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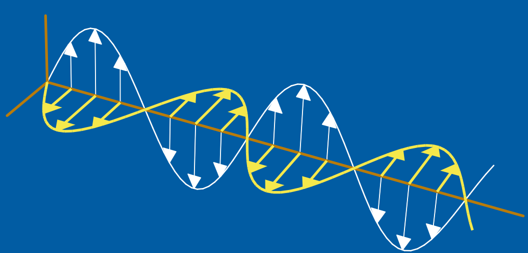

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Abstract

It is well known that planar self-complementary structures have a constant input impedance and hence they are good candidates for ultra-wideband antennas. However, introduction of a ground plane breaks the symmetry and destroys the broadband property. In this paper, it is shown that stacking of dielectric slabs above the antenna elements can reduce the degrading effect of the ground plane. The dielectric slabs act as filters adding loops in the center of the Smith chart. The results are illustrated with infinite antenna arrays with broadside bandwidths of 4.7:1 at -13dB and of 5.5:1 at -17dB for the cases of two and three dielectric slabs, respectively.

1 Introduction

Self-complementary antennas are basic prototypes of frequency independent antennas [5, 9]. They exist both as single antenna elements and antenna arrays. It is well known that planar self-complementary antennas have a constant impedance of $Z_0/2 = 188.5\,\Omega$, *i.e.*, half the intrinsic impedance of space [5, 9]. Since the planar self-complementary antenna array radiates both up and down, *i.e.*, bidirectional, the effect of inserting a backing ground plane is devastating [1]. The effects of the ground plane can be reduced by radar absorbing material between the antenna elements and the ground plane. This gives a broadband array at the expense of half the power is absorbed in the radar absorbing material.

In this paper, it is shown that stacking of dielectric slabs above planar self-complementary antenna elements can reduce the degrading effect of the ground plane and hence be used to design ultra-wideband antennas. The dielectric slabs act as filters and transform the impedance seen by the antenna elements. The slabs are chosen to be of equal optical thickness, and, hence, resembling the use of quarter-wave length transformers in broadband matching [8, 10, 12]. Numerical results are presented for the infinite antenna array with broadside bandwidths of 4.7:1 at -13dB and of 5.5:1 at -17dB for the cases of two and three dielectric slabs, respectively.

The use of dielectric slabs to improve antenna performance is not new. A dielectric slab can be used for wide-angle impedance matching of planar arrays as shown in [6]. In [8], it has also been shown that dielectric slabs can be used to improve the bandwidth of an array composed of closely spaced dipoles.

2 Patch array

In this paper, we consider an infinite antenna array consisting of PEC patches as depicted in Fig. 1. The patches are fed at the corners of each patch [7] giving a linear polarized field in the $\pm 45^\circ$ directions depending on the used feed points. The patch array is almost self complementary, *i.e.*, the PEC structure is almost identical to its complement. Due to the self-complementary structure, it is reasonable to assume that the characteristic of the patch does not depend strongly on the dimensions

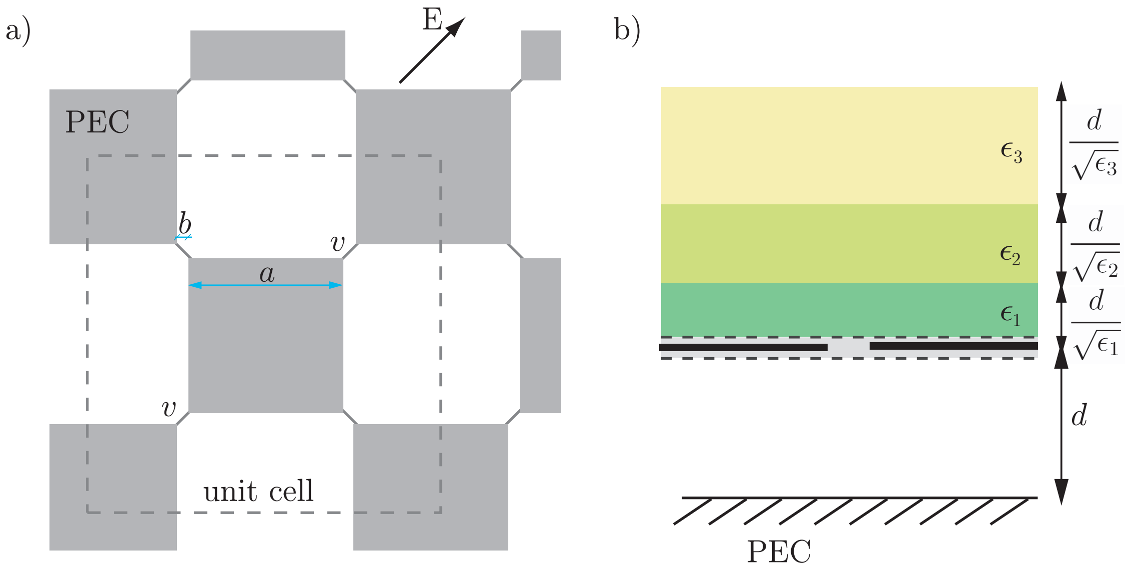

Figure 1: The array geometry. a) top view. The infinite array consists of a periodic repetition of square perfectly electric conductor (PEC) patches fed at the corners. Use of the feed points labeled with a v give a linear polarized field in the 45° direction as illustrated by the arrow. b) side view. Dielectric slabs with optical thickness d are stacked above the patches. The patches together with their environmental protection are placed at the distance d from the ground plane.

of the patch. To start, the width of the patches $a = 3.6\,\mathrm{mm}$ and the feed point distance $b = 0.3\,\mathrm{mm}$ are used, see Fig. 1a. The infinite antenna array can be simulated with either the FDTD, MoM, or FEM as long as the code can handle periodic boundary conditions [3, 8, 11]. Here, the code periodic boundary FDTD (PB-FDTD) developed by H. Holter [3] is used. Numerical simulations, using PB-FDTD, verify that the impedance is frequency independent and equal to $Z_0/2$. The input impedance normalized to $189\,\Omega$ for the frequency range 1 GHz to 20 GHz is seen as the dot in the center of the Smith chart in Fig. 2a.

A thin dielectric slab ('dielectric underware' [8]) is used as an environmental protection of the patch array. From the results in Fig. 2a, it is observed that the thin dielectric slab (1 mm with $\epsilon = 2.33$) hardly changes the impedance at all. The effect is seen as the small arc going from the center in the Smith chart. Due to the constant impedance character of the complementary array, the effect of a ground plane, here at the distance $d = 8\,\mathrm{mm}$, is profound as seen in Fig. 2a. The impedance grazes the rim of the Smith chart at approximately 18 GHz, corresponding to the destructive interference of a ground plane distance of half a wavelength [1]. The effect of changing the ground-plane distance is mainly a rotation and stretching of the impedance in the Smith chart, *i.e.*, a frequency scaling.

We now consider the patch array together with its environmental protection as fixed and improve the bandwidth by placing dielectric slabs above the elements. The transformation properties of the thin slab are minimal [8]. The dielectric slabs

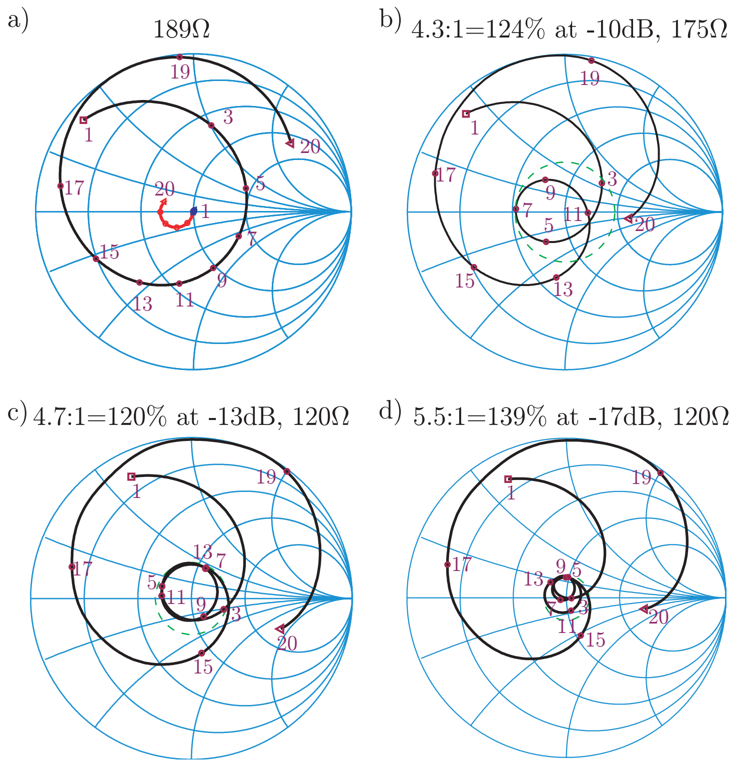

Figure 2: Simulated impedance at broadside scan. The frequencies are given in GHz. a) the patch array as the dot in the center, patch array together with the environmental protection as the short arc leaving the center, and the patch array with environmental protection and the ground plane at the distance $d = 8\,\text{mm}$. The ground plane transforms the impedance to rotate around $Z_0/2$. b) impedance normalized to $175\,\Omega$ for the single dielectric slab with $\epsilon_1 = 4$ giving a $-10\,\text{dB}$ bandwidth of 4:1. c) impedance normalized to $120\,\Omega$ for the two dielectric slabs case with $d = 8\,\text{mm}$, $\epsilon_1 = 7$, and $\epsilon_2 = 3$ giving a $-13\,\text{dB}$ bandwidth of 4.7:1. d) impedance normalized to $120\,\Omega$ for the three dielectric slabs case with $d = 8\,\text{mm}$, $\epsilon_1 = 7.2$, $\epsilon_2 = 3.4$, and $\epsilon_3 = 1.8$ giving a $-17\,\text{dB}$ bandwidth of 5.5:1.

act as a filter matching the antenna for a range of frequencies $f_\text{l} \leq f \leq f_\text{u}$. The upper frequency f_u is limited by the onset of grating lobes and the destructive interference from a ground plane at half a wavelength distance. In analogy with quarter-wave transformers in broadband matching, the ground plane distance and the slabs are chosen to be of equal optical thickness, *i.e.*, a slab thickness of $d/\sqrt{\epsilon_i}$ is used [8, 10, 12]. The case with a single dielectric slab is easily analyzed with a parametric study. The result with a single dielectric slab is seen in Fig. 2b. In this case the dielectric slab can be designed to give one single loop in the center of the Smith chart. The $-10\,\text{dB}$ bandwidth of approximately 4:1 is comparable to the case of wire dipoles above a ground plane without dielectric slabs [8].

It is reasonable that the bandwidth can be improved by stacking more dielectric slabs above the patch array. As the number of slabs increases, the parametric

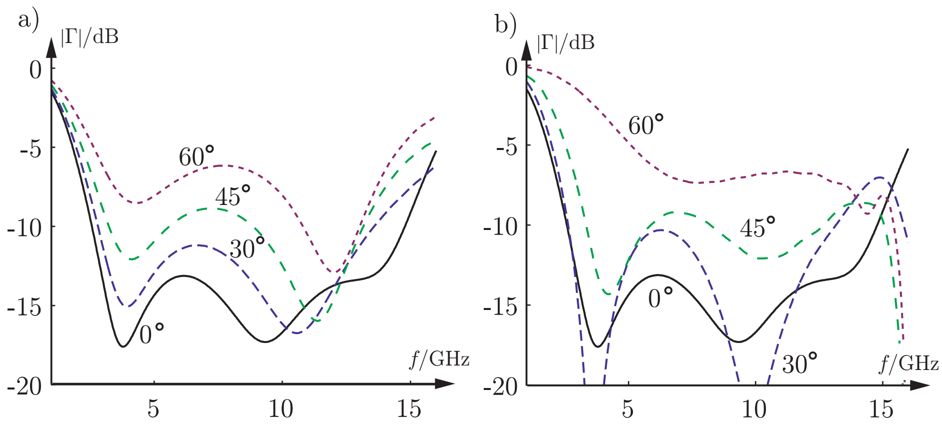

Figure 3: Simulated reflection coefficients normalized to 120 Ω for the two slab case for the scan angles of 30°, 45°, and 60°. a) H plane. b) E plane.

study gets more involved. The effect of stacking several dielectric slabs above the patch array can be analyzed with a global optimization algorithm, *e.g.*, the Genetic Algorithm [4]. However, empirical studies have showed that the permittivities can be chosen from a parametric study of a set of slabs generated by a constant reflection coefficient between two slabs, *i.e.*,

$$\epsilon_i = \epsilon_{i+1}\frac{(1+\rho)^2}{(1-\rho)^2} \tag{2.1}$$

for $i = 1,..,N$ where N is the number of slabs (here $N = 2$ or $N = 3$) and $\epsilon_{N+1} = 1$. The parametric study (or line search) in ρ gives good initial values of the permittivities. These values are easily improved by the use of a parametric study.

The -10 dB bandwidth increases to 5.8:1 and 7.1:1 for two and three dielectric slabs, respectively. The loops are centered in the Smith chart with a normalization of 120 Ω as seen in Fig. 2c and d. As seen in Fig. 2c, the impedance makes two overlaying loops in the Smith chart with two slabs. The third slab adds a loop and hence increases the bandwidth and tightens the impedance to the center of the Smith chart. The property of adding loops in the center of the Smith chart is very favorable as it gives an almost constant magnitude of the reflection coefficient over the matched frequency range. In the sense of Fano theory, this is an optimal behavior. The Fano theory is based on the analytical properties of lossless matching networks and can be used to obtain fundamental limitations on the bandwidth. It states that bandwidth is sacrificed by a perfect match at a discrete set of frequencies [2, 12]. It is also interesting to observe that the property of adding loops in the Smith chart is similar to the result of Chebyshev transformers where each quarter-wave transformer adds an approximate loop in the Smith chart [10, 12].

The magnitude of the reflection coefficient $|\Gamma|$ is used to illustrate the behavior versus the scan angle. The effect of increasing scan angles are shown in Fig. 3 for the two slab. The scan angles 30°, 45°, and 60° are considered in both the H-plane and

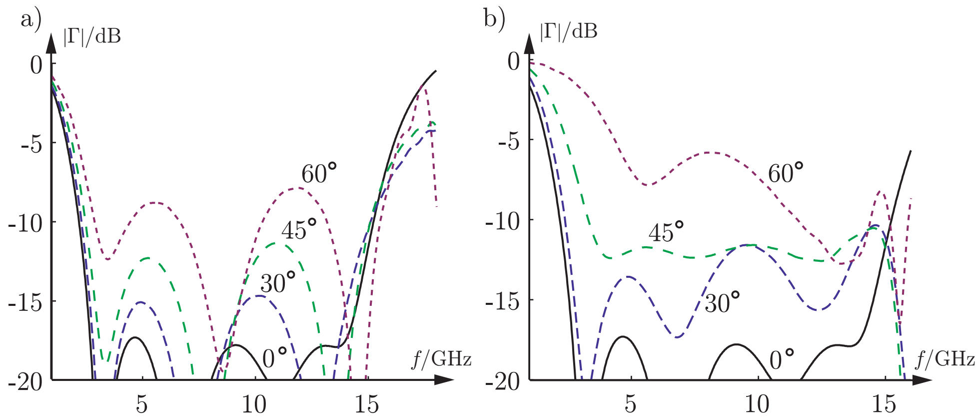

Figure 4: Simulated reflection coefficients normalized to 120 Ω for the three slab case for the scan angles of 30°, 45°, and 60°. a) H plane. b) E plane.

E-plane, where the H-plane and E-plane are the ±45° diagonal planes, see Fig. 1. As seen in Fig. 3, the reflection coefficient increases with increasing scan angle as expected. This corresponds to input impedance loops with an increased radius in the Smith chart. Hence, the bandwidth reduces as the scan angle increases. The −10 dB bandwidth is only slightly reduced for scan angles up to 30°. However, as the scan angle increases beyond 45°, there is a range of frequencies at the center frequencies that is not matched. The corresponding results for three dielectric slabs are shown in Fig. 4. Here, it is seen that the range of scan angles increases up to approximately 45°.

As the impedance of a self-complementary structure is independent of the geometry of the structure it is reasonable that the input impedance of the patch array does not depend strongly on the dimensions of the patch elements. In Fig. 5a, the input impedance, normalized to 120 Ω, of the two slab case is shown for the patch widths 3.6 mm, 4.8 mm, and 6.0 mm. The ground plane distance is 10 mm and the slab parameters are as in Fig. 2c. As seen in Fig. 5a, the input impedance is almost independent of the patch width up to 12 GHz. For higher frequencies the input impedance start to differ as the distance between two feed points approach half a wavelength and hence the onset of grating lobes. The onset of grating lobes at 15 GHz corresponds to a patch width of just above 6 mm. The frequency independent property of the patch array can also be seen in Fig. 5b, where the vertical dimensioning is changed, *i.e.*, the ground plane distance is changed from 7 mm to 14 mm.

To illustrate how the self-complementary property of the patch array is utilized in the antenna, the patch array is reshaped into a new self-complementary structure with square holes, Fig. 6a. The simulated input impedance for the cases with small ($h = a/3$) and large holes ($h = 2a/3$) are seen in Fig. 6b. As seen in the figure, the input impedances of the two cases are similar for the low frequencies. As the frequency increases the input impedances start to differ and for high frequencies (above 15 GHz) they are quite different. However, the considered patch array is

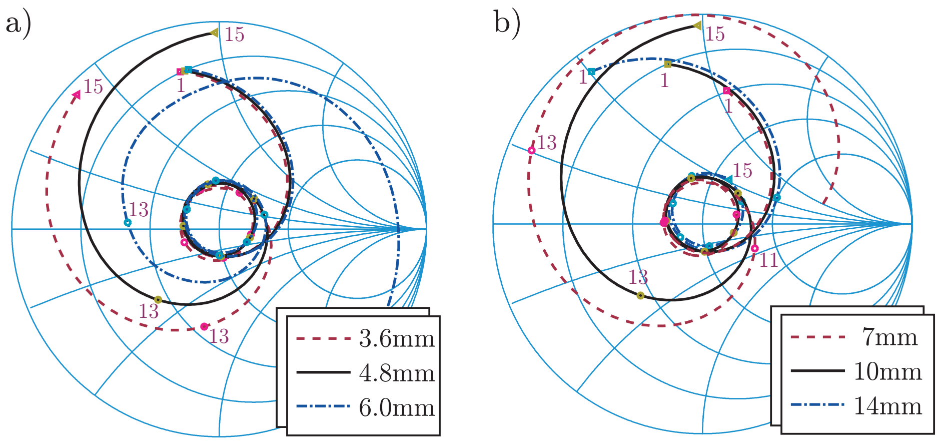

Figure 5: Parametric study of the patch array with two dielectric slabs. The impedance is simulated and normalized to $120\,\Omega$. a) variation of the patch width a for a fixed ground plane distance $d = 10\,\text{mm}$ and fixed dielectric slabs. b) variation of the ground plane distance d and slab thicknesses for a fixed patch width of $a = 4.8\,\text{mm}$.

only approximately self-complementary, *i.e.*, the PEC patches are a little smaller then their complementary structure, due to the feed-point distance $b = a/12$.

3 Conclusions

In this paper it has been shown that infinite self-complementary antenna arrays above a ground plane together with dielectric slabs above the antenna elements can be used to design broadband antennas. The dielectric slabs match the impedance of the antenna elements to free space. It is shown that, at least for the three first slabs, each slab adds one loop to the input impedance in the Smith chart. Moreover, the radius of the loops reduces with increasing number of slabs, and hence reducing the reflection coefficient over a large bandwidth. It is interesting to observe that the circular loop pattern gives an almost constant reflection factor over the matched frequencies. The presented results based on an infinite antenna and a simple feed model indicate that dielectric slabs are useful in the design of broadband arrays based on self-complementary structures. When realizing as antenna design it is of course necessary to improve the model of the feeding network, analyze finite arrays, and obtain experimental verification.

It is interesting to compare the performance of the self-complementary array presented here with results for arrays composed of closely spaced wire dipoles presented in [8]. In free space, the dipole array is broad band but not frequency independent as the self-complementary array. This is utilized in the dipole case by carefully balancing the reactive effects between the dipoles and the ground plane, and hence increasing the bandwidth [8].

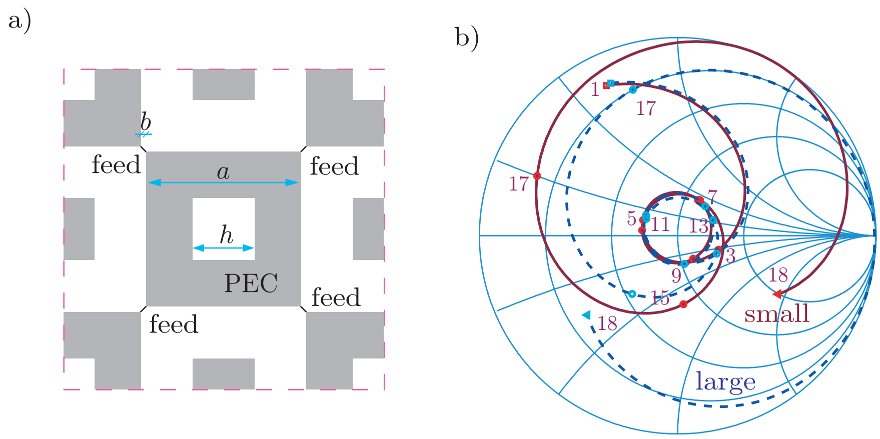

Figure 6: Complementary array. a) unit cell model of the modified complementary array. b) simulated input impedance normalized to 120 Ω for the case of small holes and large holes with two dielectric slabs with $\epsilon_1 = 7$ and $\epsilon_2 = 3$.

Acknowledgments

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References

[1] X. Dardenne and C. Craeye. Simulation of the effects of a ground plane on the radiation characteristics of self-complementary arrays. *IEEE Antennas and Propagation Society International Symposium*, **1**, 383–386, 2003.

[2] R. M. Fano. Theoretical limitations on the broadband matching of arbitrary impedances. *Journal of the Franklin Institute*, **249**(1,2), 57–83 and 139–154, 1950.

[3] H. Holter and H. Steyskal. Infinite phased-array analysis using FDTD periodic boundary conditions—pulse scanning in oblique directions. *IEEE Trans. Antennas Propagat.*, **47**(10), 1508–1514, 1999.

[4] J. Johnson and Y. Rahmat-Samii. Genetic algorithms in engineering electromagnetics. *IEEE Antennas and Propagation Magazine*, **39**(4), 7–21, 1997.

[5] J. D. Kraus and R. J. Marhefka. *Antennas*. McGraw-Hill, New York, third edition, 2002.

[6] E. G. Magill and H. A. Wheeler. Wide-angle impedance matching of a planar array antenna by a dielectric sheet. *IEEE Trans. Antennas Propagat.*, **14**(1), 49–53, 1966.

[7] D. McGrath and C. Baum. Scanning and impedance properties of TEM horn arrays for transient radiation. *IEEE Trans. Antennas Propagat.*, **47**(3), 469–473, 1999.

[8] B. Munk. *Finite Antenna Arrays and FSS*. John Wiley & Sons, New York, 2003.

[9] Y. Mushiake. Self-complementary antennas. *IEEE Antennas and Propagation Magazine*, **34**(6), 23–29, 1992.

[10] S. J. Orfanidis. Electromagnetic waves and antennas, 2002. `www.ece.rutgers.edu/~orfanidi/ewa`, revision date June 21, 2004.

[11] A. F. Peterson, S. L. Ray, and R. Mittra. *Computational Methods for Electromagnetics*. IEEE Press, New York, 1998.

[12] D. M. Pozar. *Microwave Engineering*. John Wiley & Sons, New York, 1998.