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Performance Analysis of Flame Retardant 4 Copper Plate Antenna for Lightning Remote Sensing

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Abstract. Lightning remote sensing has been used widely to measure the electromagnetic (EM) fields in various frequencies bands. Circular metal plate capacitive antenna made of iron or aluminium have been used widely for the front-end design of the remote sensing system. The circular metal plates are arranged in parallel and separated by insulators made of Teflon. However, three common problems encountered with the existing setting. First, both metals rust easily and could affect the reading of the EM fields. Second, the insulation Teflon separating the metal plates could become weak conductor during heavy rain and thus distort the EM fields reading. Third, the use of Teflon in between the parallel plates changes the overall permittivity value. In this paper, we propose a cheaper and lighter alternative to iron and aluminium plates by changing to FR4 copper plate. Rectangular FR4 copper plate capacitive antennas with 2 sizes, A4 and A3 have been designed and constructed. The rectangular A3 FR4 copper plate has been found to have similar impedance and capacitance values to the iron-based circular metal plate. Analysis of wave shape and peak amplitude ratio showed similar performance between both antennas. Therefore, we conclude that rectangular A3 FR4 copper plate antenna can be used as replacement for the existing iron- or aluminium-based circular metal plates antenna.

1. Introduction

To measure a lightning event, the measurement of electric field can be done by using a single plate or parallel plate capacitive antenna. Gauss's law is one of the primary laws that is applied during the calibration process, where it links between the charge in a region or a surface to the electric field. In Coulomb's law, it focused on the force of two charges or any number of charges where the concept of electric field is defined by force per unit charge for each point in a region of charges [1]. For a single plate capacitive antenna, the electric field is assumed as uniform and the antenna is considered electrically small. No metallic object should be place near the system to avoid any disturbance during the measurement of electric field [2]. When the antenna is in no load condition, the electric field near the antenna matched to the value that would exist in the absence on antenna. The potential difference between the ground and the antenna can then be rule by the equation of $\boldsymbol{Vg = En.d}$ [3]. In this equation, the voltage between the metallic plate and the ground is directly proportional to the electric field normal to the plate and its height respect to the ground.

Lightning is measured based on their electric field intensity and one of the crucial aspects of capturing the information is the operation of the measuring system. This system includes the geometry of the antenna, electronic circuits of the buffer circuits and the calibration of the system. The measuring system consists of a flat metallic plate above ground level to measure the lightning electric field intensity. There are two parameters that were observed for this measuring system which are the size of the antenna and the capacitive value at the electronic buffer circuit. Changing both parameters affects the potential readings for the Vg and Vm values. These parameters were simulated in the Matlab by using two main equations that would calculate the outcome of the potential at the antenna and the output. Based on the results obtained, the best design could be determined.

Circular metal plate capacitive antenna made of iron or aluminium have been used widely for the front-end design of the remote sensing system. The circular metal plates are arranged in parallel and separated by insulators made of Teflon. However, three common problems encountered with the existing setting. First, both metals rust easily and could affect the reading of the EM fields. Second, the insulation Teflon separating the metal plates could become weak conductor during heavy rain and thus distort the EM fields reading. Third, the use of Teflon in between the parallel plates changes the overall permittivity value. In this paper, we propose a cheaper and lighter alternative to iron and aluminium plates by changing to FR4 copper plate. Rectangular FR4 copper plate capacitive antennas with 2 sizes, A4 and A3 have been designed and constructed.

2. Methodology

A parallel plate antenna with air gap has been designed in Computer Simulation Technology (CST) simulator by using static and low frequency solver as shown in Figure 1. The Flame Retardant 4 (FR4) substrate was constructed using brick model with the size of 420 mm x 297 mm x 1.6 mm. The material used was Perfect Electric Conductor (PEC). Then, another brick model with the size of 380 mm x 297 mm x 0.035 mm was constructed and the material used was annealed copper. Later, another substrate and copper with the same size as previous ones were constructed. Both the copper plates were faced inside while the two substrates were faced outside just like mirrored. The spacing (air gap) between the copper plates was approximately 30 mm.

Next, by using the static and low frequency components, electric field was applied between the plates by define the total charges for both copper plates (+Q for top plate and –Q for bottom plate) and been simulated. The results for the simulation of the parallel plate are shown in Figures 2 and 3.

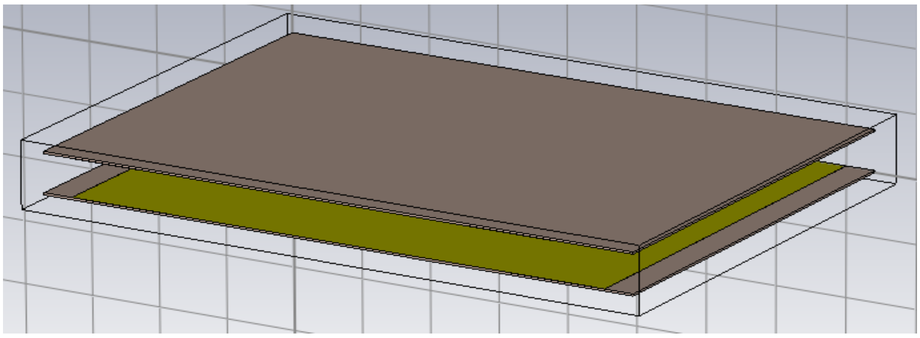

Figure 1. Model of a parallel plate with thin copper plates facing each other and separated by 3 cm air gap

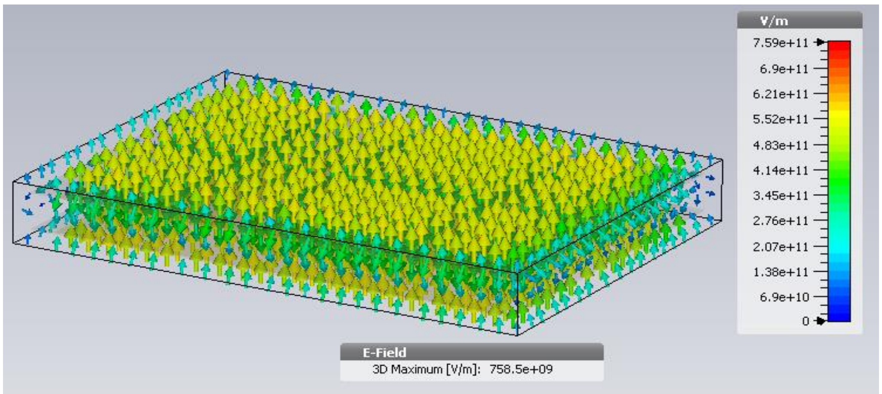

Figure 2. Plot of 3D Electric field between the copper plates. It is clear that the electric field is almost uniform between the plates (green arrows) except at the edges due to fringing effect

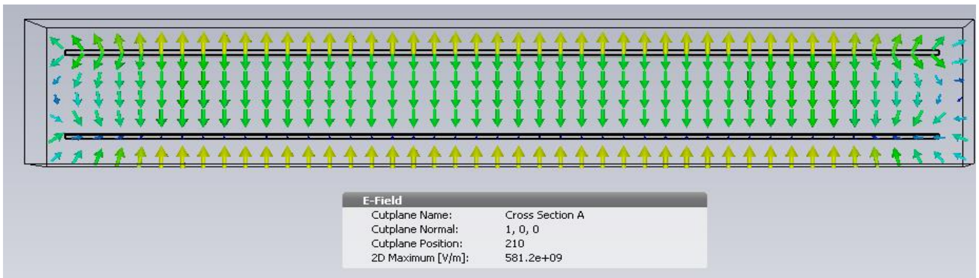

Figure 3. Plot of 2D Electric field between the copper plates where the direction of the vertical field is downward as shown by the green arrows. This is because the top plate was defined to have positive surface charge density (+Q) while the bottom plate has negative surface charge density (-Q). The fringing effect could be seen clearly at the both edges of the plot

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Figures 2 and 3 show that vertical electric field was generated between the parallel plates directed downward. The electric fields flow from positively-plate (top plate) to negatively-plate (bottom plate). The simulation of parallel plate capacitive antenna is considered a success due to the uniform vertical electric field generated between the plates which perfectly agree with Gauss's Law for Electrostatic.

As can be seen from both the 2D and 3D plots, the direction of the electric fields is uniform but at the edge of the antenna, notice that the fields are not directed vertically downward between the plates. The fields curving as the fields flow from the top plate to the bottom plate. This phenomenon is known as fringing effect that happens at the edges of an antenna and this problem is very severe for high frequency design. In this thesis, we design the antenna for low frequency application below than 3 MHz frequency band. Therefore, fringing effect can be neglected completely which will not affect the measurement campaign.

3. Results and analysis

3.1 Antenna performance under real lightning measurement

Figure 4 shows the variation of the electric fields between metal plate (iron) and FR4 copper plate antenna with A3 size. The A3 size was chosen because of comparable dimension when compared to the dimension of the metal plate antenna. This data has been taken on November 16th 2015 to compare the performance between metal plate antenna and FR4 A3 antenna. 100 selected data have been chosen to do comparison study between both antennas. The selected type of waveform chosen is Negative Cloud-to-Ground (–CG) flash and Positive Narrow Bipolar Event (+NBE). These 2 types of waveforms frequently detected by Picoscope. The peak values of the electric field were obtained from the Picoscope record (recorded as voltage value) at Channel A (metal plate) and Channel B (FR4 copper plate with A3 size). For analysis purpose, the ratio of the peak values of Channel A to Channel B is obtained.

As can be seen from Figure 4, the ratio values vary in a range between 0.8 to 1.06. The mean value is calculated to be around 0.935 which tells us that the peak amplitudes of the FR4 copper plate antenna are almost the same as the peak amplitudes of the metal plate antenna. This result is expected because the size of the copper plate antenna is not exactly the same as metal plate antenna. Thus, small difference is really expected. The variance and standard deviation are calculated to be around 0.004 and 0.063, respectively.

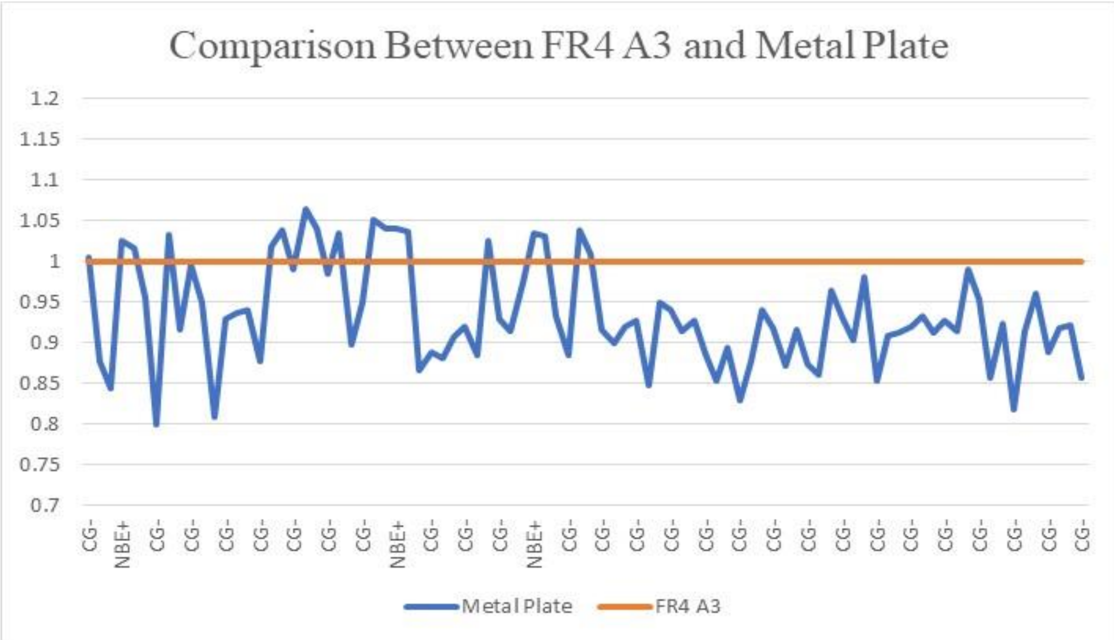

Figure 4. Plot shows the performance comparison between metal plate antenna and FR4 copper plate antenna for both –CG and +NBE flashes. The ratios are determined based on peak electric field values of metal plate over the values of FR4 antenna

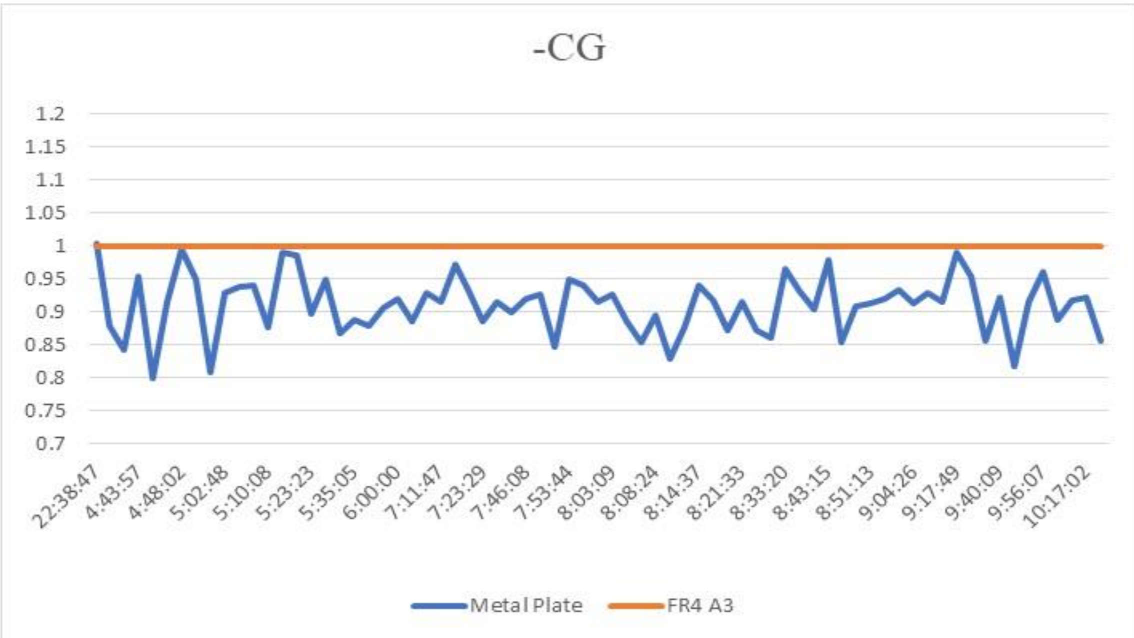

Figure 5. Plot shows the performance comparison between metal plate antenna and FR4 copper plate antenna for –CG flashes. The ratios are determined based on peak electric field values of metal plate over the values of FR4 antenna

Figure 5 shows the variation of the electric fields between metal plate (iron) and FR4 copper plate antenna with A3 size for only –CG flashes. By comparing the performance of the captured –CG flashes, we can see that the FR4 copper plate antenna performance is comparable to the metal plate antenna. The mean value is calculated to be around 0.911 which tells us that the peak amplitudes of the FR4 copper plate antenna are almost the same as the peak amplitudes of the metal plate antenna. This result is expected because the size of the copper plate antenna is not exactly the same as metal plate antenna. Thus, small difference is really expected. The variance and standard deviation are calculated to be around 0.002 and 0.044, respectively.

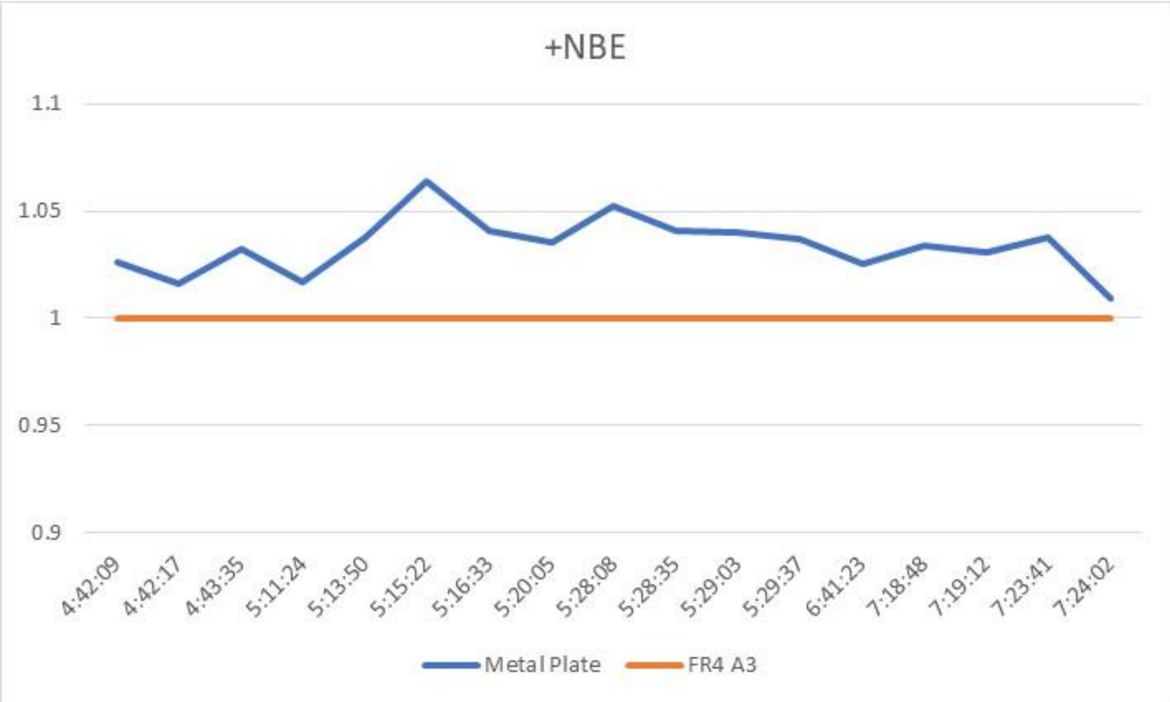

Figure 6. Plot shows the performance comparison between metal plate antenna and FR4 copper plate antenna for +NBE flashes. The ratios are determined based on peak electric field values of metal plate over the values of FR4 antenna

Figure 6 shows the variation of the electric fields between metal plate (iron) and FR4 copper plate antenna with A3 size for only +NBE flashes. By comparing the performance of the captured +NBE flashes, we can see that the FR4 copper plate antenna performance is comparable to the metal plate antenna. The mean value is calculated to be around 1.034 which tells us that the peak amplitudes of the FR4 copper plate antenna are almost the same as the peak amplitudes of the metal plate antenna. This result is expected because the size of the copper plate antenna is not exactly the same as metal plate antenna. Thus, small difference is really expected. The variance and standard deviation are calculated to be around 0.0002 and 0.013, respectively.

3.2 Analysis of captured waveforms

3.2.1 Capture waveforms by using both metal and copper plate antennas

Figures 7 and 8 show the captured waveform of –CG and +NBE flashes, respectively. We observed that the amplitudes of the electric fields of the metal plate antenna were slightly higher than the amplitudes of the electric fields of the FR4 copper plate antenna. This case is true for –CG flashes while for +NBE flashes the case is contrary. This result is expected due to the area of the metal plate antenna is slightly bigger compared to FR4 copper plate size antenna. Moreover, the shape of the metal plate antenna is circular while the FR4 copper plate is rectangular. However, the most important factor here is the shape of the waveforms is identical which means that the frequency components of both antenna systems are preserved.

In summary, the difference between metal plate and copper plate antenna systems is not that significant and we decided to use FR4 copper plate antenna system to replace the old metal plate antenna. The main reason is that the metal plate antenna is much costlier compared to FR4 copper plate antenna. The FR4 copper plate antenna can be purchased easily at any electronic shops. Moreover, FR4 copper plate antenna is much lighter and mobile compared to metal plate that is heavy and easily to corrode.

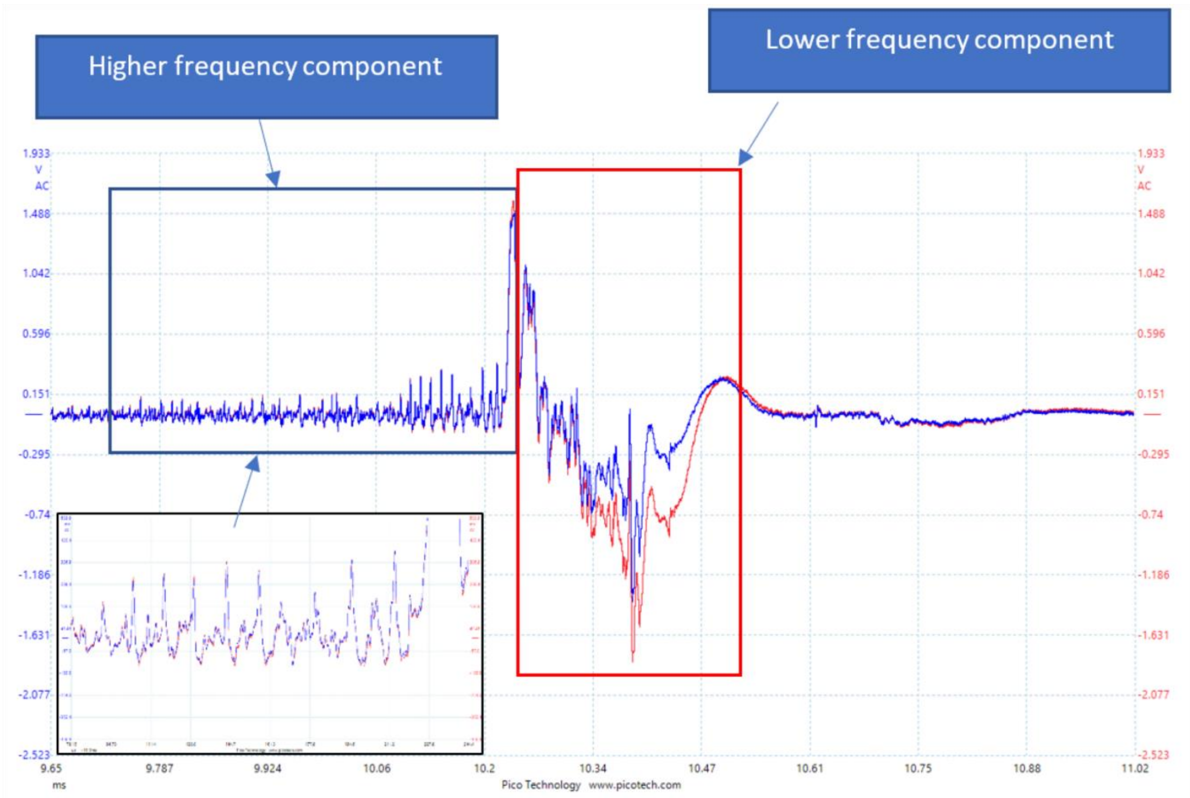

Figure 7. An example of captured waveform of –CG flash that consists of stepped leader and return stroke processes. The blue plot is signal captured by metal plate antenna system and the red plot is signal captured by FR4 copper plate antenna system

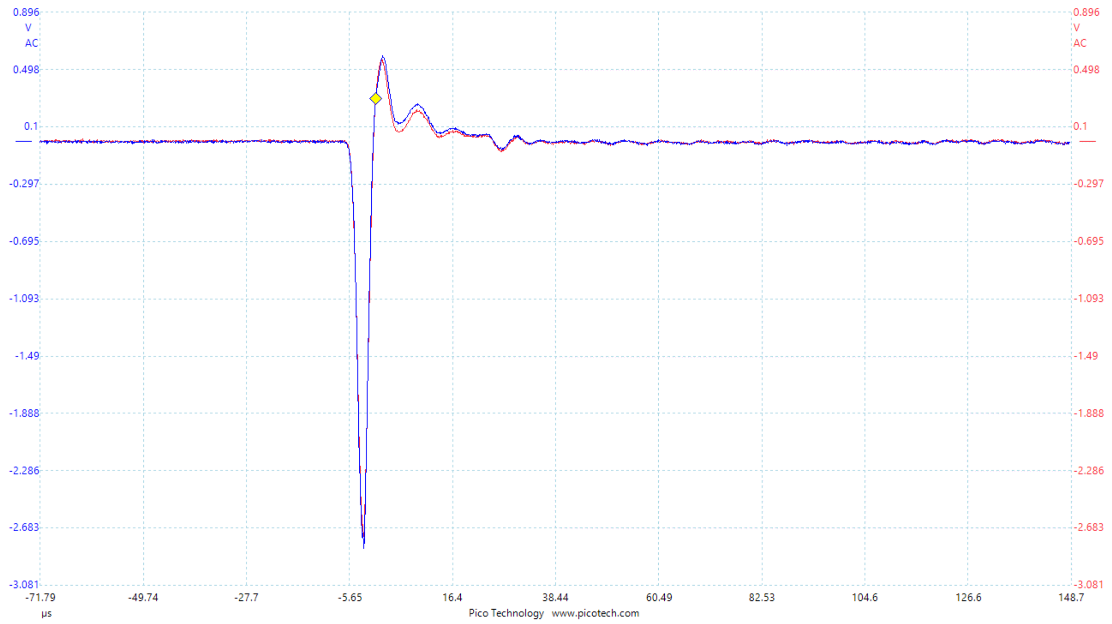

Figure 8. An example of captured waveform of +NBE flash. The blue plot is signal captured by metal plate antenna system and the red plot is signal captured by FR4 copper plate antenna system

3.2.2 Captured waveforms beyond reversal distance by using FR4 copper plate antenna

Figures 9 and 10 show captured waveforms of –CG and IC flashes beyond reversal distance (typically > 7 km [4,5] by using fast field system (top blue waveform) and slow field system (red bottom waveform) [7]. Fast field system captured mainly radiation component of the electric field emitted by the lightning while slow field system captured mainly electrostatic and inductive components of the electric field [6].

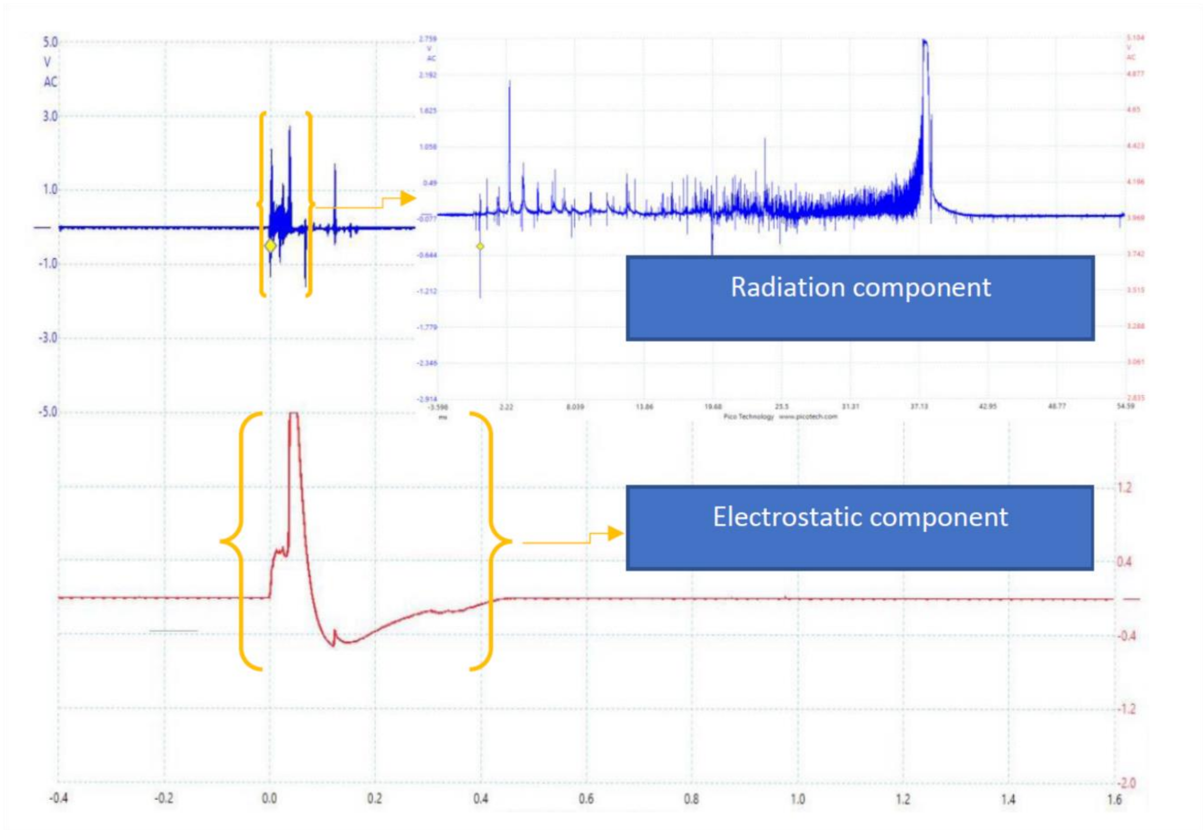

Figure 9. An example of –CG flash captured with radiation component (top blue plot) and electrostatic component (bottom red plot)

As can be seen from the fast field waveform (blue plot) in Figure 9, the captured –CG flash was initiated by preliminary breakdown and followed by step leaders and return stroke. These processes are essential part of a –CG flash [6]. Negative CG flash literally means that negative charges are brought down to the ground. When the negative charges brought down to the ground, the polarity of the emitted electric field is positive (atmospheric electricity sign convention) due to fact that the electric current flows upward [6]. In other word, the polarity of the emitted electric field pulses is determined based on the direction of the current. Therefore, the polarity of the initial part of the slow field record (red plot) should be positive. This is clear evidence that FR4 copper plate antenna could detect lightning waveforms faithfully.

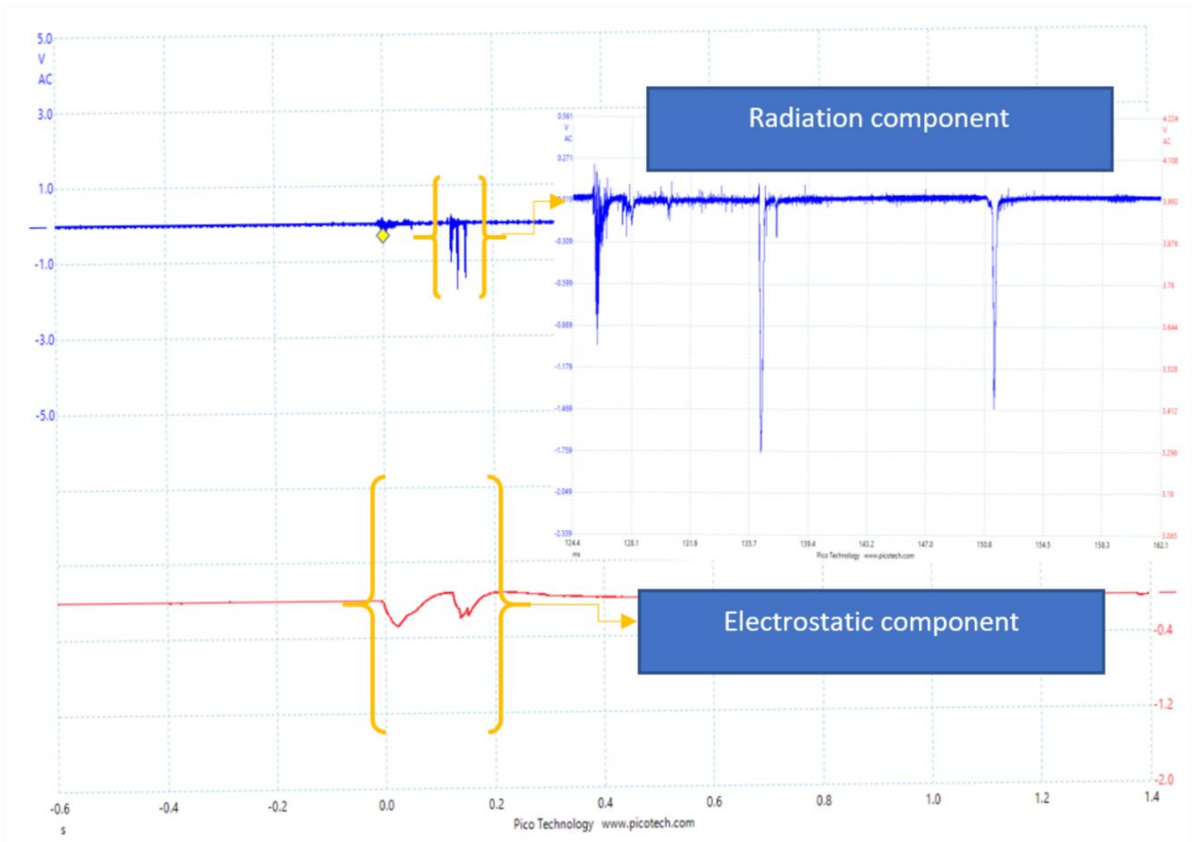

Figure 10. An example of IC flash captured with radiation component (top blue plot) and electrostatic component (bottom red plot)

As can be seen from the fast field waveform (blue plot) in Figure 10, the captured IC flash was initiated by preliminary breakdown and followed by regular bipolar pulses. These processes are essential part of an IC flash [6]. The IC flash literally means that negative charges are brought up to bridge between main negative charge and main positive charge inside thunderstorm. When the negative charges brought up, the polarity of the emitted electric field is negative (atmospheric electricity sign convention) due to fact that the electric current flows downward [6]. In other word, the polarity of the emitted electric field pulses is determined based on the direction of the current. Therefore, the polarity of the initial part of the slow field record (red plot) should be negative. This is clear evidence that FR4 copper plate antenna could detect lightning waveforms faithfully.

3.2.3 Captured waveforms within reversal distance by using FR4 copper plate antenna

Figures 11 and 12 show captured waveforms of –CG and IC flashes within reversal distance (typically ≤ 7 km [4,5] by using fast field system (top blue waveform) and slow field system (red bottom waveform). Within reversal distance, fast field system captured both radiation and electrostatic components of the electric field emitted by the lightning while slow field system captured mainly electrostatic and inductive components of the electric field [6].

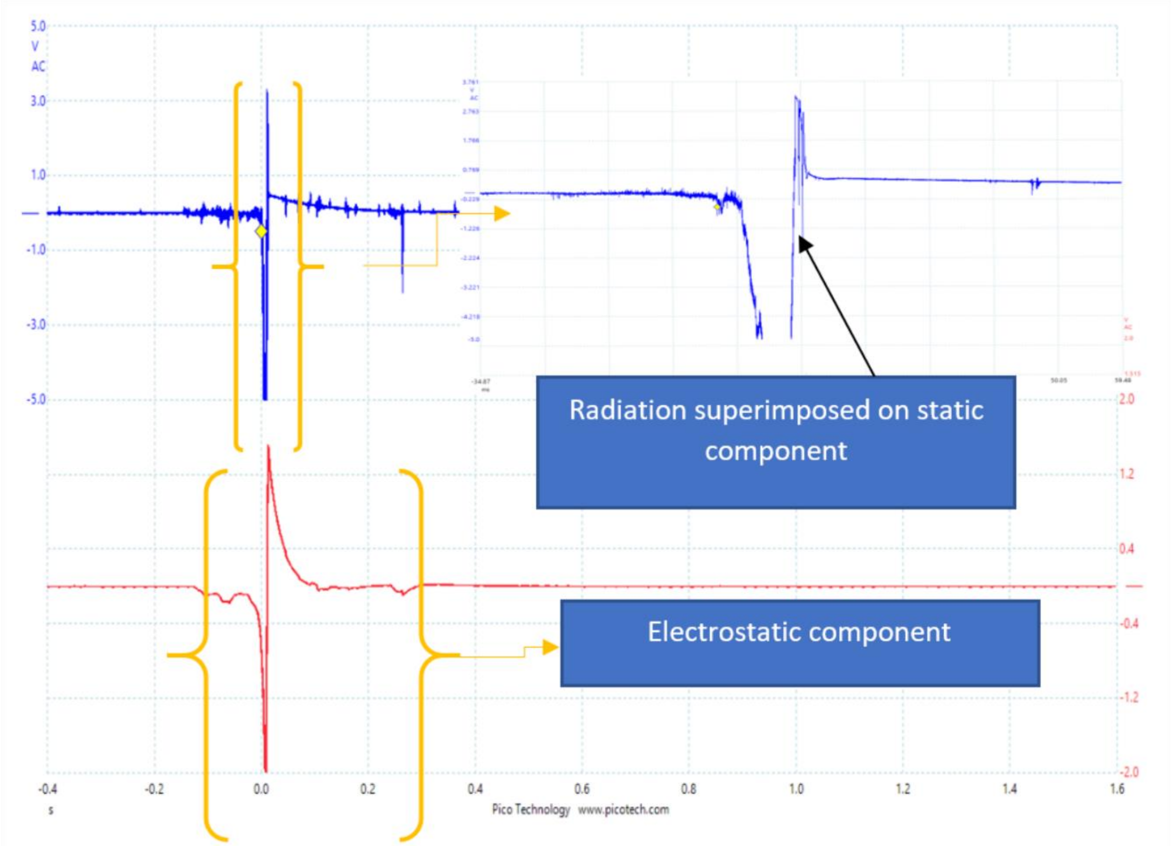

Figure 11. An example of –CG flash captured with radiation component superimposed on static component (top blue plot) and electrostatic component (bottom red plot)

As can be seen from the fast field waveform (blue plot) in Figure 11, the captured –CG flash was initiated by preliminary breakdown and followed by step leaders and return stroke superimposed on static field. These processes are essential part of a –CG flash [6]. Within reversal distance, the polarity of the emitted electric field is negative (atmospheric electricity sign convention) due to fact that the dominant field at this distance is electrostatic field even though the electric current flows upward [6]. Therefore, the polarity of the initial part of the slow field record (red plot) should be negative. This is clear evidence that FR4 copper plate antenna could detect lightning waveforms faithfully.

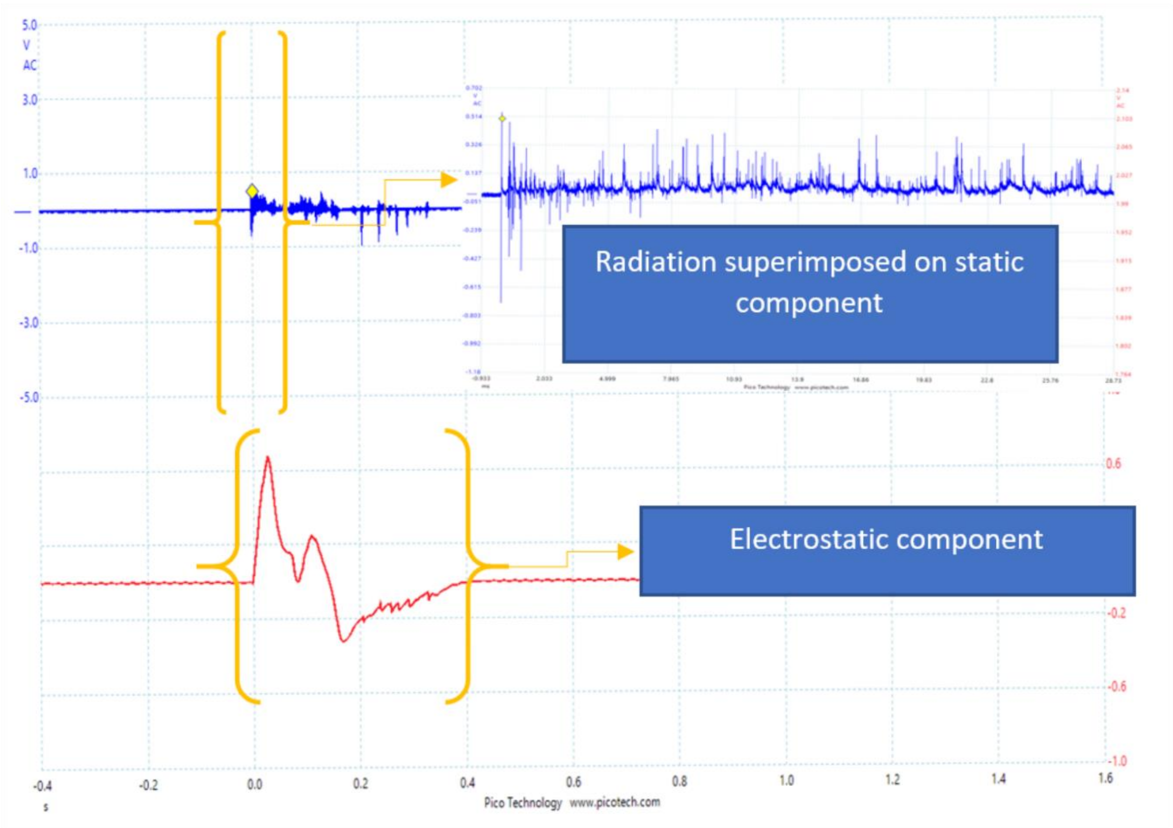

Figure 12. An example of IC flash captured with radiation component superimposed on static component (top blue plot) and electrostatic component (bottom red plot)

As can be seen from the fast field waveform (blue plot) in Figure 12, the captured IC flash was initiated by preliminary breakdown and followed by regular bipolar pulses. These processes are essential part of an IC flash [6]. Within reversal distance, the polarity of the emitted electric field is positive (atmospheric electricity sign convention) due to fact that the dominant field at this distance is electrostatic field even though the electric current flows upward [6]. Therefore, the polarity of the initial part of the slow field record (red plot) should be positive. This is clear evidence that FR4 copper plate antenna could detect lightning waveforms faithfully.

4. Conclusion

The aims of this paper is to design, simulate and fabricate FR4 A3 size antenna for wideband antenna system. The system has been simulated and fabricated successfully and had been deployed for real time measurement purpose. Therefore, the first aim has been achieved successfully. While, the second objective is to do comparison studies between metal parallel plate antenna and FR4 A3 size antenna. 100 lightning samples were captured and analysed with fast field antenna system for both antennas to evaluate the performance. The FR4 A3 size antenna is found to be suitable to replace the existing metal parallel plate antenna because it is light and easy to deploy at any places. So, the second objective has been achieved successfully.

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