FR2A_05

Proceedings of ISAP 2014, Kaohsiung, Taiwan, Dec. 2-5, 2014

Analysis of Stepped-Impedance Slot Antenna

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***Abstract*—The design procedure of the microstrip-fed stepped-impedance (SI) slot antenna has been derived by utilizing the transmission-line and lumped-element circuit topologies. The resonant analysis and modeling of the antenna are also included. This study does not only analyze the SI-slot antenna, but also systematically summarizes its frequency response characteristics, including the resonance condition and spurious response. The design formulas with respect to the impedance ratio of the SI slot antenna are analytically derived. Note that the resonant modes of the SI-slot antenna are predicted without utilizing expensive EM simulation software.**

***Index Terms* — Slot antenna, resonance condition, spurious response.**

I. INTRODUCTION

Because of an increasing demand for wireless communication systems, studies on small antennas have attracted much attention. The slot antenna, which has a patterned slot in the metallic ground plane, can exhibit resonance characteristics, thus causing wave radiation [1-3]. This slot disturbs the shield current distribution in the metallic ground plane, and this disturbance changes the frequency characteristics of the transmission line, modeled as a combination of lumped elements [2].

The fundamental and harmonic resonance characteristics of a stepped-impedance (SI) slot antenna used as a non-uniform slot radiator are studied in this work. The comparison of the slot antenna with different impedance ratios is shown. The experimental results show good agreements with theoretical results.

II. RESONANCE PROPERTIES OF THE ANTENNA

Fig. 1 shows the geometrical diagram of the microstrip-fed SI-slot antenna. The SI-slot antenna is etched in the metallic ground plane and it can provide a resonant band in some frequency. For a microstrip line on the top of the ground plane in which an SI slot of total length l_s is etched perpendicularly to the direction of the line, the resonant frequency f_0 of the SI-slot antenna is determined by its length. In general, for a uniform slot, the length is about half of a guided wavelength. The physical layout of the SI-slot antenna can be equivalently characterized as a transmission-line topology as described in Fig. 2. It is noted that Z_0 is the characteristic impedance of the 50-Ω transmission line. Following the early work in [2], the strip-to-slot coupling section can be modeled as a power transformer, for which the ideal turn ratio is n : 1, and hence, the self-coupling inductances (L_1 and L_2) of the primary and secondary windings of the transformer, respectively. Furthermore, an open-circuit at the end of the microstrip line can be equivalent to a shunt capacitor (C_f). The SI quasi-transmission-line slots between the open and short planes have different characteristic impedances, Z_1 and Z_2, and corresponding electrical lengths, θ_1 and θ_2. Hence, ignoring the influences of the step discontinuity, the input admittance of the composite-slot radiator can be written as

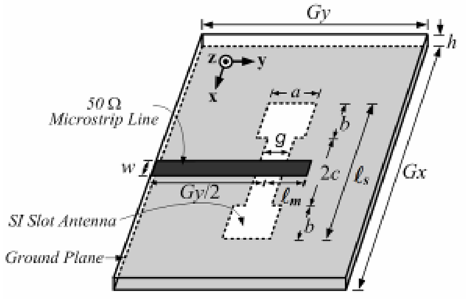

Fig. 1. Geometrical diagram of the microstrip-fed SI-slot antenna.

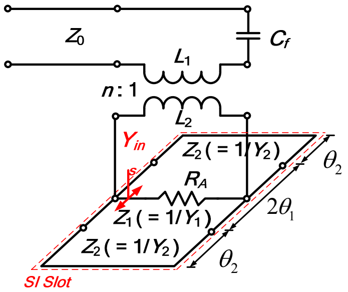

Fig. 2. Transmission-line equivalent circuit topology of the SI-slot antenna.

$$Y_{ins} = \frac{1}{Z_{ins}} = j2Y_1 \frac{K \tan\theta_1 \tan\theta_2 - 1}{\tan\theta_1 + K \tan\theta_2}, \tag{1}$$

where the impedance ratio K is defined by Z_2 / Z_1. When the boundary condition is satisfied, the fundamental resonance condition from $Y_{ins} = 0$ is described as $K\tan\theta_1 \tan\theta_2 - 1 = 0$. On this resonance condition, the radiation resistance of the slot radiator is R_A. The resonance conditions in the case of the uniform-impedance slot are determined solely based on the length of the slots. However, in determining the resonance conditions of the antenna, both the electric length (θ_1 and θ_2) and the impedance ratio (K) must be considered.

Assuming $\theta_1 = \theta_2 = \theta$ for a given K, the fundamental resonant frequency, which is represented as f_0, can be given by

$$f_0 = \frac{2v_p}{\pi \times l_s} \tan^{-1} \frac{1}{\sqrt{K}}, \tag{2}$$

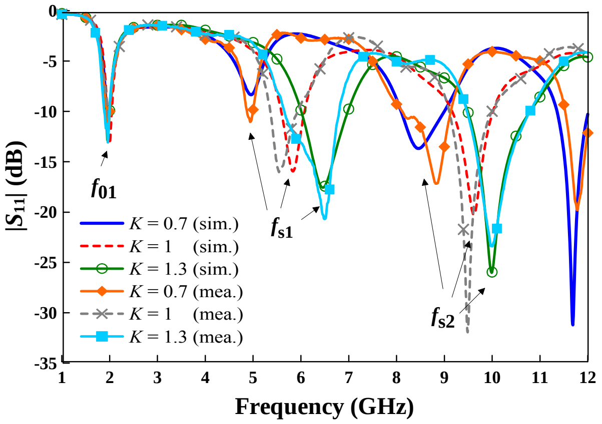

Fig. 3. Comparison of reflection coefficients (S_{11}) of the three cases of the SI-slot antenna, which are $K = 0.7$, $K = 1.0$, and $K = 1.3$.

where v_p is the phase velocity of the wave in the slot line. The value l_s (= $2b+2c$) is the physical length corresponding to the total electric length ($2\theta_2+2\theta_1$). After calculation, the relationship between the fundamental and first two spurious resonant frequencies of the antenna is given by

$$\frac{f_{s1}}{f_0} = \frac{\pi}{\tan^{-1}\dfrac{1}{\sqrt{K}}} - 1 \tag{3}$$

$$\frac{f_{s2}}{f_0} = \frac{\pi}{\tan^{-1}\dfrac{1}{\sqrt{K}}} + 1 \tag{4}$$

The two spurious resonances are the third and fifth harmonics; on the other hand, the second and fourth harmonics of the SI slot antenna are not excited owing to the symmetrical slot.

III. Results and Discussion

In our experiments, FR-4 is used as a substrate with the dielectric constant of 4.4, thickness of 0.8 mm, and ground plane size of 100 mm × 80 mm ($G_x \times G_y$), respectively. The geometrical parameters of the three cases are listed in Table I. The fundamental resonant frequency of all the examples of the SI-slot antenna on the well-matching condition is set to 2.0 GHz to compare their harmonic frequencies. Fig. 3 shows the comparison of the reflection coefficients (S_{11}) of the three cases of the slot antenna, which are $K = 0.7$, 1.0, and 1.3. The resonant length of the SI-slot antenna for the case of $K = 1.3$ is shorter than that for $K = 1.0$ and $K = 0.7$. In this figure, the measured results of the tested antennas for $K = 0.7$, 1.0, and 1.3 agree well with the simulated results.

Fig. 4 shows the relationship between the fundamental and spurious frequencies as a function of the impedance ratio. The theoretical calculation is obtained by using Eqs. (3) and (4), and the EM simulation is given by utilizing the HFSS. It can be seen in Fig. 4 that, When $K > 2.2$, the mismatch variation between the theoretical calculation and the EM simulation for the second spurious resonant frequencies (f_{s2}) of the slot antenna will be > 10 %. Meanwhile, owing to the limitation of the fabrication process for the microstrip line, K must be > 0.35. Hence, it can be concluded that the impedance ratio (K) should be set from 0.35 to 2.2. In addition, by making the impedance ratio as large as possible, it is useful for enlarging the separation between the fundamental and spurious frequencies. On the other hand, the physical length of the SI slot antenna also reduces. Hence, increasing K is essential to the size miniaturization and harmonic suppression of the SI slot antenna. The three SI slot antennas with $K = 0.7$, 1.0, and 1.3 are designed and fabricated to experimentally verify our proposed lumped-element circuit model.

TABLE I
THE GEOMETRICAL PARAMETERS OF THE SI-SLOT ANTENNA (SEE, FIG. 1)

ratio K	parameter	*h*	*w*	*g*	*a*	*b* = *c*	ℓ_s	ℓ_m
0.7	Unit: mm	0.8	1.5	3	1.1	13.9	55.6	2.9
1.0	Unit: mm	0.8	1.5	3	3	12.5	50	2.6
1.3	Unit: mm	0.8	1.5	3	5.5	11.4	45.6	2.5

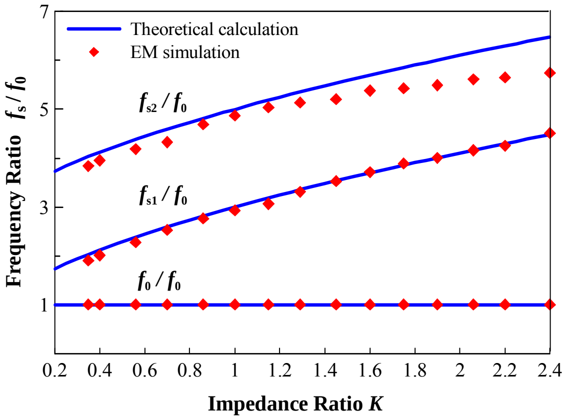

Fig. 4. Relationship between the fundamental and spurious frequencies as a function of the impedance ratio.

IV. CONCLUSION

The resonance prediction of the SI-slot antenna has been proposed. By utilizing the transmission-line analysis, the design rule and resonance-mode relation of the SI-slot antenna can be derived without the use of EM simulators. Size reduction and harmonic suppression are also achieved by increasing the impedance ratio of the slot.

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