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Wrap-around Cylindrical Printed Traveling Wave Passive Antenna for Experimental-Rocket Communication

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Abstract: This paper deals with the development of wrap-around cylindrical printed traveling wave passive antenna based on interdigital capacitor structure for experimental-rocket communication. The proposed antenna is intended to be used for 2.35MHz communication between an experimental rocket and the ground station. The antenna which has the dimension of 238.64mm x 22mm consists of 7 blocks of interdigital capacitor structure as antenna radiators and deployed on a grounded Roger RT/Duroid® 6010 dielectric substrate with the thickness of 0.127mm. The use of very thin dielectric substrate for antenna realization is aimed to have a conformable antenna which wraps around the cylindrical body of experimental rocket communication. After obtaining the optimum performance design, the proposed passive antenna is then realized through wet etching technique for experimental characterization. From the characterization result, it shows that the realized passive antenna resonates at center frequency of 2.375GHz with gain of -18.763dBi. This is comparable with the design one which has resonant frequency of 2.35GHz and gain of -19.996dBi.

Keywords: Passive antenna, experimental rocket, interdigital capacitor; traveling wave, wrap-around.

1. Introduction

The existence of antennas for air vehicles plays an essential role to ensure the interconnectedness of communication with the ground station. The antennas are also required for several purposes such as navigation, tracking, and telemetry. Due to the unique application, the design of antennas for air vehicle is much different compared with other applications. Some considerations should be taken into the design process to accomplish special requirements related to the utility of air vehicle. These also apply for unmanned air vehicle such as experimental-rocket for communication with the ground station. One of special requirements in the design of air vehicle antenna is that the shape of antenna should no disturbance to the aerodynamic system when the air vehicle is flying. Moreover, the antenna has also no disruption to the geometrical art of air vehicle. In addition, the antenna sometimes should able to be compounded together with other parts of experimental rocket in order to have more compact construction and to reduce extra materials.

A monopole antenna is the most antenna types that are commonly used for air vehicle communications [1]. Other than monopole antenna as well as its variations, there are more than 20 different antenna types suitable to be mounted on the body of air vehicle [2]. One of them which fit the special requirements is a traveling wave antenna [3]–[4]. The antenna which can be categorized as kind of microstrip antennas has many advantages compared to other types of antenna [5]–[6]. It is mainly developed based on microstrip technology and can be implemented from any kind of shapes of patch including a structure of interdigital capacitor. However, the dimension of microstip patch antenna is rather difficult to be shortened than a half-wavelength at desired operating frequency, since the patch of antenna only resonates at the

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order of half-wavelength [7]. Hece, some investigations to obtain more compact microstrip antenna dimension have been conducted intensively such as by utilizing artificial magnetic conductor (AMC) over the antenna, putting vertical transition between patches, and configuring the patch of antenna into a spiral shape [8]–[10]. In actual, a structure of interdigital capacitor has been used in the development of MMIC (Monolithic Microwave Integrated Circuit) [11]. Meanwhile for antenna application, the structure enables a compact antenna dimension since it has the size which is smaller than its wavelength [12].

By considering the merits as well as the demerits mentioned above, in this paper, a printed traveling wave passive antenna composed of interdigital capacitor structure is proposed to be used for experimental-rocket application. The proposed antenna is designed in a conformal shape to be a wraparound for the cylindrical body of experimental rocket. The antenna which is intended to work around center frequency of 2.35GHz for communication with the ground station is deployed on a very thin grounded Roger RT/Duroid® 6010 dielectric substrate. To satisfy the required specifications, some basic parameters including reflection coefficient, gain, and radiation pattern are used as performance indicator of the design. After the hardware realization, the measurement is carried out by performing an experimental characterization. Whilst the measured results of prototype antenna will be compared to the design ones in which the performance evaluation for each parameter will be presented consecutively.

2. Brief Overview of Interdigital Capacitor Structure

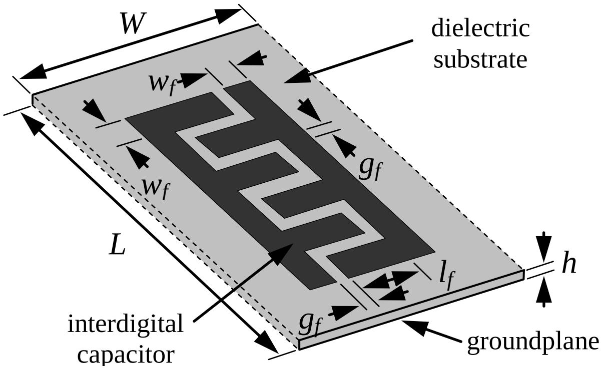


Figure 1. A unit cell of interdigital capacitor structure

As illustrated in Figure 1, a structure of interdigital capacitor unit cell is usually composed of a finger-shaped structure. The gaps between fingers can produce capacitance which ranges from 0.05pF to about 0.5pF depends on the dimension of gap [13]. The capacitance values which affects to the property of structure, i.e. resonant frequency, can be enlarged by increasing the number of fingers or by replacing the dielectric substrate with higher value of relative permittivity. One method to analyze the resonant frequency of interdigital capacitor is by modeling the structure into equivalent circuit as shown in Figure 2. The value of series capacitance (C) in pF for the structure is given by (1) [13],

$$C = (\varepsilon_r + 1) \cdot l \cdot [(N-3)A_1 + A_2] \tag{1}$$

where ε_r, l and N are the relative permittivity of dielectric substrate, the length of interdigital capacitor (in μm) and the number of finger in a unit cell of interdigital capacitor, respectively. Meanwhile, A_1 and A_2 are the capacitance values per unit cell (in pF/μm) of inner- and outerpart of interdigital capacitor, respectively, as expressed in (2) and (3) where h and w_f are thickness of dielectric substrate and finger width of interdigital capacitor, respectively.

$$A_1 = 4.409 \cdot \tanh\left[0.55 \cdot \left(\frac{h}{w_f}\right)^{0.45}\right] \cdot 10^{-6} \tag{2}$$

$$A_2 = 9.92 \cdot \tanh\left[0.52 \cdot \left(\frac{h}{w_f}\right)^{0.5}\right] \cdot 10^{-6} \tag{3}$$

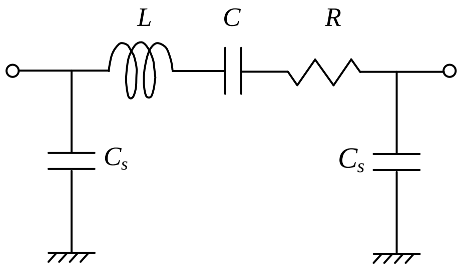


Figure 2. An equivalent circuit of interdigital capacitor

Furthermore, the value of series resistance (R) in Ohm, series inductance (L) in μH, and shunt capacitor (C_s) in μF for the structure are given by (4), (5), and (6), respectively, where R_s, Z_0, ε_{eff} and c are the surface resistance of interdigital capacitor, the impedance of interdigital capacitor, the effective permittivity of dielectric substrate, and the speed of light in free space, respectively. Here, Z_0 and ε_{eff} are parameters of microstrip line and can be calculated using microstrip line equations in [13].

$$R = \frac{4}{3}\frac{l}{w_f N} R_s \tag{4}$$

$$L = \frac{Z_0\sqrt{\varepsilon_{eff}}}{c} l \tag{5}$$

$$C_s = \frac{\sqrt{\varepsilon_{eff}}}{2Z_0 c} l \tag{6}$$

3. Wrap-around Cylindrical Printed Traveling Wave Passive Antenna

A. Simulation of Interdigital Capacitor Unit Cell

Prior the design of wrap-around cylindrical printed traveling wave passive antenna, at first some parametric studies by varying the physical parameter of interdigital capacitor unit cell are investigated through simulation. By using the configuration of interdigital capacitor unit cell shown in Figure 1, the initial design was made to follow the shape of proposed antenna design and the value of physical parameters of the interdigital capacitor unit cell. Each unit cell is designed on a grounded dielectric substrate in which the investigated physical parameters include the variation of finger length, finger width and finger gap. These attempts are conducted based on the nature characteristic of unit cell that usually produces larger shunt capacitance and smaller series inductance in connection with the ratio between finger length and finger width of interdigital capacitor.

With the model of interdigital capacitor unit cell, the resonant frequency occurs around a quarter wavelength. This resonance appears due to the coupling effect between the fingers, and occurs when the configuration of interdigital capacitor has the number of finger more than 3 pieces [14]. To achieve the resonant frequency around 2.35GHz required for proposed printed traveling wave passive antenna, based on the theoretical calculation above the initial dimension of finger length (l_f), finger width (w_f) and finger gap (g_f) is set to be 5.1mm, 1.4mm and 0.95mm, respectively. Whilst the dimension of each unit cell deployed on a grounded Roger RT/Duroid® 6010 dielectric substrate with the dielectric constant of 10.9 and the thickness of 0.127mm is 8.85mm (length) by 21.15mm (width). The use of very thin dielectric substrate with high relative permittivity in the design is intended to have the design of printed traveling wave passive antenna to be conformable and in a compact size.

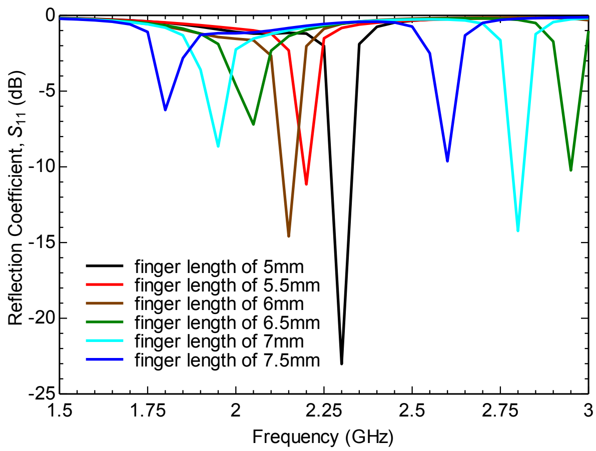


Figure 3. Effect of finger length (l_f) variation to resonant frequency

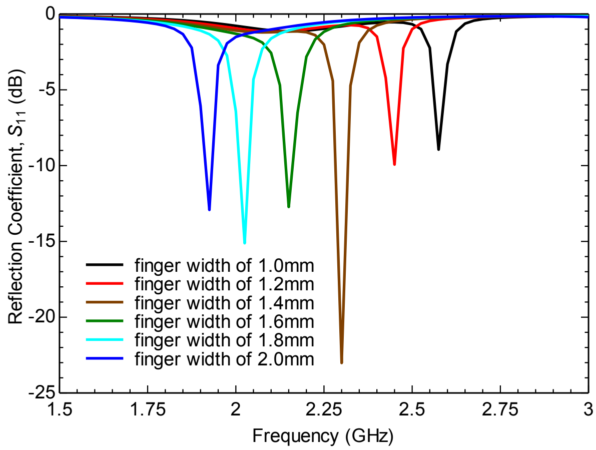


Figure 4. Effect of finger width (l_f) variation to resonant frequency

Simulation results of parametric studies related to the parameters variation of interdigital capacitor unit cell are plotted in Figures 3 – 5 for the relationship between the finger length, finger width and finger gap to the resonant frequency, respectively. It shows from Figure 3 that the longer the finger of interdigital capacitor unit cell the lower resonant frequency is obtained. Furthermore, as plotted in Figure 4 the influence of finger width produces an inverse relationship of resonant frequency. Meanwhile, from Figure 5 it can be observed the capacitance value of interdigital capacitor unit cell for the length and width of enlarged finger in which the capacitance value becomes larger for smaller finger gap affecting the increase of resonant frequency.

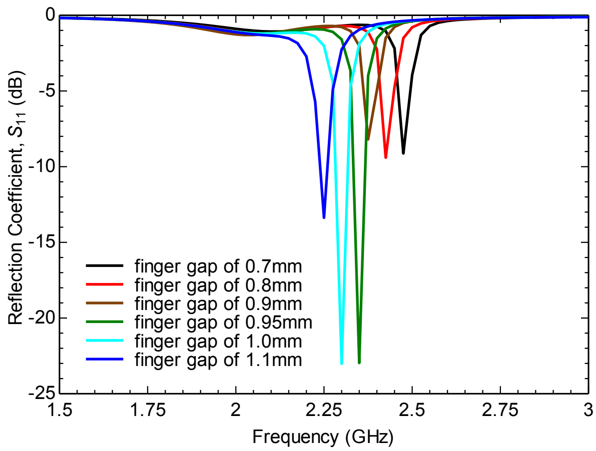


Figure 5. Effect of finger gap (g_f) variation to resonant frequency

B. Design of Wrap-around Cylindrical Printed Traveling Wave Passive Antenna

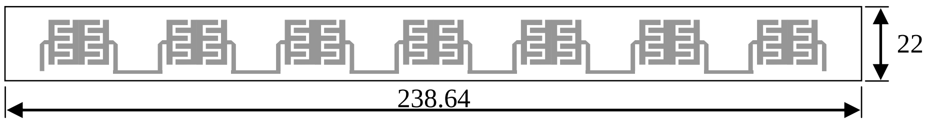


Figure 6. Rough sketch of wrap-around cylindrical printed traveling wave passive antenna (unit in *mm*)

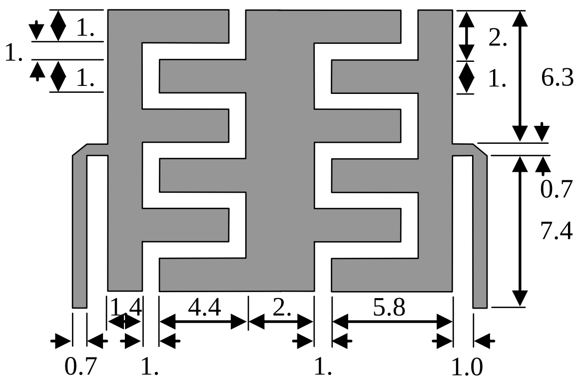


Figure 7. Geometry of each block of interdigital capacitor (unit in *mm*)

Based on the simulation results of interdigital capacitor unit cell, a wrap-around cylindrical printed traveling wave passive antenna is designed with some modification on a number of unit cells as shown in Figure 6. The proposed antenna has total dimension of 238.64mm (length) by 22mm (width) in which the length is designed to fit 76mm diameter of experimental rocket body. The antenna which is intended to operate around center frequency of 2.35GHz for experimental rocket communication is designed on the top side of grounded high permittivity dielectric substrate of Roger RT/Duroid® 6010 with the relative permittivity of 10.9 and the thickness of 0.127mm. It shows that the antenna consists of 7 blocks of interdigital capacitor structure connected each other with a microstrip line in which the thickness of copper metal for interdigital capacitor structures on the top side as well as for groundplane on the bottom side is 0.035mm. The geometry of each block of interdigital capacitor structure which gives the resonant frequency of 2.35MHz is shown in Figure 7.

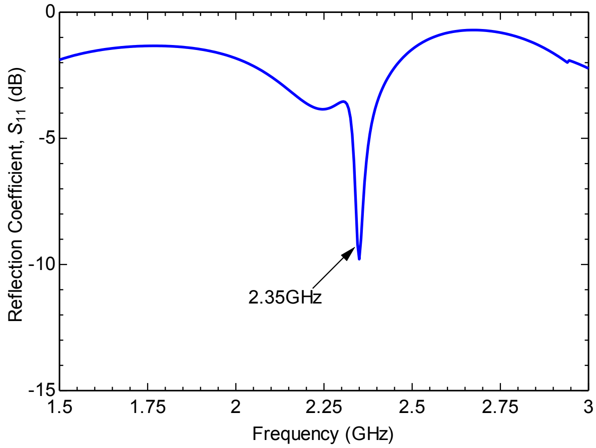


Figure 8. Simulated result of reflection coefficient for wrap-around cylindrical printed traveling wave passive antenna

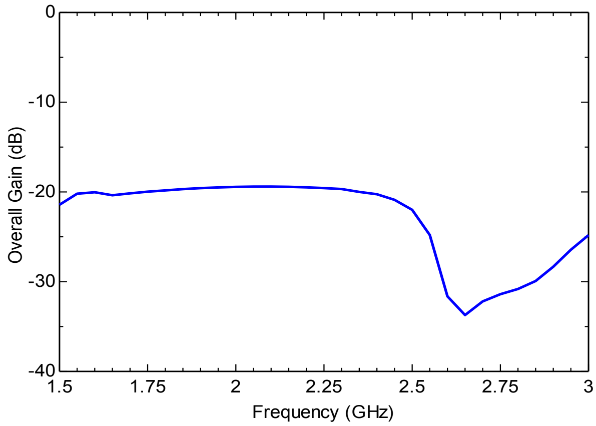
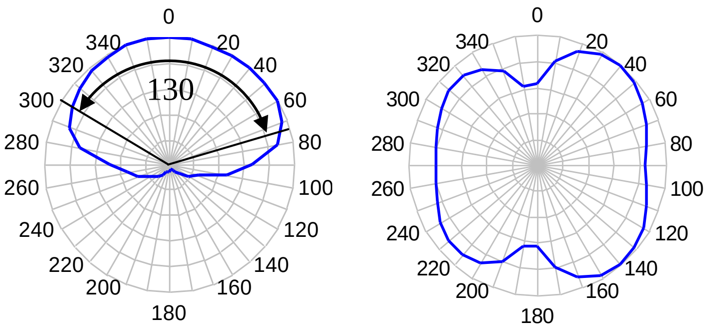


Figure 9. Simulated result of overall gain for wrap-around cylindrical printed traveling wave passive antenna

Moreover, since the proposed antenna is a traveling wave antenna type, hence to feed the antenna, an SMA connector is attached at one of the antenna ports and the other port is connected to a 50 Ohm load resistor. While to achieve an accurate analysis, the copper conductive loss of patch and ground plane as well as the substrate dielectric loss are accounted for the simulation. Figures 8, 9, 10 plot the simulation results of reflection coefficient, overall gain and radiation pattern, respectively. From Figures 8 and 9 it shows that the operating frequency of proposed wrap-around cylindrical printed traveling wave passive antenna is 2.35GHz with the gain achievement of -19.996dBi. The low-gain of antenna is mostly evoked by the 50 Ohm load resistor at the end-port of antenna where it absorbs some amount of incoming energy that should be radiated. Whereas the *E*-plane radiation pattern shown in Figure 10 has maximum directivity at 0^{o} and half power beamwidth (HPBW) of 130^{o}.



(a) *E*-plane (b) *H*-plane

Figure 10. Simulated result of radiation pattern for wrap-around cylindrical printed traveling wave passive antenna

4. Fabrication and Measurement

Figure 11. Fabricated wrap-around cylindrical printed traveling wave passive antenna

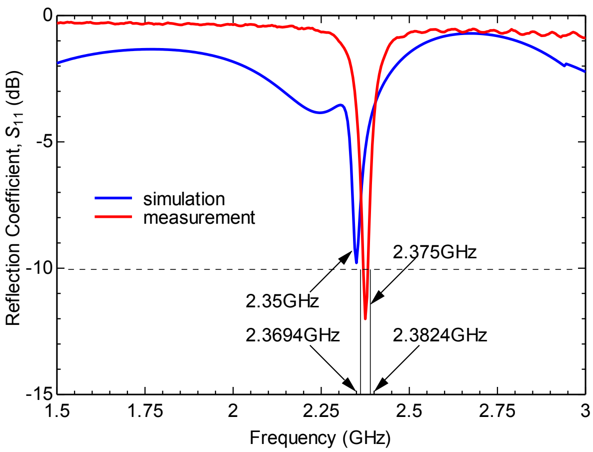


Figure 12. Measured and simulated results of reflection coefficient for wrap-around cylindrical printed traveling wave passive antenna

After obtaining the optimum design, the proposed wrap-around cylindrical printed traveling wave passive antenna is realized through wet etching technique. Figure 11 shows the picture of fabricated antenna deployed on RT/Duroid® 6010 dielectric substrates which is mounted on the dummy of experimental-rocket body for experimental characterization. The measurement results of experimental characterization for reflection coefficient, gain and radiation pattern are depicted in Figures 12, 13 and 14, respectively, with the simulation result for each corresponding parameter plotted together as comparison.

It clearly shows from Figure 12 that the operating frequency of fabricated wrap-around cylindrical printed traveling wave passive antenna is which is 25MHz higher than simulation result, i.e. 2.375GHz. The measured -10dB working bandwidth of fabricated antenna is 13MHz ranges from 2369.4–2382.4MHz. The discrepancy between experimental characterization and design results is probably caused by the different value of relative permittivity of dielectric substrate used in the fabrication and the simulation. It should be noted that the relative permittivity of dielectric substrate in the simulation is set to be 10.9 which is assumed to be uniform for all frequency ranges.

Furthermore, due to the small size aperture of interdigital capacitor structures, the gain of fabricated antenna as depicted in Figure 13 is low around -18.763dBi at working frequency of 2.375GHz, while the simulation result is -19.996dBi at working frequency of 2.35MHz. The different gain between measurement and simulation results is mostly affected by the different value of losses of dielectric substrate. As depicted in Figure 14, the radiation patterns of fabricated antenna have good agreement qualitatively for both planes with the simulation results. It is seen that the measured radiation pattern for *E*-plane has maximum directivity at 350^{o} and HPBW of 90^{o}.

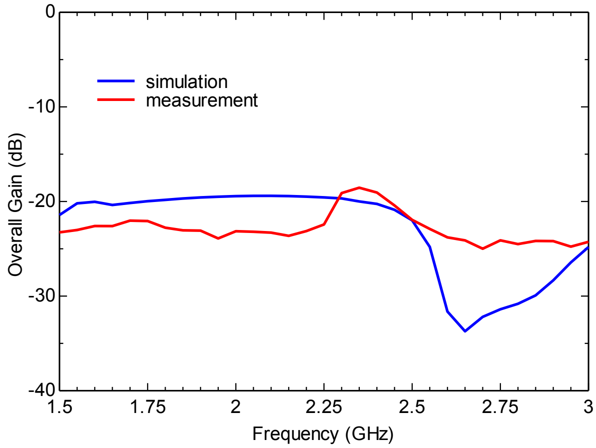


Figure 13. Measured and simulated results of overall gain for wrap-around cylindrical printed traveling wave passive antenna

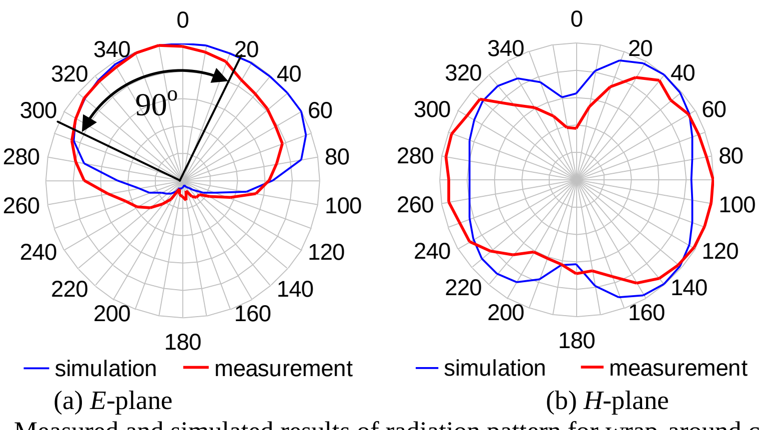


Figure 14. Measured and simulated results of radiation pattern for wrap-around cylindrical printed traveling wave passive antenna

5. Conclusion

The development of wrap-around cylindrical printed traveling wave passive antenna composed of interdigital capacitor structures has been presented and demonstrated experimentally. The proposed antenna with the dimension of 238.64mm x 22mm has been designed using 7 blocks of interdigital capacitor structure as antenna radiators and deployed on a grounded Roger RT/Duroid® 6010 dielectric substrate with the thickness of 0.127mm. The use of interdigital capacitor structures deployed on a very thin dielectric substrate with high relative permittivity have been implemented to produce a conformal printed traveling wave passive antenna in compact size which fits the cylindrical body of experimental-rocket. It has been demonstrated that the fabricated antenna has had operating frequency of 2.375GHz with gain of -18.763dBi and -10dB working bandwidth of 13MHz. Meanwhile the simulation results have shown that the proposed antenna has resonated at center frequency of 2.35GHz with gain of -19.996dBi. Although there were discrepancies in some results, however it has been shown that the fabricated antenna were coincided with the simulation ones and suitable for communication between an experimental-rocket and the ground station.

6. References

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