Design and Analysis of a Novel Compact Metamaterial Absorber Based on Double-Layer ITO Resistive Film for Improving Signal Integrity

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ABSTRACT This paper presents a compact metamaterial absorber (MMA) based on double-layer ITO resistive film for suppression of electromagnetic interference (EMI) to improve signal quality and signal integrity (SI). In the design of MMA, based on the classic Jerusalem cross, circular and fan-shaped structures are combined to increase its equivalent capacitance to achieve frequency shift, and an equivalent circuit model is established to analyze the key factors affecting its absorption rate. At the same time, the full-wave simulation results show that more than 90% absorption rate is achieved in the frequency range of 8.9 GHz-14.0 GHz, and the measurement results show that the absorption rate of MMA at different incident angles is consistent with the simulation. Moreover, microstrip antenna and differential microstrip transmission line are also designed as equivalent radiation sources. The co-simulation results show that the 3 m field radiation of the patch antenna is reduced by 10 dBμV at 10 GHz. At the same time, the eye height of the differential microstrip transmission line has increased from 68 mV to 340 mV, indicating that the signal integrity problem has been significantly improved. The proposed MMA has the characteristics of miniaturization, ultra-wideband, high absorption rate, and polarization insensitivity, which provides a new suppression method for the radiation problem of gradually miniaturized electronic equipment.

INDEX TERMS Miniaturized, ITO resistive film, metamaterial absorber (MMA), signal integrity (SI), electromagnetic interference suppression

I. INTRODUCTION
The advent of 5G has led higher operating frequencies and integration levels of existing electronic equipment, and EMI problems become increasingly serious [1]. In order to solve such problems, reflection and absorption schemes are generally used for radiation suppression [2]. The reflection suppression scheme is relatively simple. For example, radiation suppression can be achieved by sputtering and electroplating a thin metal layer of less than 10 μm on a single package unit with radiation exceeding the standard. However, on the one hand, the cost of this method is very high, on the other hand, electromagnetic waves reflected inside the package will cause electromagnetic immunity problems and affect the quality of signal transmission [3]. However, another solution can effectively absorb the incident electromagnetic wave, and there will be neither
transmission nor reflection in the working frequency band, and it is easier to ameliorate SI [4]-[7].

MMA is widely used because of its small thickness, high absorption rate and adjustable resonance frequency. In 2008, Landy et al. designed a perfect metamaterial absorber for the first time, and the electromagnetic characteristics were adjusted by changing the size of the surface structure to achieve perfect matching with free space impedance and achieve high absorption rate [8]. However, the early MMA unit has a narrow bandwidth, a large size, and depends on the incident angle and polarization direction of electromagnetic waves. Therefore, many researchers have proposed different design schemes for such problem. A large number of studies have found that loading lumped elements (capacitors, inductors, and resistors) are the most direct and effective way to expand bandwidth, mainly because the introduction of lumped elements makes it easier to achieve impedance matching and convert the incident electromagnetic energy absorption into heat [9]-[13]. However, the MMA unit cell structure cannot be miniaturized due to the size limitations of the lumped element itself. With the deepening of the research, the mainstream bandwidth expansion methods have been proposed, including stacked and spoof surface plasmon polaritons to confine the incident electromagnetic wave to the surface and then consuming them. However, the above method are limited by the thickness and complex material, resulting in difficulties in practical application [14]-[19]. At the same time, in the actual complex electromagnetic environment, not only the bandwidth needs to be considered, but polarization-sensitive and incident angle stability are also the key considerations. When the angle of incident electromagnetic wave increases, impedance mismatch and central frequency shift will occur. Most researchers use central symmetric structure to avoid polarization sensitivity at the beginning of design. The miniaturization of MMA also improves the angle stability. Therefore, the design of an ultra-wideband polarization insensitive absorber is easy to realize miniaturization has become a research hotspot [20]. In this paper, a high absorption rate MMA with the size of 2.2 mm × 2.2 mm × 1.6 mm for the X and Ku waveband is proposed. The MMA structure consists of a Jerusalem cross printed on glass and a fan-shaped ITO conductive film. The backplane uses ITO with a surface resistance of 5 Ω/sq instead of all metal copper to realize a double-layer ITO resistive film. The thickness of the substrate is 0.047 λω, which breaks through the requirement (1/4 λω) of the traditional absorber. At the same time, the patch antenna and transmission line are designed as radiation sources to verify the influence of MMA on electromagnetic radiation and signal integrity.

The rest of this article is organized as follows. Section II presents the design of the MMA unit structure and analyzes the factors affecting the absorption performance of the absorber. In Section III, the absorbing mechanism of MMA is introduced through the extraction of the equivalent electromagnetic parameters. At the same time, the application of MMA in improving SI is introduced. The corresponding patch antenna is designed as the radiation source and the absorption rate of MMA is verified through experiments in Section IV. Finally, a brief conclusion is given in Section V.

II. DESIGN AND SIMULATION OF MMA

A. DESCRIPTION OF MMA UNITS

The MMA is printed on the dielectric substrate in a periodic array pattern to achieve impedance matching with free space impedance. When the electromagnetic wave is incident on the surface of the medium, part of the energy is reflected and transmitted, the rest of the energy is absorbed. According to the law of energy conservation, the absorptivity is calculated as:

\[ A(\omega) = 1 - R(\omega) - T(\omega) , \]  

where \( R(\omega) \) and \( T(\omega) \) denote reflectance and transmissivity respectively,\( R(\omega) = |S_{11}|^2 \) and \( T(\omega) = |S_{21}|^2 \).

Since the backplate of the absorber is all metal, which leads to the transmission coefficient \( T(\omega) = 0 \), the calculation equation of the absorptivity is rewritten as:

\[ A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2 . \]  

Figure 1 shows the structure of the MMA unit. The parameter values of the absorber are shown in Table I. The periodic unit is composed of three parts: the ITO resistive film on the top layer, the substrate in the middle layer and the ITO resistive film on the bottom layer. The top layer resistance film on the increases its equivalent capacitance and inductance by increasing the circular and fan-shaped structures, which causes the resonance point to move to a low frequency. In order to illustrate the design principle more clearly, based on the equivalent circuit theory, the structure of the MMA is replaced by circuit analog. The change of impedance is used to characterize the transmission characteristics of incident electromagnetic wave in the MMA. As shown in Figure 2, \( Z_0 \) is the free space impedance, \( Z_{in} \) is the input impedance, \( Z_b \) is the dielectric impedance. The structure of the top layer resistive film is equivalent to an RLC series circuit, where \( R, L \) and \( C \) respectively represent the equivalent resistance, inductance and capacitance of the top part of the MMA.

![FIGURE 1. Total MMA structure design, (a) Front view, (b) 3D view.](image)
According to the transmission line theory, the input impedance $Z_m$ of the absorber is equivalent to the parallel value of the dielectric impedance $Z_h$ and the surface impedance $Z_p$, which can be retrieved from the equivalent circuit diagram using the following equation:

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

where, $R$ is related to the sheet resistivity $R_f$ of the top resistive film, can be approximately obtained as,

$$R = \frac{S_1}{S_2} R_f,$$

where $S_1$ is the area of the unit structure, $S_2$ is the area of the resistive film. Using transmission line theory, $Z_m$ can be expressed as:

$$Z_m = \frac{1}{1/Z_p + 1/Z_h} = \frac{Z_p \times Z_h}{Z_p + Z_h}.$$  

The dielectric impedance $Z_h$ from the absorber can be calculated as:

$$Z_h = Z_{re} + jZ_0 \sqrt{\frac{1}{\varepsilon_r}} \tan(\omega h \sqrt{\varepsilon_\epsilon \mu_0}),$$

where, $\varepsilon_\epsilon$ is the vacuum permittivity, $\mu_0$ is the vacuum permeability, $Z_{re}$ represents the impedance corresponding to the lossy grounding plane, $\varepsilon_r$ is the relative permittivity of the medium, $\omega$ is the resonant angular frequency, $h$ is the thickness of the medium.

The equivalent inductance $L$ of the MMA is mainly composed of the mutual inductance of the resistive film between the top and bottom layers and the self-inductance inside the top resistive film structure. Since the structure pattern has been determined, it is considered that the $L$ is a fixed value. The equivalent capacitance $C$ is also composed of two parts, including the capacitance $C_1$ between the top and bottom resistive films and the gap capacitance $C_2$ between the top resistive film structure. Considering that the electric field resonance of the absorber is dominant, and the electric field component of electromagnetic radiation is mainly distributed in the gap, it can be considered that the equivalent capacitance $C$ is approximately equal to $C_2$. Therefore, $C$ can be expressed as:

$$C \approx C_2 < \varepsilon_r / h,$$  

where $h$ is the gap size between the top-level unit structure. When other parameters remain unchanged, $C$ is only related to and proportional to the permittivity of the medium. When impedance matching is achieved, the MMA will generate electromagnetic resonance, and the resonance frequency can be expressed as [21]:

$$f = \frac{\omega}{2\pi} = \frac{c}{4h\sqrt{\varepsilon_\epsilon}}.$$  

In summary, the permittivity $\varepsilon_r$ and thickness $h$ of the medium and the sheet resistivity $R_f$ of the surface resistive film are the key parameters that affect the MMA, and the perfect absorber can be achieved through proper adjustment.

### B. INFLUENCING FACTORS OF ABSORPTION RATE

According to the above theory, the full-wave simulator, CST Microwave Studio is employed to simulate MMA in frequency-domain, and the boundary conditions is set as "unit cell" in the X and Y directions and "open add space" in the Z direction. First, the influence of medium thickness on the absorbing performance is explored. Keep other variables remain unchanged and the thickness of the medium increases in the range of 1.4 mm-1.7 mm to obtain $S_{11}$ of the absorber. According to equation (8), the resonant frequency of the MMA is inversely proportional to the thickness of the medium, and the increase of the thickness of the medium will lead to the shift of the resonant frequency to the low frequency when other conditions remain unchanged. At the same time, according to equation (6), the increase in thickness will also lead to an increase in $Z_h$. Once $Z_h$ increases, $Z_m$ will inevitably increase. When $h$ is the optimal value, the input impedance is equal to the free space impedance, the reflection coefficient tends to 0, and the absorption rate tends to 100%. When the thickness continues to increase, it will inevitably lead to impedance mismatch, which leads to a decrease in the resonance depth and a decrease in the absorption rate. The simulation results in Figure 3(a) are consistent with the theoretical derivation. Therefore, thickness is one of the key parameters affecting the MMA, and the impedance matching is realized when $h = 1.6$ mm.
Similarly, it is necessary to further study the influence of the permittivity $\varepsilon_r$ on the S parameter. In general, the real part of the $\varepsilon_r$ is two orders of magnitude larger than the imaginary part. Therefore, the influence of the change of the real part of the dielectric constant on the absorbing performance is mainly discussed here. Set the dielectric constant of the medium as a variable and increase it from 4.5 to 7.5 at intervals of 1. It can be seen from Figure 3(b) that as the permittivity $\varepsilon_r$ increases, the resonant frequency shifts to low frequency and the absorption rate increases. When the permittivity is 6.5, the resonance depth of 10 GHz is -57dB. When the $\varepsilon_r$ continues to increase, the resonance frequency continues to shift to low frequencies and the absorption rate decreases. According to the equivalent circuit analysis, the dielectric constant is inversely proportional to the square of the resonant frequency. As the dielectric constant increases, the resonant frequency continuous to shift to low frequencies. In addition, according to equations (3) and (7), with the increase of dielectric constant, the equivalent capacitance increases, resulting in the increase of input impedance. Similarly, when the dielectric constant is at the optimal value, the input impedance and freedom are realized. Therefore, when the $\varepsilon_r = 6.5$, the input impedance matches the free space impedance, thus confirming that the $\varepsilon_r$ is one of the important parameters that affect the absorption rate of the MMA.

The surface resistance of the MMA is very high. In order to study the influence of the sheet resistivity of the resistive film on the S parameter, the resistance value $R$ is set as a variable for simulation analysis without changing other conditions. According to the equivalent circuit theory, $R$ will not change the resonant frequency, but will affect the surface impedance to control impedance matching. As shown in Figure 3(c), the simulation results are consistent with the theoretical analysis. When $R = 92.8 \text{ sq}/\Omega$, the input impedance can be matched with the free space impedance.

Of course, sometimes when the above three conditions are determined, the frequency offset and impedance matching can also be achieved by changing the resistive film structure of the top layer. As shown in Figure 4, when circular and fan-shaped patches are added to the traditional Jerusalem cross, the equivalent inductance and capacitance are increased. According to the equivalent circuit, the resonance frequency is shifted to low frequencies and the surface impedance is increased, which makes the input impedance faster to achieve impedance matching, i.e., the absorption rate increases.

**C. NUMERICAL SIMULATION**

After determining the value of each parameter of the structure, the absorption rate is analyzed by CST simulation. The absorption rate curve is calculated by (2). As shown in Figure 5, the red curve represents the $S_{11}$ parameter, the resonance depth reaches -57dB, and the black curve represents the calculated absorption rate. The absorption rate of more than 90% is achieved at 8.9 GHz-14.0 GHz, the relative bandwidth reaches 44.5% to achieve ultra-wideband.

**FIGURE 3.** The influence of key parameters on S-parameters, (a) Change of dielectric thickness, (b) Change of dielectric constant, (c) Change of resistance film square resistance.

**FIGURE 4.** The effect of top structure changes on the absorption rate.
When the electromagnetic environment is complex, the polarization angle and incident angle are the key factors that affect the absorption performance of MMA. Due to the central symmetry of the structure itself, it has polarization-insensitive characteristics. As shown in Figure 6 (a) and (b), when the polarization angle changes in the range of 0°-90°, the absorption rate in TE and TM polarization modes remains unchanged, which proves that the structure is insensitive to polarization.

In order to ensure the angle stability, the structure of the MMA is simulated by the oblique incident. Figure 7(a) and (b) show the relationship curves of absorption rate affected by different incident angles in TE and TM polarization modes, respectively. When the incident angle of the electromagnetic wave is in the range of 0°-40°, the absorption rate of the absorber in the working frequency band is always higher than 90%. With the increase of the incident angle, the absorption rate gradually decreases. When the incident angle is 60°, the absorption rate and bandwidth of the TE mode are significantly reduced, but the absorption rate is still more than 80% in the frequency range of 9.4 GHz-12.8 GHz. However, the absorption bandwidth increases in TM mode and the absorption rates after 8 GHz is higher than 80%, so the structure has good angular stability.

III. ABSORPTION MECHANISM

A. EQUIVALENT ELECTROMAGNETIC PARAMETER ANALYSIS

In order to verify the absorbing mechanism of MMA, the surface electric field and current were analyzed in detail by CST simulation software. The surface current and the electric field distributions of the proposed MMA at the resonant frequency, i.e., 11 GHz, are shown in Figure 8. Figure 8(a) and (b) show the surface current of the top and bottom layer of the MMA at 11 GHz. As shown in Figure
For this reason, a simple program is written to calculate the real and imaginary parts of the equivalent impedance using the S-parameter inversion method. As shown in Figure 9(a), the black curve and red curve represent the real and imaginary parts of the equivalent impedance respectively. It can be seen that in the range of 8.9 GHz-14.0 GHz, the black curve is close to 1, and the red curve is close to 0, which realized the impedance matching with the free space. Since \( z(\omega) \neq 1 \), the absorption rate cannot reach 100% and can only be infinitely close.

In addition, the constitutive parameters are also one of the important means to verify the absorbing mechanism of MMA. As mentioned above, the backplane of our MMA is equivalent to all copper-clad, so the equivalent medium theory is no longer applicable. The new calculation equations for equivalent dielectric constant \( \varepsilon(\omega) \) and permeability \( \mu(\omega) \) are as follows [23]:

\[
\varepsilon(\omega) = 1 + \frac{2j}{k_0h} \left( \frac{1 - S_{11}}{1 + S_{11}} \right),
\]

\[
\mu(\omega) = 1 + \frac{2j}{k_0h} \left( \frac{1 + S_{11}}{1 - S_{11}} \right),
\]

where \( k_0 \) is the free space wave number, \( h \) is the thickness of the substrate.

Figure 9(b) and (c) show the equivalent permittivity and permeability of the absorber, respectively. where the black curve and red curve represent the real and imaginary parts, respectively. The comparison results show that the working bandwidth is basically the same, the real part of the \( \varepsilon(\omega) \) and \( \mu(\omega) \) is close to 0, and the impedance matching with the free space is realized. The imaginary part of the equivalent electromagnetic parameter represents the loss of the absorbing body to the incident electromagnetic wave, and the imaginary part is all greater than 0 in 8.9 GHz-14.0 GHz, showing obvious absorption loss.
The loss of absorbers is generally divided into dielectric and ohmic loss. Figure 6(a) shows the absorption rate curve of the MMA glass substrate (lossy and loss-free). In order to see the trend of the two curves clearly, the red and blue dashed lines are used to indicate lossy and loss-free respectively. The results show that the two curves have the same trend, and the absorption rate in the range of 8.9 GHz-14.0 GHz is higher than 90%. Therefore, the loss of the glass substrate of the absorber has no effect on the absorptivity, and there is no dielectric loss. In order to further verify whether there is the ohmic loss in the top structure, figure 6(b) is obtained by comparing different materials, i.e., resistive film and PEC. The two curves in the figure are very different. The introduction of the resistive film makes the absorption rate of the structure much higher than that of traditional metal materials. Therefore, the MMA belongs to the ohmic loss type. In short, the loss type of MMA is not single, including dielectric loss and magnetic resonance loss, and ohmic loss is the main loss in this study. This means that the change in the permittivity of the dielectric material will not have a certain effect on the absorption rate. Therefore, several materials with different permittivity were simulated and analyzed to verify the above conjecture. Since the permittivity of the glass itself is 6.5, in order to ensure the reliability of the simulation results, two different materials with permittivity higher than 6.5 and lower than 6.5 are selected respectively, i.e., Rogers TMM 10 and Polyimide. Figure 6(c) shows the absorption rate curves of these three different materials, while Table II shows the material name, permittivity, working frequency band, and relative bandwidth. The results show that the change of the dielectric constant has little effect on the absorption rate. According to equation (8), as the permittivity of the substrate increases, the overall absorption frequency band shifts to low frequencies, and the absorption rate is not affected. Therefore, the high permittivity dielectric substrate is beneficial to the miniaturization of the MMA.

### B. EQUIVALENT CIRCUIT ANALYSIS

In order to better analyze the absorbing principle of the metamaterial absorber, construct its equivalent circuit, as shown in Figure 11. Different from Figure 2, the parameters

![Figure 9](image.png)

**FIGURE 9.** Equivalent parameters of MMA. (a) Equivalent impedance. (b) Equivalent permittivity. (c) Equivalent permeability.

![Figure 10](image.png)

**FIGURE 10.** The effect of material property changes on the absorption rate. (a) Absorption rate of glass with or without loss. (b) Absorption rate under different top layer materials. (c) Absorption rate under different substrate materials.

| Substrate material | Permittivity | Bandwidth (GHz) | Relative bandwidth (%) |
|--------------------|--------------|-----------------|------------------------|
| Polyimide          | 3.5          | 11.4-17.0       | 39.4                   |
| Glass              | 6.5          | 8.9-14.0        | 44.5                   |
| Rogers TMM 10      | 9.8          | 7.4-11.2        | 40.9                   |
of the top-level structure are analyzed in detail, and the overall structure is divided into two parts, the fan shape and the Jerusalem cross. Therefore, $R_1$ and $L_1$ respectively represent the equivalent resistance and inductance of the Jerusalem cross in the center of the model, and $C_{g1}$ represents the equivalent capacitance between the edge part and other unit structures. In addition, $R_2$ and $L_2$ represent the equivalent resistance and inductance of the surrounding sector structure, and $C_{g2}$ represents the equivalent capacitance between the sector portion and the central structure. As determined in the previous analysis, the necessary condition for achieving high absorption is that the real part of the equivalent impedance is equal to 1 and the imaginary part is equal to 0, i.e., the real part of the input impedance is equal to the free space impedance and the imaginary part is equal to 0. The bottom plate of the absorber and the dielectric layer can be regarded as a terminal transmission line of length $h$, and the input admittance $Y_{in}$ of the absorber is the accumulation of the admittance values of each layer. $Z_d$ represents ground loss. Therefore, the relationship between capacitance, inductance and resistance when perfect absorbing is obtained:

$$\frac{\omega^3 R_1 C_{g1}^2}{(1-\omega^2 L_1 C_{g1})^2} + \frac{\omega^3 R_2 C_{g2}^2}{(1-\omega^2 L_2 C_{g2})^2} = \frac{1}{Z_0} \quad (13)$$

$$\frac{\omega C_{g1} - \omega^2 L_{g1} C_{g1}^2}{(1-\omega^2 L_{g1} C_{g1})^2} + \frac{\omega C_{g2} - \omega^2 L_{g2} C_{g2}^2}{(1-\omega^2 L_{g2} C_{g2})^2} + \frac{\sqrt{\varepsilon_r} \cot \left( \frac{2\pi f \sqrt{\varepsilon_r} h}{c} \right)}{Z_0} = 0 \quad (14)$$

where $c$ represents the speed of light in free space, other parameters have been explained in the second section. Through ADS extraction and calculation, the parameter values of absorber lumped element are as follows: $R_1 = 152.8 \ \Omega$, $R_2 = 572.2 \ \Omega$, $L_1 = 15.4 \ \mu H$, $L_2 = 12.4 \ \mu H$, $C_{g1} = 20.7 \ \mu F$, $C_{g2} = 11.3 \ \mu F$. As shown in Figure 12, the S parameters obtained in ADS are converted into absorptivity, and compared with the simulation results of CST, the two curves basically coincide.

C. RADIATION SUPPRESSION AND SI ANALYSIS

Because the ITO absorber has the characteristics of miniaturization, it can be used for chip level radiation suppression. At present, most of the radiation in the chip comes from inter board resonance, so the MMA can be placed under the heat sink in the form of array, and the top structure is facing the PCB. Suppress the radiation before it leaks into the space, so as to block the radiation path. Due to the chip model is confidential, we designed a microstrip antenna working at 10 GHz instead. As shown in Figure 13, the antenna is composed of a top metal patch, an intermediate dielectric layer, and a slotted metal ground plane at the bottom. The purpose of the slotted antenna is to excite the current and increase a certain bandwidth, making it easier to generate the operating frequency of 10 GHz for replacing the chip. The dielectric substrate adopts FR4, and the overall size is 20 mm×20 mm×1.6 mm, the width of the feeder port is 0.2 mm, the upper end of the ground plane of the backplane is slotted 4.3 mm. The parameter values of the microstrip antenna are shown in Table III.
TABLE III
GEOMETRIES OF THE MICROSTRIP ANTENNA (UNIT: MM)

| a  | b     | c  | L  | h   | h₁  |
|----|-------|----|----|-----|-----|
| 0.2| 15.2  | 4.3| 20 | 1.6 | 0.035 |

FIGURE 14. S parameter of patch antenna.

CST Microwave Studio is employed to simulate microstrip antenna in time-domain, and the boundary conditions is set as "open add space" in the X, Y and Z direction. Figure 14 shows the S parameters of the microstrip antenna. The resonance frequency is 10 GHz, which means that there will be a radiation peak near 10 GHz. As shown in Figure 15, the resistive film absorbing structure is placed 1 mm above the antenna. And the closer the distance, the more obvious the suppression effect. Figure 16 shows the 1 m far-field result after loading the absorbing structure. It has obvious suppression effect in the range of 8 GHz–12 GHz, and the radiated energy at 10 GHz is reduced by 10 dBμV. Since there is the slot on the back of the microstrip antenna, there is a certain radiation leakage, which reduces a certain suppression effect, but the purpose of radiation suppression can be generally achieved. In the same way, it is equally effective when applied to the radiation suppression of miniaturized electronic equipment. Compared with traditional suppression schemes, resistive film absorbers can expand the suppression bandwidth, miniaturize the design structure, and maximize the suppression of specific frequency points.

FIGURE 15. Arrangement of resistive film structure.

In order to further verify the influence of the metamaterial absorber on the signal integrity, the corresponding transmission line structure needs to be designed. Therefore, in order to simplify the design, the thickness and material of the base are the same as that of the antenna, with specific parameters L₁ = 30 mm, L₂ = 20 mm, L₃ = 5 mm and L₄ = 10 mm, as shown in Figure 17. The red diamond-shaped frame in the figure is the metamaterial absorber structure. The co-simulation model is similar to the antenna loading method, and the structure is tiled on the top layer with the strongest radiation. In order to intuitively obtain the influence of the MMA structure on the signal transmission capability, the eye diagram is an indispensable indicator. First, use the CST simulation software to set the step signal to generate the excitation source at port 1, and the total simulation time is 200 ns. Immediately, set the eye diagram tool through the obtained transient response, and observe the signal quality of port 2. As shown in Figure 18(a), the eye diagram of the differential microstrip transmission line is obtained, and the eye height is only 68 mV. The metamaterial absorber does not reduce the radiation of the microstrip differential line itself, it is intended to cut off the radiation leakage problem in the propagation path. This results in very little radiation transmission to the terminal, so the eye chart of the receiving end will be improved and the eye height will increase significantly. As shown in Figure 18(b), the eyes diagram is obviously opened and the eye height is 340 mV, which proves that MMA will improve the signal integrity to a certain extent.

FIGURE 16. 3 m far field result comparison chart.

FIGURE 17. Differential microstrip transmission line.
the MMA is much greater than $2L^2/\lambda_L$ ($L$ represents the maximum diameter of the horn).

In order to verify the absorption rate of the absorber in different polarization modes, the directions of the two double-ridged horn antennas were rotated at $0^\circ$ and $90^\circ$ at the same time, and the S parameters of the TE and TM polarization modes were measured at normal incidence. According to equation (2) obtain the absorption rate curve. The absorptivity measurement result in TE and TM polarization modes are shown in Figures 19(c) and (d). Comparing the simulation and measurement results, the trend of the curve is basically the same, and there is an absorption peak near 11 GHz. Because the processing accuracy and environmental interference errors in the measurement are inevitable, the measured curve obtained is not smooth and there is noise interference, but the overall absorption bandwidth of the resistive film absorber is similar to the simulation, which further verifies the absorption performance of the absorber.

At the same time, in order to verify the angular stability of the absorbing body, the angle of the absorbing structure is rotated to measure the absorption rate when electromagnetic waves are incident in the range of $0^\circ$–$60^\circ$. As shown in Figure 19(e) and (f), with the increase of the incident angle, the absorption rate of the absorber decreases significantly, and the absorption bandwidth decreases in TE polarization mode, while increases in TM polarization mode, which is generally consistent with the simulation results. However, when the incident angle is $20^\circ$, the measurement result of the absorptance is shifted. The main reason is that when the angle of incidence is $20^\circ$, the measurement structure is tilted, which causes a certain change in the distance when the electromagnetic wave enters the absorber, thus causing the frequency to occur Certain offset.

The performance of this designed resistive film absorber was compared with some relevant works, as shown in Table IV. If the application is considered, the electromagnetic wave with an incident angle of $60^\circ$ will not be affected by the reduction in bandwidth and absorptance at all, so I mark the incident angle as $60^\circ$ in Table IV. Compared with other researches, the proposed absorber has miniaturization and a stable incidence angle. Although the relative bandwidth is only 44.5%, it also achieves ultra-wideband and has a high absorption rate in the X-band.
V. CONCLUSION

In this paper, a new type of the metamaterial absorber based on double layer ITO resistive film is designed to solve the radiation problem at chip package level and improve signal integrity. Full-wave simulations and measurement were carried out for validation of the structure. The structure realizes the polarization insensitivity due to the central symmetry and the result shows that the absorptivity is higher than 90% in the range of 8.9 GHz – 14.0 GHz when the electromagnetic wave is incident vertically. Additionally, the absorption rate of 10.0 GHz is still higher than 80% when the electromagnetic wave incident angle is 60°. When the absorber structure is loaded on the differential microstrip line, the eye diagram is significantly improved, and the eye height is increased from 68 mV to 340 mV. When a microstrip antenna is used as a radiation source, the suppression effect of the MMA achieves 10 dBμV at 10 GHz. The structure we designed is more compact and has stronger angular stability by comparing with the recent research in Table IV, which is suitable for electromagnetic interference problem of complex chip packaging.

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