Communications

A Short Open-End Slot Antenna With Equivalent Circuit Analysis

Yu-Shin Wang and Shyh-Jong Chung

***Abstract*—A novel configuration is described for a compact microstrip-line fed slot antenna which is shorter than one-eighth wavelength at the operating frequency. Antenna size is reduced by placing two matching capacitors at both sides of an electrically small open-end slot, through the use of a wideband antenna equivalent circuit model established by considering the physical geometry. With the proposed antenna configuration, a 2.45 GHz slot antenna is first designed using an open-end slot of size 9 mm by 1.5 mm that is originally resonant at 4.8 GHz in a conventional design. Experimental results correlate well with those of the full-wave simulation and the equivalent circuit calculation, which shows a bandwidth of 109 MHz and peak gain of 1.89 dBi. By using the same slot size, several slot antennas operating at even lower frequencies (1.9, 1.64, 1.57 GHz) are then designed and demonstrated. Nearly omni-directional radiation patterns with peak gains 0 dBi and radiation efficiencies larger than 45% are obtained. Given its simplicity and compactness, the proposed electrically small antenna is feasible for circuit integration and highly promising for wireless mobile devices.**

***Index Terms*—Antenna equivalent circuit, electrically small antenna, slot antenna.**

I. Introduction

Electrically small antennas have received considerable attention for mobile communication. Additionally, accelerated growth of wireless communications in recent decades has increased the demand for mobile devices and the subsequent miniaturization of their size. Moreover, the increasing demand for miniaturized wireless products necessitates compact antenna designs with a high circuitry integration capability. Therefore, the miniaturization of various antennas, including slot ones, have received considerable interest.

The conventional approach to miniaturizing a slot antenna is to spiral it while maintaining the required resonant length [1]–[3], i.e., a half wavelength for a short-circuited to short-circuited slot or a quarter wavelength for a short-circuited to open-circuited slot (herein called open-end slot). Other methods are available to reduce the slot length. In [4], a meandered slot with open ends shows its compactness. In [5], a slot ring was miniaturized based on fractal geometry. Although these approaches reduced the antenna area, the required total electrical length along the slot remained unchanged. In [6], the size of a microstrip-fed slot antenna was reduced by using a dumbbell shape as inductive loading and a cantilever shape on center providing a capacitive loading, subsequently reducing the size by 52.9% with a bandwidth of 2.8%. Also, a previous work [7] developed a capacitor-loaded folded slot line for antenna miniaturization. Above examples used higher density routing or reactive loading for their traces to ensure that the antennas could achieve the required electrical lengths at the operation frequency in smaller sizes. The electrical lengths of these antennas are typically near quarter or half the wavelength for resonance. Our recent work devised a compact slot antenna design using a right/left-handed transmission line feed [8]. Antenna resonance was achieved by balancing the positive and negative phase delays of the equivalent right- and left-handed transmission lines.

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The authors are with the Department of Communication Engineering, National Chiao Tung University, Hsinchu, Taiwan 30050, R.O.C. (e-mail: sjchung@cm.nctu.edu.tw).

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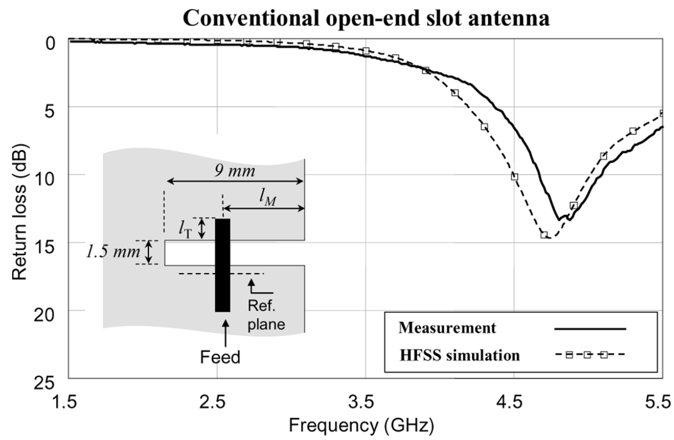


Fig. 1. Configuration of a conventional microstrip-line fed open-end slot antenna and its simulated and measured return losses. $l_T = 1.1$ mm, $l_M = 5$ mm. Ground plane size $= 65 \times 42$ mm^2.

Microstrip-fed slot antennas have been developed for quite some time, and many circuit models can explain the antenna performance [1]. In addition to understanding the antennas operation, the circuit models but may also facilitate the miniaturization design. The miniaturization design in this work involves a radiating open-end slot. This problem is resolved by initially considering a conventional open-end slot antenna (inset of Fig. 1). For a conventional open-end slot antenna, the operation frequency is determined by the slot length, which is generally a quarter wavelength. An open-end microstrip line is conventionally adopted to feed the antenna through electromagnetic coupling. Impedance matching for this structure can be controlled by the length of open stub, l_T, and the feeding position, l_M. Fig. 1 shows the measured and simulated return losses of this conventional slot antenna. Here, the slot antenna is designed on an FR4 substrate with a thickness of 0.4 mm, a dielectric constant of 4.5, and a loss tangent of 0.03. The slot size is 9 mm by 1.5 mm with a ground plane size of 65 mm by 42 mm, $l_T = 1.1$ mm and $l_M = 5.38$ mm. Experimental results indicate that the 9 mm long slot is resonant at a frequency around 4.8 GHz. This length is approximately a quarter wavelength for a slot line at 4.8 GHz. To achieve miniaturization design, this work attempts to use the identical slot in order to design an antenna operating at a frequency lower than half the natural resonant frequency, i.e., a slot antenna with a shorter than one-eighth the effective wavelength at the operation frequency.

This work achieves the miniaturization design using the equivalent circuit approach. An equivalent circuit is established in prior, that exhibits resonance at the antenna's operation frequency. The proposed antenna is directly synthesized from the equivalent circuit instead of the simulation iteration in full wave analysis. In the proposed design, the circuit model of a short slot radiator is initially extracted. By using

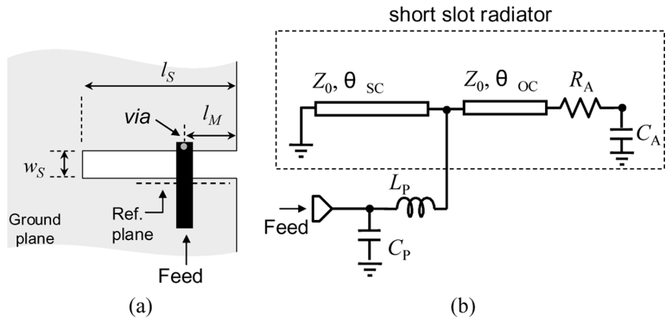


Fig. 2. (a) Configuration of an open-end slot antenna fed by a short-circuited microstrip line and (b) the corresponding equivalent circuit model. $Z_0 = 140\ \Omega$, $\theta_{OC} + \theta_{SC} = 39^\circ$ as referred to 2.45 GHz, $R_A = 650\ \Omega$, $C_A = 0.12$ pF, $L_P = 0.5$ nH, and $C_P = 0.04$ pF.

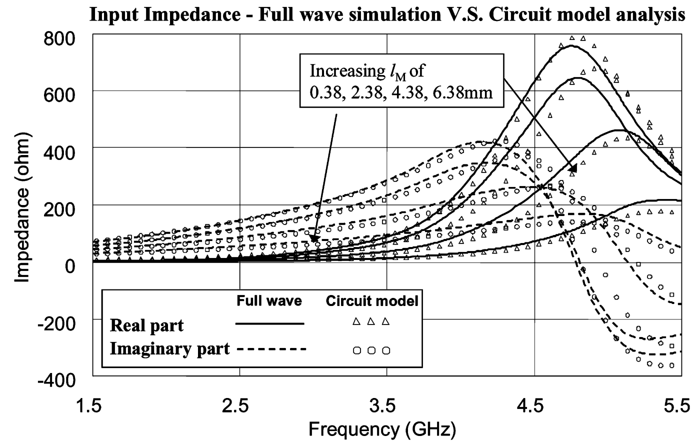


Fig. 3. Input impedances for different l_M, obtained from (a) the full wave simulation and (b) the equivalent circuit model.

this model, the slot can be treated as a circuit element that can be matched for resonance. The rest of this communication is organized as follows. Section II describes the circuit model of a short open-end slot, Section III then presents the synthesis of less than one-eighth the wavelength slot antenna by using the equivalent circuit. Next, Section IV summarizes the experimental results. Conclusions are finally drawn in Section V, along with recommendations for future research.

II. Equivalent Circuit of an Open-End Slot

Antenna design first requires considering the extraction of the equivalent circuit model for a short open-end slot. Fig. 2(a) depicts the geometry of an open-end slot fed by a microstrip line. Notably, to obtain the exact model, the microstrip fee line is short-circuited to the ground by a via immediately after passing the slot. The slot line has a length of $l_S = 9$ mm and width of $w_S = 1.5$ mm on a ground plane with a size of 65 mm by 42 mm. The distance between the center of microstrip and ground edge is l_M, i.e., the feeding position of the slot. The thickness of the FR4 substrate is 0.4 mm, the width is 50 Ω, and the microstrip feed line is 0.76 mm. Fig. 2(b) illustrates the corresponding equivalent circuit model, as determined by considering the physical geometry of the slot. Each circuit component represents one part of the slot. The slot line is modeled using the transmission line sections in the equivalent circuit, of which the electrical length θ_{OC} is related to l_M and θ_{SC} is related to the electrical distance from the short end to the feeding position. Notably, this transmission line model is only appropriate for a narrow slot antenna as in this work. For a wide slot, the equivalent circuit should consider additional parasitic effects. Where L_p and C_p refer to the parasitic series inductance and shunt capacitance produced when the microstrip line passes across the slot. Additionally, L_p also includes the parasitic inductance of the grounding via. Notably, the resistive impedance over a wide frequency bandwidth is modeled using R_A together with C_A, in which C_A is also related to the fringing field capacitance at the open end of the slot line. The model parameters use a frequency independent value to simplify the analysis. Moreover, all of the resistive effects, i.e., the radiation resistor, metal ohmic loss, and dielectric loss, are covered using R_A. R_A describes only overall input resistance to facilitate impedance matching. The values of circuit elements are extracted based on EM simulation results. The electrical length and characteristic impedance of the slot line can be obtained by individual simulation the slot line. The parasitic inductance L_p can be initiated estimating the partial inductances of a strip with length w_S and the grounding via. Other circuit components, C_p and C_A, are then exacted by curve-fitting.

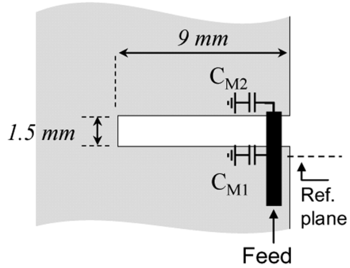
The curve-fitting method is adopted for the circuit model to fit the full wave simulation result ($l_M = 0.38$ mm). Because the proposed antenna operates in the lower frequency band (lower than resonant frequency of the slot), the criteria are set to achieve minimum mean absolute difference in the lower frequency band (2–4 GHz) with unit weighting and in the higher frequency band around 4–5 GHz with smaller weighting (0.2).

This work performs simulation using commercial tools, Ansoft HFSS and AWR MWO. Circuit parameters are extracted as follows: characteristic impedance $Z_0 = 140\ \Omega$, $\theta_{OC} + \theta_{SC} = 39^\circ$ as referred to 2.45 GHz, $R_A = 650\ \Omega$, $C_A = 0.12$ pF, $L_p = 0.5$ nH, and $C_p = 0.04$ pF. The equivalent circuit is examined by making several comparisons with different feeding positions l_M from 0.38 to 6.38 mm). The corresponding θ_{OC} in the equivalent circuit are 1.7°, 10.2°, 18.8°, and 27.5° for l_M equal to 0.38, 2.38, 4.38, and, 6.38 mm, respectively. The values of $(\theta_{OC} + \theta_{SC})$, Z_0, R_A, C_A, l_p,and C_p in all the calculations remain unchanged since the identical slot size is used. Fig. 3 shows the input impedances of the antenna with different l_M obtained from the full-wave simulation and equivalent circuit calculation. The results of the circuit calculation appear to agree with those of the full-wave simulation over a wide bandwidth from 1.5 GHz to 5.5 GHz. A slight discrepancy is found, especially in a higher frequency range because curve fitting for the circuit model emphasizes a lower frequency range. Calculation results further indicate that the slot resonates around 5 GHz, whereas the reactance curves change from inductive to capacitive as the frequency increases. As expected, the short slot provides inductive reactance at low frequencies.

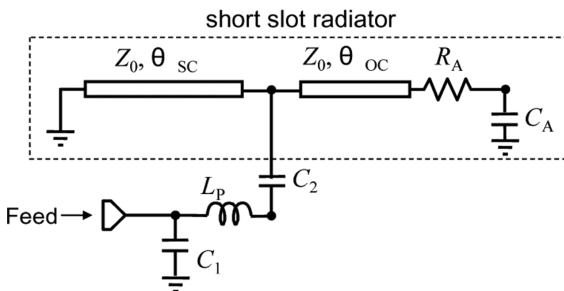
III. Shorter Than One-Eighth Wavelength Slot Antenna

An antenna operating at a frequency lower than the nature resonant one based on the same slot size (9 mm by 1.5 mm) can be designed by adding capacitive loading to the slot for canceling the inductive reactance of the slot at the lower frequency. Therefore, this work presents a antenna configuration (Fig. 4(a)), which contains a slot radiator fed by a microrstrip line at the open end of the slot, and the matching circuits C_{M1} and C_{M2}. As is demonstrated later, appropriately designing the matching components allows the antenna to operate at a frequency lower than half the natural resonant frequency of the slot, i.e., at a frequency lower than 2.5 GHz. This finding implies that the antenna length is shorter than one-eighth the wavelength at the operation frequency. Notably, the capacitors C_{M1} and C_{M2} can be realized by using lumped elements or printed capacitors on the substrate. Compared with an ordinary microstrip-fed slot antenna (Fig. 1), the proposed structure provides an additional matching capacitor C_{M1} at the antenna input.

To explore the resonance mechanism of the proposed antenna, we first establish the corresponding equivalent circuit as shown in



(a)



(b)

Fig. 4. (a) Configuration of the proposed slot antenna with length shorter than one-eighth wavelength and (b) the corresponding equivalent circuit. $Z0 = 140\ \Omega$, $\theta_{OC} + \theta_{SC} = 39^\circ$ as referred to 2.45 GHz, $R_A = 650\ \Omega$, $C_A = 0.12$ pF, $L_P = 0.5$ nH, $C_1 = 2.2$ pF, and $C_2 = 0.6$ pF (C_1 and C_2 using Murata GRM1555C1H2R2CZ01 and GRM1555C1HR60CZ01 model).

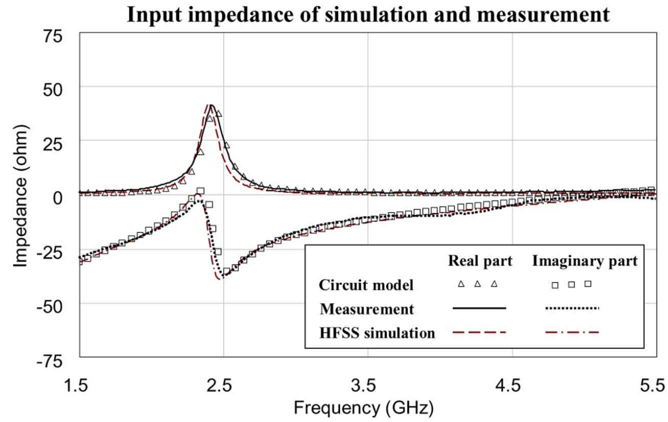


Fig. 5. Comparison of the input impedances from the circuit model calculation, full-wave simulation, and measurement for the 2.45 GHz electrically small slot antenna.

Fig. 4(b), where the short-circuited transmission line with $R_A - C_A$ termination represents, as before, the slot radiator. The capacitor C_2 equals C_{M2}, and $C_1 = C_{M1} + C_p$, which is dominated by C_{M1} since the parasitic capacitor C_p is much smaller. L_p is still the parasitic inductor related to the microstrip section over the slot and the grounding via. Since the slot is the same as before and the same grounding via is used, the corresponding equivalent circuit components can be reused here, i.e., $R_A = 650\ \Omega$, $C_A = 0.12$ pF, and $L_p = 0.5$ nH. And because the slot is fed near the open end, using $l_M = 0.5$ mm, and thus $\theta_{OC} = 2.17^\circ$, which results in $\theta_{SC} = 36.83^\circ$ at 2.45 GHz. (Note that $\theta_{OC} + \theta_{SC} = 39^\circ$ at 2.45 GHz.)

After determining the circuit parameters of the slot radiator, we first design the values of C_1 and C_2 to obtain a slot antenna operating at 2.45GHz. In order to have accurate result for experiment, C_1 and C_2 employ the models in MURTA chip capacitor library [9]. C_1 and C_2 choose the capacitors of 0.6 pF and 2.2 pF (part no. GRM1555C1HR60CZ01 and GRM1555C1H2R2CZ01 in Murata library) to have best matching at 2.4GHz. Fig. 5 shows the antenna's input impedances calculated from the equivalent circuit model and the HFSS full-wave simulation. The results agree with each other over a wide frequency bandwidth, which verifies the feasibility of the circuit model. To implement the antenna, two Murata SMD chip capacitors with $C_{M1} = 2.2$ pF and $C_{M2} = 0.6$ pF (capacitors using the same part number as the model analysis) are used. A coaxial cable is used to connect the 50 Ω microstrip feed line for measurement. Fig. 5 also shows the measurement result as a comparison to the simulation one from HFSS. The results agree to others in the whole frequency band. The antenna is resonant at 2.45 GHz, with a measured return loss of 17 dB and 10-dB return-loss bandwidth of 109 MHz (4.4%). Comparing to the result of a conventional slot antenna shown in Fig. 1, it is evident that the proposed antenna operates at a frequency only half that of the conventional one, although both antennas use the identical slot. Since the conventional slot antenna exhibits a quarter-wavelength resonance, the proposed slot antenna with the present design is thus only one-eighth wavelength long at the operation frequency. Fig. 6 shows the measured radiation patterns in the principal planes at 2.45GHz. Omni-directional patterns are obtained due to the short slot radiator. The measured peak gain of 1.89 dBi occurs at the broadside direction (z-axis). The averaged gains are -3.8 dBi, -1.1 dBi and -1.2 dBi in the *xy*-, *xz*-, and *yz*-plane respectively. It is noted that in the *yz*-plane, the radiation pattern is composed of E_θ and E_ϕ components with similar levels. The E_θ component is contributed mainly by the vertical current flowing along the ground edge (in the y direction) and partly by the equivalent magnetic current along the short slot. And the E_ϕ component is produced by the horizontal currents along the upper and lower ground edges (in the x direction). These two horizontal currents come out from the vertical ground edge current and have opposite current directions, thus result in an out-of-phase two-element array pattern like the inverted digit-8 solid-curve pattern in the *yz* plane. It is also noticed that there are two radiation nulls in the *xy* plane, which may be resulted from the interference of the radiation fields from these vertical and horizontal ground edge currents. The nulls in the *xy* plane also cause lower averaged gain in the *xy* plane than other planes.

Through the equivalent circuit approach, the resonance of the synthesized antenna is caused from the circuit resonance formed by the reactive elements including the inductive slot and chip capacitors. The resonant frequency is determined by the values of these components only, which means that the frequency should be stable against the variation of the ground size. To examine this, the designed antenna is fabricated on ground planes with different sizes: USB dongle size (20 mm by 50 mm), medium size (40 mm by 70 mm), and panel size (170 mm by 250 mm). The slots are located on the short edge. The slot size (9 mm by 1.5 mm) and the matching components are kept the same. Although not shown here, the frequency responses of the measured return losses are almost the same for the identical antenna designed with different ground sizes. The resonant frequencies of these antennas are unchanged and located at 2.45 GHz. This demonstrates the stability of the antenna resonance for different applications. Nevertheless, due to the re-distribution of the ground edge currents, the radiation pattern has little variation when the ground size changes.

As presented above, we have demonstrated a 2.45 GHz slot antenna with a slot of nature resonant frequency at 4.8 GHz. Based on the proposed antenna configuration, the same slot can even be designed to operate at a lower frequency. Considering the antenna equivalent circuit in Fig. 4(b), the circuit configuration can be re-arranged as in Fig. 7, where the positions of the series components, C_2 and L_p, are exchanged. Then, the circuit configuration turns into a series capacitor and shunt capacitor matching scheme. With this matching scheme, the

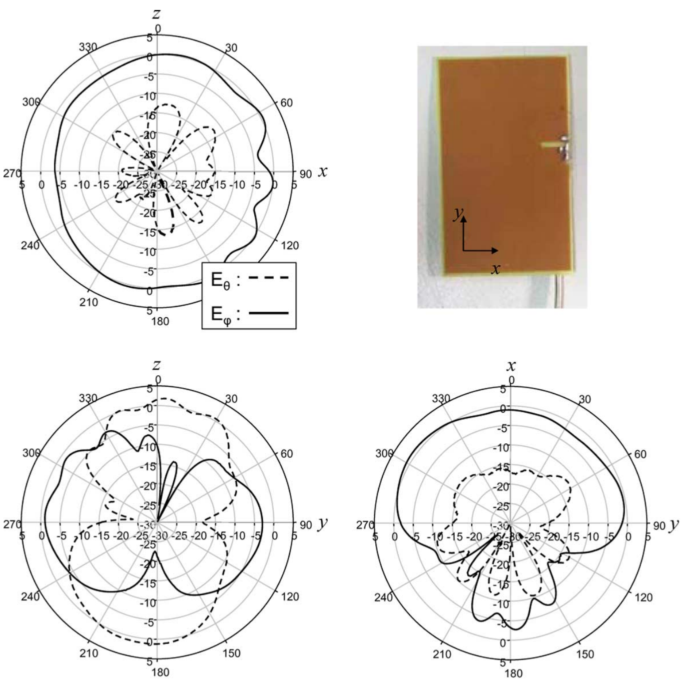


Fig. 6. Measured radiation patterns of the proposed antenna at 2.45 GHz.

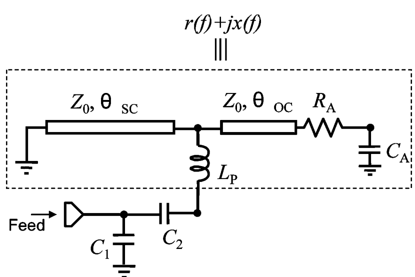


Fig. 7. A new antenna equivalent circuit by exchanging the positions of the series components, C_2 and L_p, in the original equivalent circuit shown in Fig. 4(b).

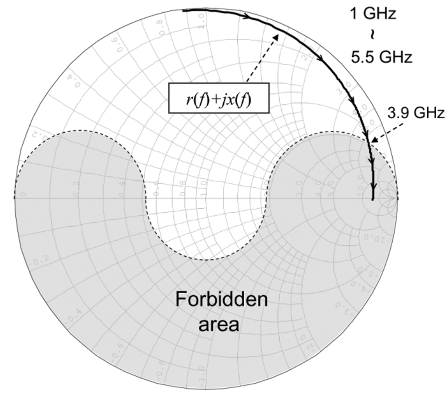
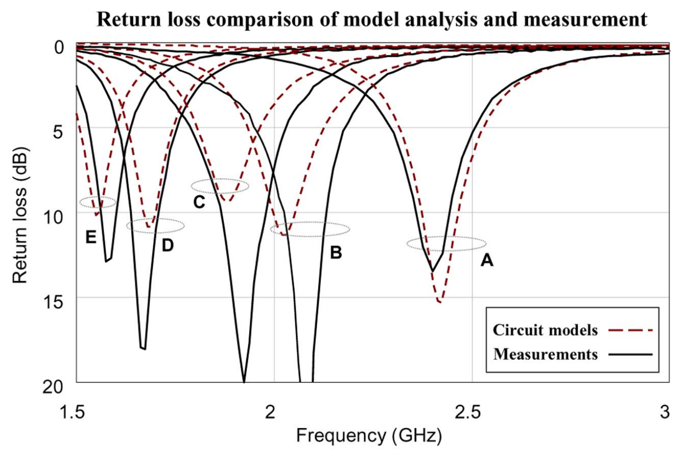


Fig. 8. The forbidden region for series-C/ shunt-C matching scheme as referred to 10-dB return loss. The curve of $r(f) + jx(f)$ is calculated from the circuit model of Fig. 7, with component values the same as those in Fig. 4(b).



	A	B	C	D	E
C_{M1} (pF)	0.6	1.0	1.2	1.5	1.8
C_{M2} (pF)	2.2	2.4	2.7	3.9	4.7

Fig. 9. Measured return losses of antennas using the same slot size (9 mm by 1.5 mm) while with different capacitors C_{M1} and C_{M2}.

antenna can operate at other frequencies as long as the input impedance $r(f) + jx(f)$ of the open slot located outside the forbidden area as shown in Fig. 8. Here, the forbidden area is defined so that the total input return loss is no better than 10 dB for any possible values of the matching capacitors C_1 and C_2. It can be found that the impedance matching can be achieved over almost the upper half plane of the Smith chart. This means that the slot radiator, with the proposed configuration, can be matched to operate at almost any frequency as long as the slot possesses an inductive reactance at that frequency. The required value of C_1 and C_2 can also be estimated through equivalent circuit model. It is noticed here that the accuracy of the circuit model over the frequency range for antenna operation is necessary for correctly synthesizing the antenna.

Fig. 9 shows the return losses from the measurement and the circuit model calculation for antennas using the same slot size (9 mm by 1.5 mm) while with different chip capacitors C_{M1} and C_{M2}. The table in the Fig. 9 illustrates the final capacitor values used for the five antennas. The size of ground plane is 65 mm by 42 mm. In the equivalent circuit calculation, the capacitor model in Murata library (GRM 0402 series) is used for C_1 and C_2. While during the measurement, the values of these capacitors are initially obtained through the equivalent circuit and then fine tuned for a better impedance matching. The measured return losses show good agreement with the calculated ones. The circuit model analysis predicts quite well about the resonant frequency of the antenna, which helps to speed up the antenna design. The result also shows that the short slot is capable to operate in the lower frequency range by varying the capacitors. Since the same slot size is used, the corresponding electrical length of the slot is thus shorter when the operating frequency is designed lower. For example, for the 1.64 GHz antenna (antenna E), the slot is only 0.05 free-space wavelength.

As the antenna becomes electrically smaller, the radiation efficiency of the antenna may deteriorate [10]. Fig. 10 shows the measured radiation patterns in the yz-plane of the designed antennas at 2.45 GHz, 1.9 GHz, and 1.64 GHz. The peak gains of the antennas are all higher than 0 dBi and occur at the broadside direction (z-axis). Notably, the patterns are similar and are near omni-directional since the antennas are all electrically small ones. The radiation efficiencies of the antennas are also measured using a SATIMO 3D antenna measurement system. The efficiencies are 69% at 2.45 GHz, 50% at 1.9 GHz, and 45% at 1.64 GHz. The radiation efficiency decreases as the operation frequency becomes lower.

IV. Conclusion

This work has described a microstrip-line fed open-end slot antenna with a new impedance matching scheme, which is composed of an

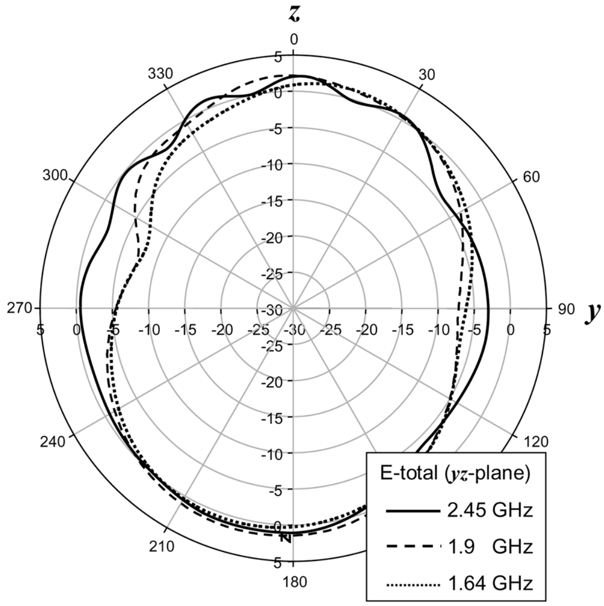


Fig. 10. Measured radiation patterns in the *yz* plane of the antennas at 2.45 GHz, 1.9 GHz and 1.64 GHz.

electrically small slot antenna and two matching capacitors placed at the two sides of the slot near the open end. Appropriately designing the capacitor values allows us to demonstrate the ability of the proposed antenna to operate at a frequency lower than half the natural resonant frequency of the slot. This finding implies that the slot is shorter than one-eighth the wavelength at the operating frequency. The design is based on a wideband equivalent circuit of the antenna established by considering the physical geometry of the slot. The calculated input impedance from the equivalent circuit closely corresponds to that from the full-wave simulation over a wide frequency range.

With the proposed antenna configuration, a 2.45 GHz slot antenna is first realized by using an open-end slot of size 9 mm by 1.5 mm that is originally resonant at 4.8 GHz in a conventional design. The measured bandwidth of 109 MHz and peak gain of 1.89 dBi demonstrate the performance of the proposed miniaturized design. Our results further demonstrate that, with the proposed configuration, the slot radiator can be matched to operate at nearly any frequency as long as the slot possesses an inductive reactance at that frequency. Several antennas using the same slot size while operating at even lower frequencies (down to 1.64 GHz) are thus designed and demonstrated, which present acceptable radiation efficiencies and patterns.

The proposed antenna is miniaturized by using circuit resonance instead of wave resonance. Consequently, the operating frequency can be varied by changing the matching circuit components but without varying the slot size. Therefore, a frequency tunable antenna can be designed using the proposed configuration by simply replacing the fixed valued capacitors with the varactors. The proposed design is simple and compact with a wide frequency tuning range, making it highly promising for many wireless applications.

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A Planar Dual-Arm Equiangular Spiral Antenna

W. Fu, E. R. Lopez, W. S. T. Rowe, and K. Ghorbani

***Abstract*—The design is described of a planar dual-arm equiangular spiral antenna incorporated with chip resistors inside the substrate. The chip resistors were applied to this equiangular spiral antenna to achieve 9:1 impedance bandwidth (2 to 18 GHz) with an extremely low profile structure. The simulated and measured magnitude of the reflection coefficient (S_{11}), gain, and measured radiation patterns are presented.**

***Index Terms*—Chip resistor, equiangular spiral, microstrip antenna, ultra-broadband.**

I. INTRODUCTION

Spiral antennas have been employed in many applications since 1950s. The usual solution for obtaining unidirectional radiation is to place a one quarter wavelength deep cavity [1] or a microwave absorbing material filled cavity [2] on one side of the spiral structure to diminish the backward radiation. Unfortunately this kind of configuration adds extra volume and weight into the antenna system as well as lowering its gain. The spiral-mode microstrip (SMM) antenna [3], SMM-like designs [4] and spirals with a stepped cavity [5] partially solve the problem of this extra weight and size introduced by the cavity. However in airborne applications, the severe thermal and mechanical operational environment may pose a significant challenge

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The authors are with the School of Electrical and Computer Engineering, RMIT University, Melbourne VIC 3001, Australia (e-mail: s3089134@student.rmit.edu.au; s3008525@student.rmit.edu.au; wayne.rowe@rmit.edu.au, kamran.ghorbani@rmit.edu.au).

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