circuits, especially at higher microwave frequencies [14]. Figure 3 shows the structure of an interdigital capacitor.

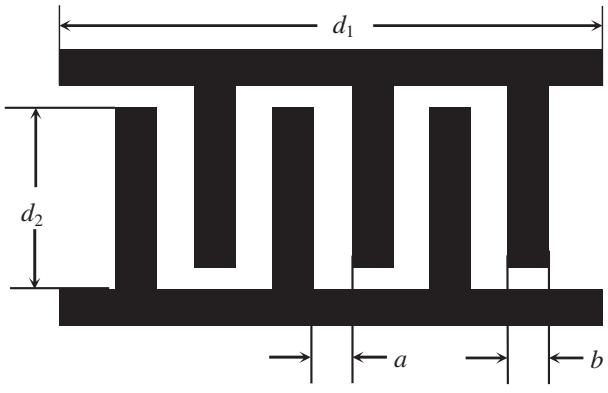

Figure 3. Structure of an interdigital capacitor.

An approximate expression for the interdigital capacitance is given by [14]

$$c = (\varepsilon_r + 1)d_2\left[(N-3)\,A_1 + A_2\right]\ (\text{pF}) \tag{7}$$

where d_2 is the length of the fingers; N is the number of fingers; A_1 (the interior) and A_2 (the two exterior) are the capacitances per unit length of the fingers; and ε_r is the relative dielectric constant of the substrate.

For a finite substrate, A_1 and A_2 can be approximately expressed as

$$A_1 = 4.409\tanh\left[0.55\left(\frac{h}{b}\right)^{0.45}\right] \times 10^{-6}\ (\mathrm{pF/\mu m}) \tag{8}$$

$$A_2 = 9.92\tanh\left[0.52\left(\frac{h}{b}\right)^{0.5}\right] \times 10^{-6}\ (\mathrm{pF/\mu m}) \tag{9}$$

where h is the thickness of the substrate, and b is the width of the fingers.

When Eq. (7) is integrated into Eq. (4), the microstrip structure parameters of the interdigital capacitor can be obtained under the premise that the parameters of the coupled microstrip lines are known.

$$(\varepsilon_r + 1)d_2\left[(N-3)A_1 + A_2\right] = l\left(\frac{m}{Z_o^2} - c_m\right) \tag{10}$$

In the interdigital capacitor structure, $a = b$ is generally taken. According to the spacing of the coupled microstrip lines, the length of the fingers d_2 can be preliminarily determined, and the number of fingers N can be calculated by Eq. (10). Therefore, the microstrip structure parameters of the interdigital capacitor used for capacitance compensation are determined.

For non-parallel microstrip lines, the size of the compensation capacitor is obtained by discretization as parallel microstrip lines. Under the premise of known compensation capacitance, the number of fingers can be obtained after the length of the fingers is determined according to the distance of the near end of the non-parallel microstrip lines.

As the coupling between non-parallel microstrip lines is mainly concentrated at the near end, the interdigital capacitor should be placed at the near end to achieve the goals of coupling compensation and crosstalk reduction.

4. EXPERIMENT AND RESULT ANALYSIS

To verify the effect of adding interdigital capacitor to reduce crosstalk between non-parallel microstrip lines, HFSS software is used for simulation; PCBs are made; and VNA E8363C is used in this section.

The parameters for setting the non-parallel microstrip lines are as follows: line length is $l = 100\,\mathrm{mm}$, line width $w = 1\,\mathrm{mm}$, and near-end distance $s = 1\,\mathrm{mm}$. The angle of the non-parallel microstrip line is 10°, the thickness of the dielectric substrate $h = 0.6\,\mathrm{mm}$, and the metal thickness of the microstrip line $t = 60\,\mu\mathrm{m}$. The dielectric substrate material is FR4, and the characteristic impedance of the microstrip line is 50 ohms. The non-parallel microstrip lines are discretized as equivalent to parallel microstrip lines, and the value needed to add a coupling compensation capacitor can be obtained. Set the fingers spacing $a = 0.2\,\mathrm{mm}$, the fingers width $b = 0.2\,\mathrm{mm}$, and the finger length $d_2 = 0.8\,\mathrm{mm}$. These parameters are brought into Eq. (7), and then the amount of fingers index that needs to be added becomes $N = 12$. The interdigital capacitor is placed at the near end of the non-parallel microstrip lines, and the simulation model set in the HFSS software according to these parameters and layout structure is shown in Figure 4. This model can simulate the far-end crosstalk S_{41} and insertion loss S_{21}.

To further verify the effectiveness of the method, a PCB is made according to the same parameters (Figure 5). The far-end crosstalk S_{41} is measured by VNA. The simulation and measurement results of

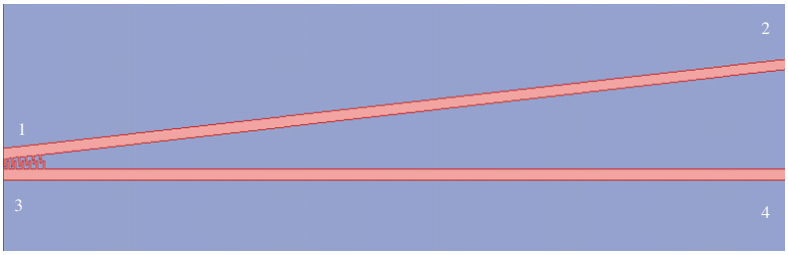

Figure 4. The simulation model with interdigital capacitor added.

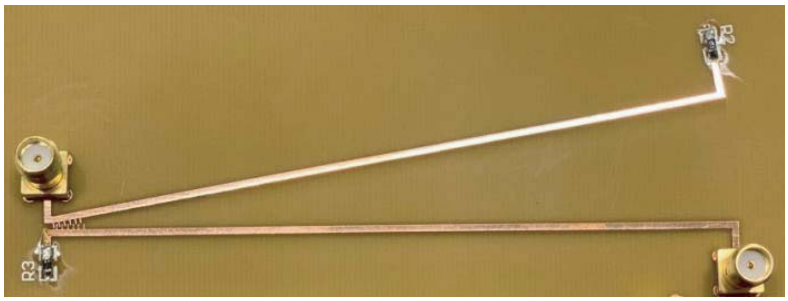

Figure 5. Measurement with interdigital capacitor added.

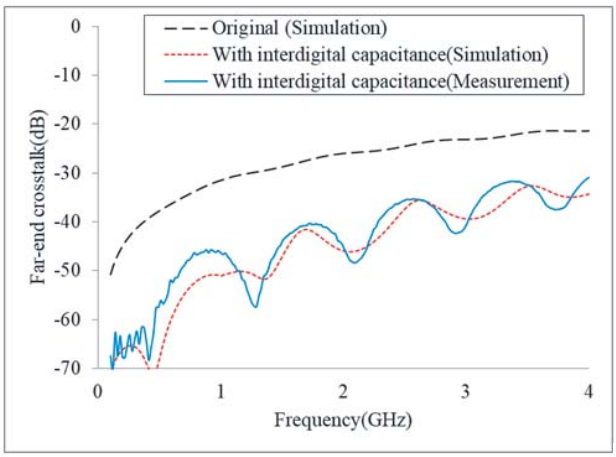

Figure 6. Crosstalk S_{41} comparison before and after interdigital capacitor are added.

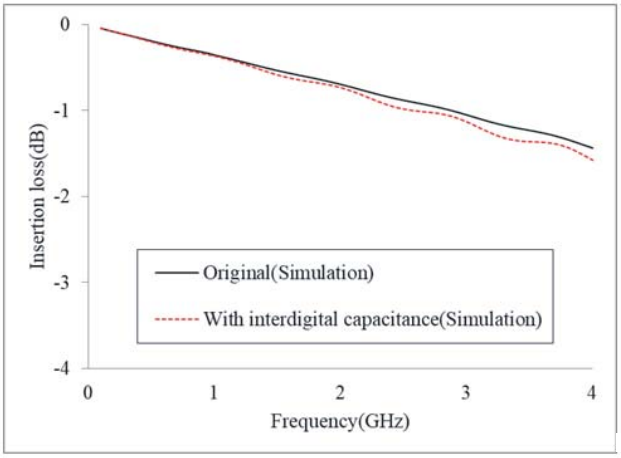

Figure 7. Insertion loss S_{21} comparison before and after interdigital capacitor are added.

the far-end crosstalk S_{41} are shown in Figure 6. The figure reveals that after the interdigital capacitor is added, the far-end crosstalk is dropped by approximately 9 dB within the range of $0.1 \sim 4$ GHz. The measured and simulated results are almost the same.

Meanwhile, the simulation results of the insertion loss S_{21} are shown in Figure 7. The figure illustrates that after the interdigital capacitor is added, the insertion loss is dropped by approximately 0.1 dB within the $0.1 \sim 4$ GHz range.

Simulation and actual measurement results show that the method of adding interdigital capacitor can effectively reduce crosstalk. Furthermore, the method has a simple structure, is easy to implement, and has low cost. Although the structure of the interdigital capacitor is affected by the gradient of line spacing at the near end, the effect is less from the simulated and experimental results.

5. CONCLUSION

The electromagnetic coupling between non-parallel microstrip lines is mainly concentrated at the near end. This research proposes to reduce crosstalk by adding interdigital capacitor at the near end of the non-parallel microstrip lines and a method that will compensate the imbalance of capacitive coupling and inductive coupling, thereby reducing crosstalk. HFSS simulation and VNA measurement show that this method can effectively reduce crosstalk. Moreover, the method has a simple structure, is easy to implement, and has low cost.

ACKNOWLEDGMENT

This work is supported by the Young Scientists Fund of the National Natural Science Foundation of China (Grant No. 61601038) and Training Programme Foundation for the Beijing Municipal Excellent Talents (Grant No. 2014000020124G102).

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