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Estimation of the Substrate Size with Minimum Mutual Coupling of a Linear Microstrip Patch Antenna Array Positioned Along the H-Plane

Eun-Hyuk Kwak*, Young-Min Yoon* and Boo-Gyoun Kim†

Abstract – Mutual coupling between antenna elements of a linear microstrip patch antenna array positioned along the H-plane including the effect of edge reflections is investigated. Simple formulas are presented for the estimation of the grounded dielectric substrate size with minimum mutual coupling. The substrate sizes calculated by these formulas are in good agreement with those obtained by the full-wave simulation and experimental measurement. The substrate size with minimum mutual coupling is a function of the effective dielectric constant for surface waves and the distance between the antenna centers. The substrate size with minimum mutual coupling decreases as the effective dielectric constant for surface waves on a finite grounded dielectric substrate increases.

Keywords: Mutual coupling, Antenna array, Microstrip antennas, Substrate size, Edge effects, Surface wave

1. Introduction

Microstrip patch antennas have become one of the most popular antennas because they have many advantages such as low-profile, light weight, low fabrication cost, and easy integration with monolithic microwave integrated circuits (MMICs) [1]. While microstrip patch antennas fabricated on high-permittivity substrates are compact and easily integrated with MMICs, they can excite large surface waves. Surface waves could increase the mutual coupling between antenna elements in phased array antennas, which degrades the performance of phased array antennas such as a decrease in the scan range and an increase in the sidelobe levels [2].

Various methods have been developed to suppress mutual coupling effects, such as electromagnetic band-gap (EBG) structures [3-6], defected grounded structures (DGSs) [7], inductive loaded microstrip patch antennas [8], a U-shaped microstrip line section inserted between antenna elements [9], and a pattern etched onto the ground plane between antenna elements [10]. However, the effect of edge reflections on the mutual coupling was not considered in those studies.

In a practical microstrip patch antenna array fabricated on a finite grounded dielectric substrate, the effect of edge reflections on the mutual coupling between the antenna elements in antenna arrays must be considered. Recently, the effect of edge reflections on the mutual coupling of a linear microstrip patch antenna array positioned along the E-plane was investigated [11].

In this paper, simple formulas are presented for the estimation of the grounded dielectric substrate size with minimum mutual coupling of a linear microstrip patch antenna array positioned along the H-plane. To validate these formulas, mutual coupling of a two-element linear microstrip patch antenna array positioned along the H-plane was investigated through an experiment and a simulation using HFSS. In Section II, simple formulas obtained by using geometrical optics are presented to estimate the substrate size with minimum mutual coupling. In Section III, both the numerical and experimental results are presented for antenna arrays with various distances between the antenna centers fabricated on various high-permittivity substrates. Finally, Section IV concludes this paper.

2. Simple Formulas for the Estimation of the Substrate Size with Minimum Mutual Coupling

Fig. 1 shows the schematic diagram of a two-element linear microstrip patch antenna array positioned along the H-plane and a conceptual representation using geometrical optics for the estimation of the substrate size with minimum mutual coupling between two antennas. The quantity d represents the distance between the antenna centers. The distances between the antenna center and the substrate edges on the E-plane and H-plane are represented by the quantities d_E and d_H, respectively. A coaxial probe feeding method is used to excite the microstrip patch antennas. The probe-fed point x_f is offset from the center of

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† Corresponding Author: School of Electronic Engineering, Soongsil University, Korea. (bgkim@e.ssu.ac.kr)
* School of Electronic Engineering, Soongsil University, Korea. ({ehkwak, runmini}@ssu.ac.kr)

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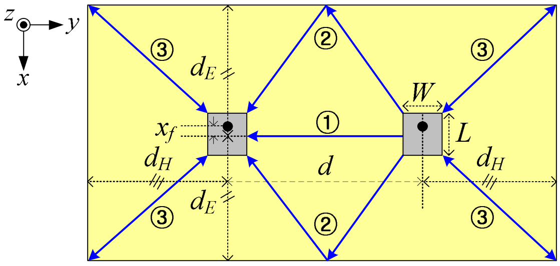


Fig. 1. A schematic diagram of a two-element linear microstrip patch antenna array positioned along the H-plane.

a rectangular patch ($L \times W$) in the *x*-axis.

Since surface waves mainly propagate along the E-plane direction [12], the effect of the reflected surface waves from the substrate edges on the H-plane on the mutual coupling between the antenna elements positioned along the H-plane can be very small compared to that of the reflected surface waves from the substrate edges on the E-plane. Thus, the mutual coupling between the antenna elements positioned along the H-plane can be determined by the following three types of surface waves: ① one that is directly propagated between two patch antennas; ② one that is caused by the reflection from the substrate edges on the E-plane; and ③ one that is caused by the reflection from the corner of the substrate.

The geometrical optics shown in Fig. 1 was used to derive the simple formulas for the grounded dielectric substrate size with minimum mutual coupling of a linear microstrip patch antenna array positioned along the H-plane. In this paper, the quantities d_E and d_H that have minimum mutual coupling are represented by the quantities $d_{E,\min}$ and $d_{H,\min}$, respectively.

The quantity $d_{E,\min}$ is d_E at which the phase difference of π between the direct surface wave ① and the reflected surface wave from the substrate edges on the E-plane ② occurs. The simple formula for $d_{E,\min}$ can be expressed as

$$d_{E,\min} = \frac{\lambda_g}{2}\sqrt{\frac{d}{\lambda_g} + \frac{1}{4}}, \tag{1}$$

where $\lambda_g = c/(f\sqrt{\varepsilon_{sw}})$ denotes the guided wavelength of surface waves on a grounded dielectric substrate. The effective dielectric constant for surface waves on a grounded dielectric substrate, ε_{sw}, is given by $(\beta_{sw}/k_0)^2$, where β_{sw} is the propagation constant of the TM_0 surface-wave mode and k_0 is the free-space wave number. The effective dielectric constant for surface waves on a grounded dielectric substrate increases as the dielectric constant and thickness of a dielectric substrate increase [13].

The quantity $d_{H,\min}$ is d_H at which the one round-trip phase delay of 3π for the reflected surface wave from the corner of the substrate ③ occurs because the quantity d_E is usually longer than $\lambda_g/4$ in practical antenna arrays. The simple formula for $d_{H,\min}$ can be expressed as

$$d_{H,\min} = \sqrt{\frac{9}{16}\lambda_g^2 - d_E^2} \tag{2}$$

3. Numerical and Experimental Validations

Since mutual coupling becomes very significant when the substrate is relatively thick and has a high permittivity, a 3.18-mm-thick Taconic CER-10 substrate (ε_r = 10.8) and a 3.18-mm-thick RF60A substrate (ε_r = 6.75) were selected for this study. Microstrip patch antennas with a resonant frequency f_r of 5 GHz were positioned along the H-plane with the distances between the antenna centers of 0.5 λ_0 and 0.7 λ_0, respectively, where λ_0 denotes the free space wavelength. Table 1 shows the dimensions and parameters of the patch antennas printed on a CER-10 substrate and a RF60A substrate.

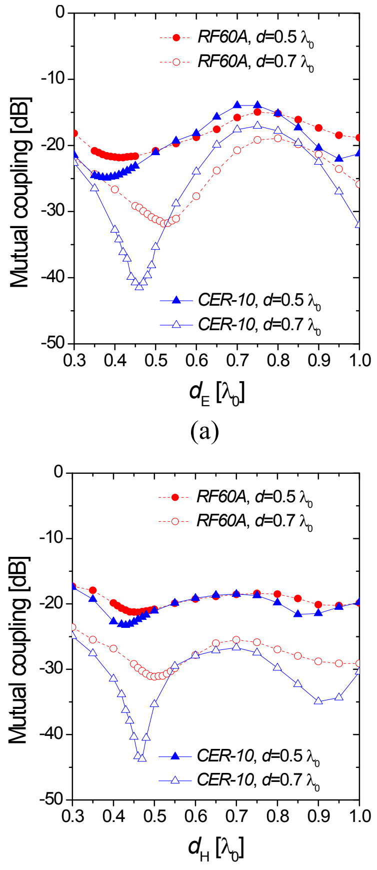
Table 1. Dimensions and parameters of the microstrip patch antennas printed on a CER-10 substrate and a RF60A substrate

Substrate	h [mm(λ_0)]	ε_r	L [mm λ_0)]	W [mm(λ_0)]	x_f [mm]	f_r [GHz]	ε_{sw}
RF60A	3.18 (0.05)	6.75	9.8 (0.16)	8.4 (0.14)	1.70	5.00	1.13
CER-10	3.18 (0.05)	10.8	7.2 (0.12)	6.0 (0.10)	1.12	5.00	1.23

Fig. 2(a) shows the simulated mutual coupling values between the two patch antennas printed on a 3.18-mm-thick CER-10 substrate and a 3.18-mm-thick RF60A substrate, respectively, for the quantity d of 0.5 λ_0 and 0.7 λ_0 versus the quantity d_E ranging from 0.3 λ_0 to 1.0 λ_0, with a step size of 0.05 λ_0. In the vicinity of $d_{E,\min}$, simulations were performed in detail with a step size of 0.01 λ_0. The quantity d_H was fixed at 0.5 λ_0 in all the cases considered.

Fig. 2(b) shows the simulated mutual coupling values versus the quantity d_H ranging from 0.3 λ_0 to 1.0 λ_0, with a step size of 0.05 λ_0. In the vicinity of $d_{H,\min}$, simulations were performed in detail with a step size of 0.01 λ_0. For each case in Fig. 2(b), the quantity d_E was fixed at 0.5 λ_0. In Fig. 2, the variation in the mutual coupling increases with the substrate permittivity due to the increase of surface wave power. Furthermore, as the distance between the antenna centers increases, the variations in the mutual coupling versus d_E and d_H increase for the same substrate permittivity.

From Fig. 2, we can see that the quantities $d_{E,\min}$ and $d_{H,\min}$ decrease as the substrate permittivity increases. This phenomenon can be explained as follows. As the substrate permittivity increases, the guided wavelength of the surface wave, λ_g, decreases because ε_{sw} increases. Thus, the quantities $d_{E,\min}$ and $d_{H,\min}$ decrease as the



(a)

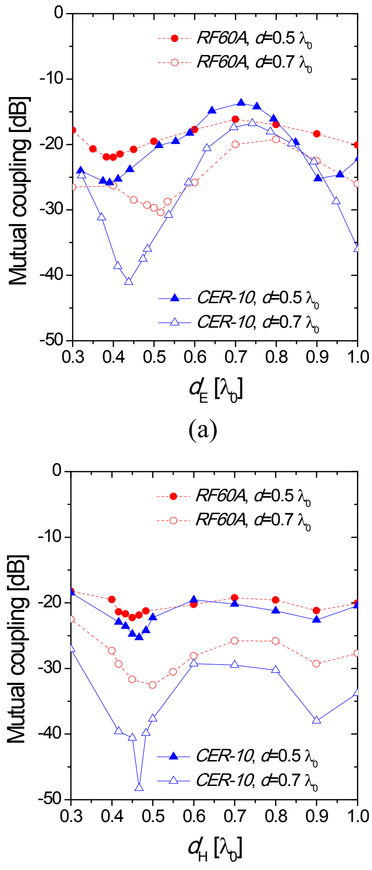
(b)

Fig. 2. Simulated mutual coupling between the two patch antennas printed on a 3.18-mm-thick CER-10 substrate and a 3.18-mm-thick RF60A substrate, respectively, for the quantity d of 0.5 λ_0 and 0.7 λ_0 versus (a) the quantity d_E and (b) the quantity d_H.

substrate permittivity increases, as shown in formulas (1) and (2). It is also seen that the quantity $d_{E,\min}$ decreases as the distance between the antenna centers decreases, as shown in formula (1). The variation of the quantity $d_{H,\min}$ with the decrease of the quantity d is small compared to that of $d_{E,\min}$ because there is no dependence of d, as shown in formula (2).

Figs. 3(a) and (b) shows the experimental results on the mutual coupling between the two patch antennas, the simulation results of which are shown in Fig. 2(a) and (b), respectively. The experiment results agree well with the simulation results. In Fig. 3(a), the variations in the mutual coupling versus d_E for d =0.5 λ_0 and 0.7 λ_0 are about 12.1 dB (5.8 dB) and 24.3 dB (11.2 dB), respectively, for the CER-10 substrate (the RF60A substrate). In Fig. 3(b), the variations in the mutual coupling versus d_H for d = 0.5 λ_0 and 0.7 λ_0 are about 6.8 dB (4.0 dB) and 21.2 dB (10.0 dB), respectively, for the CER-10 substrate (the RF60A substrate).

As the substrate permittivity increases, the variations in the mutual coupling versus d_E and d_H increase for the same distance between the antenna centers. Furthermore, as the distance between the antenna centers increases, the variations in the mutual coupling versus d_E and d_H increase for the same substrate permittivity.



(a)

(b)

Fig. 3. Measured mutual coupling between the two patch antennas printed on a CER-10 substrate and a RF60A substrate, respectively, for the quantity d of 0.5 λ_0 and 0.7 λ_0 versus (a) the quantity d_E and (b) the quantity d_H.

Table 2. Comparison of the values of $d_{E,\min}$ and $d_{H,\min}$ obtained by the simple formulas, simulation, and experiment, for two different pairs of patch antennas printed on a 3.18-mm-thick CER-10 substrate and a 3.18-mm-thick RF60A substrate.

Substrate	ε_r	ε_{sw}	d [λ_0]	$d_{E,\min}$ [λ_0]			$d_{H,\min}$ [λ_0]		
				Formula (1)	Sim.	Mea.	Formula (2)	Sim.	Mea.
RF60A	6.75	1.13	0.5	0.42	0.41	0.42	0.50	0.46	0.45
			0.7	0.47	0.52	0.52	0.50	0.50	0.50
CER-10	10.8	1.23	0.5	0.40	0.38	0.39	0.46	0.43	0.47
			0.7	0.46	0.46	0.44	0.46	0.47	0.47

The results of the simulation and experiment are summarized and compared with the results of formulas (1) and (2) in Table 2. The results calculated by using the simple formulas are in good agreement with the simulation and experimental results. It can be seen that the quantities $d_{E,\min}$ and $d_{H,\min}$ decrease as the substrate permittivity increases. It is also seen that the quantity $d_{E,\min}$ decreases as the distance between the antenna centers decreases. The variation of the quantity $d_{H,\min}$ with the decrease of the quantity d is small compared to that of $d_{E,\min}$.

4. Conclusion

The mutual coupling between antenna elements of a linear microstrip patch antenna array positioned along the H-plane is investigated. Simple formulas obtained by using geometrical optics are presented to estimate the grounded dielectric substrate size with minimum mutual coupling. The substrate size with minimum mutual coupling is easily calculated by using the simple formulas. The substrate sizes calculated by using the simple formulas are in good agreement with the results obtained by the full wave simulation and experimental measurement.

The substrate size with minimum mutual coupling is mainly determined by the effective dielectric constant for surface waves on a grounded dielectric substrate. Since the effective dielectric constant for surface waves increases as the dielectric constant and thickness of a dielectric substrate increase, the substrate size with minimum mutual coupling decreases as the dielectric constant and thickness of a dielectric substrate increase. When the substrate is a Taconic CER-10 with a thickness of 3.2 mm and a dielectric constant of 10.8, significant 12.1 dB and 24.3 dB mutual coupling reductions are achieved by adjusting the substrate size for the distances between the antenna centers of 0.5 λ_0 and 0.7 λ_0, respectively.

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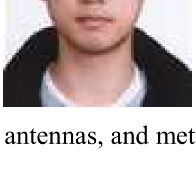

Eun-Hyuk Kwak He was born in Seoul, Korea. He received the B.S. and M.S. degrees in electronic engineering from Soongsil University, Seoul, Korea, in 2009 and 2011, respectively. Currently, he is pursuing the Ph.D. degree. His main research interests are in the areas of patch antennas, phased array antennas, and metamaterials.

Young-Min Yoon He was born in Seoul, Korea. He received the B.S., M.S., and Ph.D. degrees in electronic engineering from Soongsil University, Seoul, Korea, in 2003, 2005, and 2013, respectively. His main research interests are in the areas of patch antennas, phased array antennas, and EMI/EMC.

Boo-Gyoun Kim He was born in Daejon, Korea. He received the B.S. degree in electronic engineering from Seoul National University, Seoul, Korea, in 1979, the M.S. degree in electronic engineering from the Korea Advanced Institute of Science and Technology, Seoul, in 1981, and the Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, in 1989. He joined the School of Electronic Engineering, Soongsil University, Seoul, in 1981, where he is now a Professor in the School of Electronic Engineering. His main research interests are in the areas of patch antennas, electromagnetic bandgap structures, phased array antennas, and EMI/EMC.