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An Interdigital Capacitor Loaded Slot Antenna with Compact Size

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Abstract—A new compact interdigital capacitor loaded open slot antenna and its lumped model are presented in this letter. Equivalent model analysis shows that the introduction of the interdigital structure increases the capacitive element of the slot and thus reduces the operating frequency of the slot antenna. And the antenna operating frequency as well as its size can be easily reduced by simply increasing the capacitance of the interdigital capacitor and the characteristic impedance of the slot. Experimental results of the exemplary antenna agree well with those of the full-wave simulation, proving that the proposed open slot antenna structure is viable in antenna design.

1. INTRODUCTION

Slot antennas are candidate for compact antenna design since they are of compact size, low profile and ease of integration with other components. Recently, various slot structures have been proposed for antenna size reduction. Folding or bending the slot is a conventional approach for size reduction [1]. However, they always lead to very low gain. Loop loaded slot [2], stepped-impedance slot [3] and C-shaped ring embedded slot [4] are all found effective to reducing antennas' size. However, further size eduction is still required. Another compact slot antenna by employing serial resonance between the slot and lumped capacitor is reported in [5]. However, the employment of multiple lumped components increases the design complexity and fabrication cost.

In this letter, a new compact slot is proposed. Unlike other reported antennas in [1–5], not only transmission line model but also full lumped model is established to gain an insight into the size reduction mechanism of the proposed antenna. The theoretical analysis about equivalent-circuit model indicates that the size-miniaturization effect is brought by the loaded capacitor which brings more capacitive elements to the slot. The experimental results show good agreement with theoretical predictions, confirming the effectiveness of modelling method for the open slot antenna.

2. EQUIVALENT-CIRCUIT MODEL ANALYSIS

Figure 1(a) shows the geometrical configuration of the microstrip fed open-end slot antenna, and an open-end slot etched in the ground plane whose total length is L_S has an interdigital structure at the open end. The antenna is fabricated on a 0.8 mm substrate with a dielectric constant of 4.4 and loss tangent of 0.02. By characterizing the open slot as a transmission line with characteristic impedance Z_S, the proposed antenna can be modelled as the equivalent circuit in Figure 1(b). The electrical length θ_1 is related to MD, and θ_2 is related to the electrical distance from the long end to the feeding position. The capacitor of C represents the capacitance brought by the interdigital structure. And the resistor R symbolizes all the resistive effects of the proposed slot antenna such as radiation resistor, metal ohmic loss and dielectric loss. Considering the coupling between the microstrip line and the

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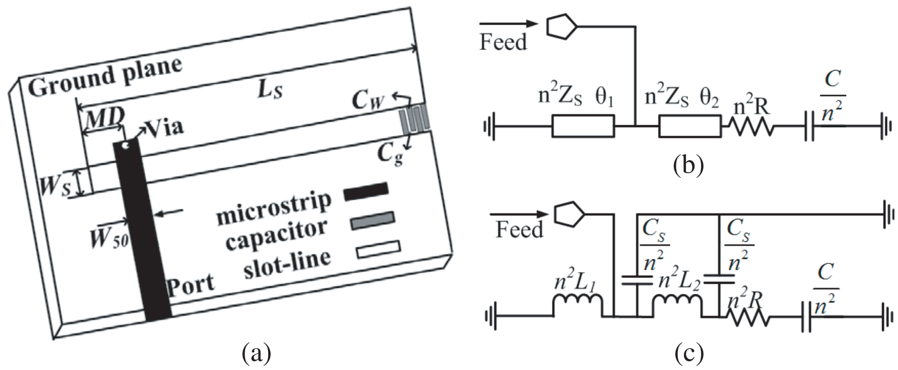

Figure 1. Model of the proposed interdigital capacitor loaded slot antenna. (a) Open slot antenna configuration. (b) Corresponding equivalent circuit model. (c) Lumped equivalent circuit model.

slot-line, the values of characteristic impedance, capacitance and resistance can be expressed by n^2Z_S, C/n^2 and n^2R, respectively. To have a deep insight into the size-reduction mechanism of the antenna, the equivalent circuit in Figure 1(b) can be transformed to the lumped one in Figure 1(c). As shown in Figure 1(c), the shorted transmission lines with electrical length θ_1 in Figure 1(b) is replaced by an inductor L_1, and the transmission lines with electrical length θ_2 is represented by a π-shaped circuit composed of one inductor and two capacitors. And the values of L_1, L_2 and capacitance C_S can be obtained as

$$L_1 = Z_S \tan\theta_1/w \tag{1}$$

$$L_2 = Z_S \sin\theta_2/w \tag{2}$$

$$C_S = (1-\cos\theta_2)/wZ_S\sin\theta_2 \tag{3}$$

Generally, the resonance of the open slot antenna is caused from the parallel resonance formed by the inductive shorted-slot and the capacitive open-slot. As seen in Figure 1(c), as the result of introducing the interdigital capacitor, the series LC circuit replaces the capacitive open-slot. Thereby the capacitive element of the slot is greatly magnified, leading to size-reduction. Specially, at the operating frequency f, the following equation derived from the parallel resonance should be satisfied.

$$(1-2w^2L_2C_S)^2[1-w^2C(L_1+R^2C)]+w^4L_2^2C^2-w^2L_2C(1-2w^2L_2C_S)(2-w^2L_1C)=0 \tag{4}$$

As previously described, the size reduction effect is caused by the increase of capacitive element of the slot. And thus increasing C is good for size reduction since doing that provides more capacitance to the slot. Figure 2 shows theoretical calculation f and C. As shown in Figure 2, a larger C leads

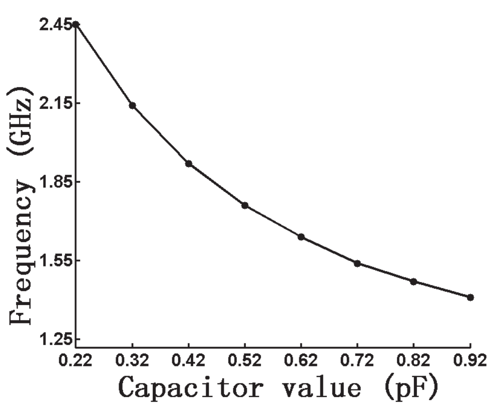

Figure 2. The theoretical calculation frequency of f with different C.

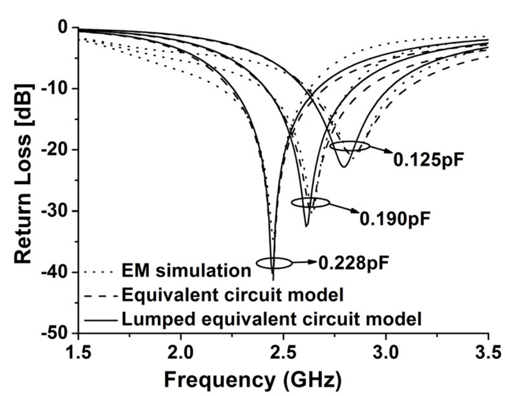

Figure 3. The EM simulated and the theoretical calculation return loss with different C.

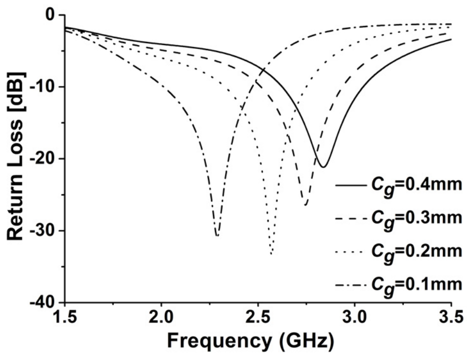

Figure 4. Compare the EM simulated frequency of f_0 with different gap width of the interdigital capacitor.

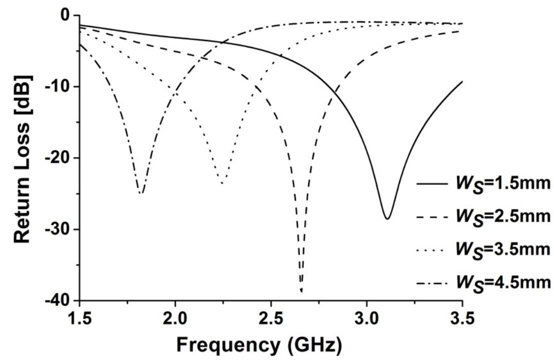

Figure 5. Compare the EM simulated frequency of f_0 with different slot width W_S.

to a smaller f. Therefore, a larger C helps minimize the antenna's size. Figure 3 presents the EM simulated and the theoretical calculation return loss (S_{11}) with different C. It can be observed that good agreement can be observed between the simulation and equivalent circuit model. Hence the equivalent circuit model and lumped equivalent circuit model can be verified when changing the capacitance value. In general, larger capacitance can be achieved by increasing the length or the number of interdigital capacitor fingers, or decreasing the gap of the interdigital capacitor. Here only decreasing the gap of the interdigital capacitor is discussed. As demonstrated in Figure 4, the bandwidth is enhanced when a narrower gap is adopted. Similarly, increasing the length or the finger number of the interdigital capacitor can achieve the same antenna miniaturization.

Additionally, another method to reduce the operating frequency is to increase L_2, which can be obtained by increasing Z_S by widening the width of the slot. And with the increase of slot width, the capacitance of the interdigital structure also increases since the finger length is lengthened. As a result, as shown in Figure 5 a wider slot width W_S leads to a smaller f. Hence a wider slot width is selected in this work.

3. FABRICATION AND MEASUREMENTS

According to the design concept, the dimensions of the antenna are obtained as: $L_S = 16.3\,\text{mm}$, $W_{50} = 1.5\,\text{mm}$, $C_g = 0.15\,\text{mm}$, $C_W = 0.15\,\text{mm}$, $W_S = 3\,\text{mm}$, $MD = 5.15\,\text{mm}$. The proposed side-fed slot antenna owns a quite compact size of merely $16.3\,\text{mm} \times 3.9\,\text{mm}$, which corresponds to $0.0113\lambda\text{g}^2$ ($0.217\lambda\text{g} \times 0.0519\lambda\text{g}$). And λg is the guided wavelength of a $50\,\Omega$ microstrip line at its central frequency 2.45 GHz. The parameter values of the models in Figure 1 are extracted as $Z_S = 237\,\Omega$, $\theta_1 = 20.16°$, $\theta_2 = 46.08°$, $R = 98.05\,\Omega$, $n = 0.95$, $L_1 = 5.65\,\text{nH}$, $L_2 = 11.1\,\text{nH}$, $C_S = 0.116\,\text{pF}$ and $C = 0.228\,\text{pF}$.

Figure 6 presents return loss comparison among corresponding equivalent circuit model, lumped equivalent circuit model, EM simulation and measurement. Good agreement between the measured and simulated frequency response can be observed. Therefore, the validity of the presented open slot antenna model employing interdigital capacitor is successfully verified. Measured frequency response is centered at 2.45 GHz with 10 dB impedance factional bandwidth (FBW) about 18.7%. The fabricated prototypes in xz-plane and yz-plane radiation patterns are measured, and the results are shown in Figure 7. Measured peak gain is 2.075 dBi at 2.45 GHz. Figure 8 shows the simulated surface current distribution around the slot at 2.45 GHz. As shown in Figure 8, the surface current is concentrated at the vicinity of the coupling location and the interdigital structure. The surface current density behavior indicates that resonant modes can be tuned and controlled by the feeding position and interdigital structure.

A comparison of the proposed open slot antenna with other reported slot antennas is provided in Table 1. Compared with the slot antennas in [1–5], the proposed interdigital capacitor loaded slot antenna possesses an excellent balance among size, peak gain and FBW. The proposed slot antenna

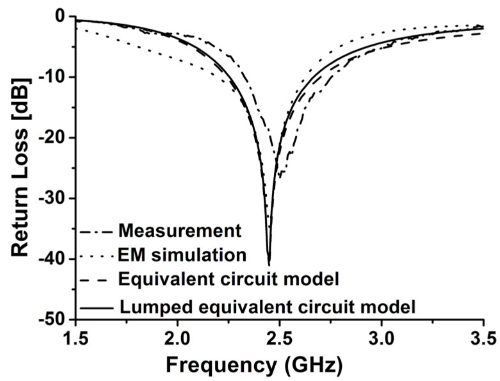

Figure 6. Return loss (S_{11}) characteristics of the open slot antenna.

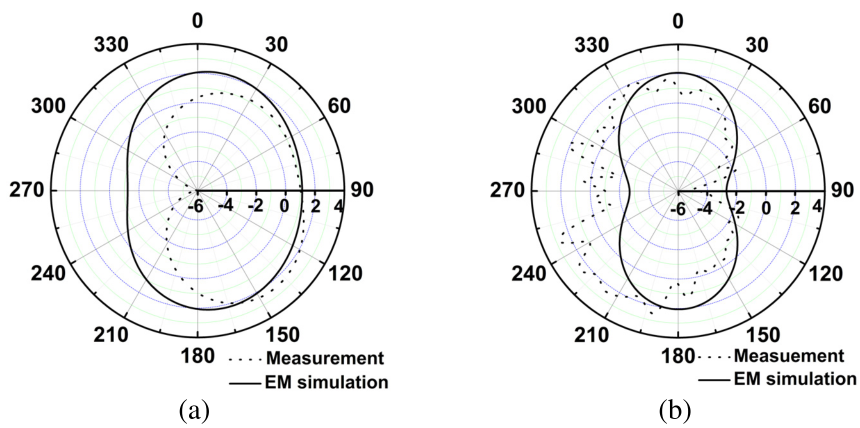

Figure 7. Radiation patterns of the open slot antenna. (a) xz plane. (b) yz plane.

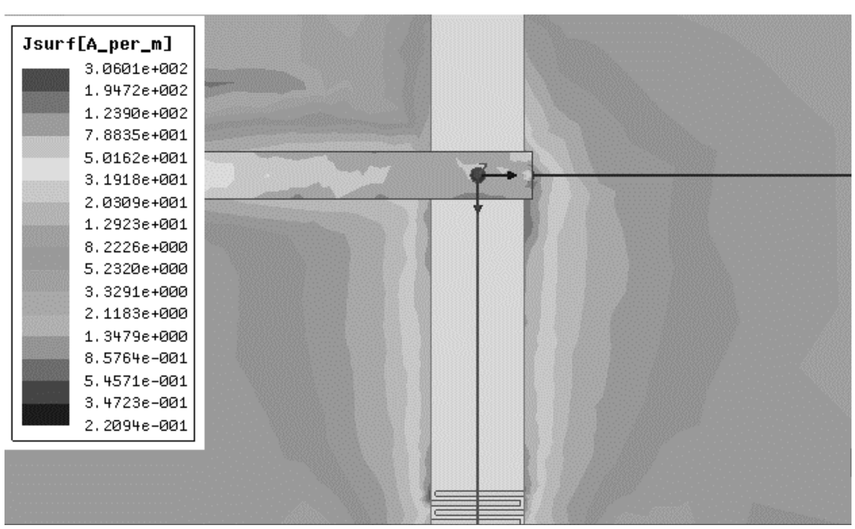

Figure 8. Simulated surface current distribution around the slot at 2.45 GHz.

Table 1. Comparison between the reported slot antennas.

References	Circuit Size (λ_g^2)	FBW (%)	Peak gain (dBi)
[1]	0.0047	0.034	−3.0
[2]	0.2611	3.75	−1.2
[3]	0.9442	unkown	3.07
[4]	0.0222	1.6	2.0
[5]	0.0025	4.4	1.89
This work	0.0113	18.7	2.075

structure has a much more compact size than other antennas except those in [1] and [5]. However, the proposed antenna has higher gain and much wider FBW than antennas in [1] and [5]. Unlike the antenna in [5], no lumped impedance circuit is employed to obtain impedance matching, which facilitates design and decreases fabrication cost. In addition, the size of the proposed antenna can be further reduced by increasing capacitance of the interdigital structure without varying the slot size.

4. CONCLUSIONS

This letter proposes an interdigital capacitor loaded open slot antenna with compact size. The fabricated antenna possesses an excellent balance among size, peak gain and FBW. Measured results indicate that bandwidth of 18.7% and peak gain of 2.075 dBi can be achieved with the compact size of $0.0113\lambda g^2$. With these advantages, the new slot antenna is very promising for the use in mobile wireless communication devices.

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