Communication

Characteristics of TCDA With Polarization Converting Ground Plane

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Abstract—In this study, we propose a tightly coupled dipole array (TCDA) with a polarization converter (PC) to overcome the bandwidth limitation at \( h = 0.5 \lambda \) and \( 1 \lambda \) of a conventional TCDA. Ultrawideband and low-profile array antennas are gaining considerable attention with widespread of wireless electronic systems. Although TCDA has such characteristics and several advantages compared with others, their bandwidth is still limited by the ground plane (GP) reflection. The use of resistive frequency selective surface (FSS) to overcome this limitation entails ohmic losses which deteriorate the radiation efficiency of the array antenna. In the present study, we propose a 20.9:1 TCDA antenna without resistive FSS. The proposed array antenna employs a PC to overcome the limitation of bandwidth due to GP reflection when the height of the array antenna is \( 0.5 \lambda \) and \( 1 \lambda \). The concept neither involves any dielectric superstrates nor does it introduce any resistive loss. Thus, beam steering is possible without surface wave generation. As a result, the proposed array antenna is expected to be successfully applied to wideband and beam-scannable array with improved performance of wireless electronic devices.

Index Terms—Low-cost, low-profile, low-weight, phased array, polarization conversion, tightly coupled dipole array (TCDA), wideband.

I. INTRODUCTION

Ultrawideband and electrical beam-scannable phased array antennas with low profile are in high demand for many wireless electronic systems. One of these antennas is a Vivaldi antenna [1]. However, it has a high-profile structure. The patch antennas are low profile [2], but their bandwidth is narrow. Uniform amplitude current sheet array (CSA) in free space ideally has infinite impedance bandwidth (IBW) [3] and tightly coupled dipole array (TCDA) imitating CSA has been designed in recent years due to its many attractive features such as low profile and ultrawideband, even on the ground plane (GP) [4]–[9]. Nevertheless, the bandwidth of TCDA is still limited by the GP reflection whenever the height of the array antenna becomes an integer multiple of a half wavelength. Some studies have overcome this by introducing the resistive frequency selective surface (FSS) [10], [11]. Although this can increase the bandwidth, additional ohmic losses more than 3 dB also occur. To reduce these ohmic losses, a complimentary superstrate is introduced. This has been known to reduce ohmic losses to \(-1.4\) to \(-1.1\) dB, where the relative dielectric constant of complimentary superstrate is 4 [12]. However, the high dielectric superstrate can incur the surface waves that, in turn, limit the scan-angle [13]. In addition, a dielectric superstrate inevitably increases the height of array antenna, making it bulky, heavy, and expensive.

In this communication, the characteristics of TCDA replacing the GP to a polarization converter (PC) is investigated. It is a special approach to avoid the GP reflection without inducing any ohmic losses. The potential problems in [12], particularly ohmic losses and surface wave, can be addressed. Our study can help improve radiation efficiency from \(-1.4\) to \(-1.1\) dB to \(-0.7\) to \(-0.0\) dB. Furthermore, in contrast with the structure presented in [12], the proposed structure helps reduce the weight and cost of the antenna since it does not employ the superstrate. Furthermore, the proposed array operates successfully at low frequency bands by employing the perfect electric conductor (PEC) side walls even though it has a small finite size of \(4 \times 4\) TCDA. In fact, the introduction of the PC generates high cross-polarization which is not favorable in general. However, the polarization purity of an antenna may not be critical for easily depolarizing applications, such as mobile communications. Thus, it can be utilized for polarization-insensitive systems as an ultrawideband array antenna. In addition, if the proposed array antenna is rotated by 90°, the orthogonal polarization can be obtained and used to increase the diversity gain of communication systems.

The communication is organized as follows: In Section II, the characteristics of the proposed unit cell antenna is described by an equivalent circuit. In Section III, the performance of a \(4 \times 4\) finite array antenna composed of the proposed unit is presented; performances include array gain, beam patterns, and beam scanning. In Section IV, conclusions are drawn from the study.

II. DEVELOPMENT AND DESCRIPTION OF THE PROPOSED UNIT CELL ANTENNA

In this section, we present the development of the proposed unit cell antenna and explain two advantages obtained by introducing the PC. In the beginning, the impedance characteristics of TCDA in free space and TCDA with a GP are described. Next, we explain the PC design to convert polarization, which can neutralize the effect of GP reflection, so that the antenna acts like in free space. Finally, we combine the PC and the TCDA. Then, we show how the limitation of the high-frequency band is overcome. In the last discussion of this section, by introducing the PC, it is shown that a superstrate is not needed for impedance matching. All electromagnetic (EM) simulations were performed via Computer Simulation Technology (CST-2018).

Fig. 1(a) shows the unit cell of TCDA. Fig. 1(b) and (c) shows the equivalent circuits of Fig. 1(a) with and without the GP, respectively. All PCB boards are FR-4 (\(\varepsilon_r = 4.3, \tan\delta = 0.025\)) and the thickness is 1.6 mm. The 120 \(\Omega\) discrete port is used at the center of the dipole. \(Y_{air} = \sqrt{\varepsilon_0/\mu_0} = 1/377\) is the characteristic admittance of the virtual waveguide [3]. The coupling capacitance \(C_1\) of the equivalent circuit can be obtained by extracting the odd mode capacitance by putting a PEC wall at the center of gap between two dipole arms. The self-inductance of dipole, \(L_1\) can be found by (1) [14]. The self-capacitance, \(C_2\), and the inductance of the dipole, \(L_2\), introduced by Riviore and coworkers [16] are calculated by two different
where $\text{radius of a flat dipole}$ [15], $\text{In general, the bandwidth of TCDA in free space is limited by}$ $r_{xx}$ $\text{broadside direction.}$ $\text{periodic conditions.}$ (a) Unit cell of PC. $\text{Reflection coefficient at the}$ $\text{horizontal plane wave is incident on the PC along the}$ $\text{x-polarized plane wave}$ $\text{polarization.}$ ($\text{Vacuum.}$ $\text{Initial values of these four parameters are calculated and}$ $\text{optimized to be fit with full wave simulation of TCDA in free space.}$ $\text{result, very large bandwidth can be obtained if we choose large}$ $\text{at high-frequency band which is at 2287 MHz in this design. As a}$ $\text{self-resonance frequencies by the following equations:}$ $\text{Fig. 2(a) shows the unit cell of PC that is periodic on the}$ $\text{height } h_{pc}$ $\text{is on the } x\text{-plane with the proper}$ $\text{periodic conditions.}$ (a) Unit cell of PC. (b) Reflection coefficient at the $\theta_\Pi$ $\text{is quarter}$ $\text{wavelength and it is hard to match the impedance to } 50 \Omega$ $\text{array antenna.}$ $\text{Fig. 3 shows the proposed unit cell and its equivalent circuit}$ $\text{of TCDA which is the combination of TCDA and PC shown}$ $\text{in Figs. 1(a) and 2(a), respectively. From 0 to 600 MHz, the equivalent}$ $\text{circuit is same as that given in Fig. 1(b) since the PC acts as GP. From}$ $\text{700 to 2200 MHz, the equivalent circuit is shown in Fig. 1(c). The}$ $\text{reflected wave from the PC, whose polarization is rotated, cannot be}$ $\text{coupled to the dipole due to the orthogonal polarization. As a result,}$ $\text{the TCDA overcomes not only the high-frequency band limitation}$ $\text{at 811 MHz but also at 1622 MHz, which are } h = 0.5 \lambda$ $\text{and}$ $\text{at high-frequency band which is at 2287 MHz in this design. As a}$ $\text{result, very large bandwidth can be obtained if we choose large}$ $\text{and small } C_2$. $\text{Fig. 1(b) shows the unit cell and the equivalent circuit of TCDA}$ $\text{on the GP where } h \text{ and } \theta_\Pi \text{ are the physical and electrical lengths,}$ $\text{respectively, between TCDA dipole antenna and GP.}$ $\text{Fig. 2(a) shows the unit cell of PC that is periodic on the}$ $\text{xy-plane. The operating bandwidth of the proposed PC is improved}$ $\text{to 3.14:1 by modifying the design at a bandwidth of 2.25:1 [17].}$ $\text{When the } x\text{-polarized plane wave is incident on the PC along the}$ $\text{broadside direction, the polarization is converted to } y\text{-direction at}$ $\text{700–2200 MHz, as shown in Fig. 2(b).}$ $\text{Fig. 3 shows the proposed unit cell and its equivalent circuit of}$ $\text{TCDA which is the combination of TCDA and PC shown}$ $\text{in Figs. 1(a) and 2(a), respectively. From 0 to 600 MHz, the equivalent}$ $\text{circuit is same as that given in Fig. 1(b) since the PC acts as GP. From}$ $\text{700 to 2200 MHz, the equivalent circuit is shown in Fig. 1(c). The}$ $\text{reflected wave from the PC, whose polarization is rotated, cannot be}$ $\text{coupled to the dipole due to the orthogonal polarization. As a result,}$ $\text{the TCDA overcomes not only the high-frequency band limitation}$ $\text{at 811 MHz but also at 1622 MHz, which are } h = 0.5 \lambda$ $\text{and}$ $\text{h = 1 } \lambda$, $\text{respectively.}$ $\text{This can be confirmed by the impedance}$ $\text{matching characteristic shown in Fig. 4: without the PC, the IBW for}$ $\text{voltage standing wave ratio (VSWR) } < 3 \text{ is 92–688 MHz (7.48:1),}$ $\text{whereas it is 98–1854 MHz (18.9:1) by introducing the PC to the}$ $\text{TCDA. Herein, dipole and PC are used to obtain extremely wideband}$ $\text{array antenna.}$ $\text{In Fig. 4, the EM simulation results of the proposed unit cell (solid line) are shown to agree well with those of the proposed equivalent}$ $\text{circuits except in the transition region (600–700 MHz). This is because both } x\text{- and } y\text{-polarized waves are reflected from the PC}$ $\text{in this region; this cannot be accurately represented by the proposed}$ $\text{equivalent circuits.}$ $\text{Fig. 5(a) shows the proposed unit cell consisting of a dipole and 100 } \Omega$ $\text{coplanar strip feed line.}$ $\text{Fig. 5(b) shows its matching characteristics for the reference impedance of 100 } \Omega$. $\text{To match the } 50 \Omega \text{ SMA connector, the impedance should be halved}$ $\text{using the ultrawideband balun (MABA-010247-2R1250). The IBW}$ $\text{for VSWR } < 3 \text{ is 98–1854 MHz (18.9:1) which corresponds to the}$ $\text{height of antenna } h + h_d/2 = 0.072 \lambda_{low} \text{ at the lowest operating}$ $\text{frequency.}$ $\text{Fig. 6 shows the unit cell of TCDA with a superstrate which is the}$ $\text{Taconic TLY-5 (s, tan s = 2.2, tan s = 0.0009). } \theta_\Pi \text{ is the electrical}$ $\text{length of the superstrate of height } h_{sup}. \ Y^+ = Y_{air} + Y_{sup}, \ Y^- = -jY_{air} \cot \theta_\Pi \text{ and } Z_{in} \approx j \omega L_2 + 1/(j \omega C_1) + 1/(Y^+ + Y^-)$ $\text{at low and middle frequency band.}$ $\text{For TCDA without a superstrate, } \text{Real}(1/(Y^+ + Y^-)) \text{ is equal to } Y_{air} (=377 \Omega \text{ when the } \theta_\Pi = \text{quarter}$ $\text{wavelength and it is hard to match the impedance to 50 } \Omega$. $\text{Therefore, many people have employed a superstrate to TCDA}$ $\text{since it can reduce the } \text{Real}(1/(Y^+ + Y^-)) \text{ when } \theta_\Pi = \text{quarter}$ $\text{wavelength [4], [6], [8]. However, the roles of superstrate mentioned}$ $\text{above are not required to the proposed antenna because the reactive}$ $\text{energy reflected from the GP does not interact with dipole and the}$ $\text{Real}(1/(Y^+ + Y^-)) \text{ is half of 377 } \Omega \text{ in all the operating band}$ $\text{of PC. Therefore, the proposed antenna does not need a superstrate}$ $\text{for impedance matching which results in a low-weight and low-cost}$ $\text{antenna.}$
III. SIMULATED AND EXPERIMENTAL RESULTS FOR THE 4 × 4 FINITE ARRAY ANTENNA

In this section, the 4 × 4 finite array antenna composed of the proposed unit cells is presented and the performances of gain, beam patterns, and beam scanning are studied. For the finite array simulation, the discrete ports (differential ports) are used for simplicity and the insertion loss of balun chip is included to the realized gain. In order to reduce the boundary effects of finite array, we introduced the PEC side walls at the end of E-plane of the array as shown in Fig. 7 which is similar to the case of unit element [18]. In addition, the GPs are extended by \( w_{\text{ext}} \) along the E-plane.

Fig. 8 shows the pictures of prototype 4 × 4 array antenna. The baluns can be seen under the GP.

Fig. 9 shows the active VSWR for the center element of the 4 × 4 finite array. Measured VSWR is derived by active reflection coefficient as given by the following equation [19]:

\[
\Gamma_i(\theta_0, \phi_0) = \sum_{n=1}^{N} S_{i,n} a_n \exp[-j k_0 (x d_E \sin \theta_0 \cos \phi_0 + y d_H \sin \theta_0 \sin \phi_0)]
\]  

where \( S_{i,n} \) is the measured complex coupling coefficients between element \( i \) and the \( n \)th element of the array, \( a_n \) is the complex excitation coefficient of the radiating \( n \)th element, \( N \) is the total number of elements, \( k_0 \) is the free-space wavenumber. For the broadside radiation, the simulated VSWR shows IBW of 90–1778 MHz (19.8:1) and measured VSWR shows IBW of 91–1901 MHz (20.9:1). In fact, it is found that the scan range is limited by the characteristics of the PC which works for narrow incidence angles.

Fig. 10 shows the simulated and measured power gain pattern (black) \( G_{\text{array}}(\theta, \phi) \), copolarization gain pattern (red) \( G_{\text{coarray}}^{\text{c}}(\theta, \phi) \), and cross-polarization gain pattern (blue) \( G_{\text{array}}^{\text{cr}}(\theta, \phi) \) from scanning the beam up to 30° on the E-, D-, and H-planes. The copolarization
Fig. 9. Simulated and measured active VSWRs of the proposed 4×4 finite array antenna on the E-plane (ϕ = 0°), D-plane (ϕ = 45°), and H-plane (ϕ = 90°).

and cross-polarization patterns are obtained using Ludwig’s third definition as follows [20]:

\[ e^{co}(\theta, \phi) = \hat{e}(\theta, \phi) \cdot (\hat{\theta} \cos \phi - \hat{\phi} \sin \phi) \]  
\[ e^{tr}(\theta, \phi) = \hat{e}(\theta, \phi) \cdot (\hat{\theta} \sin \phi + \hat{\phi} \cos \phi) \]  

where \( \hat{e}(\theta, \phi) \) represents the far electric field of the array antenna. The definition of array gain follows realized gain, which considers impedance mismatch and any ohmic losses including that from the balun chip. The gain was measured by superposition of the active element pattern [21] using the following equation:

\[ E(\theta, \phi) = \sum_{i=1}^{N} V_i g_i(\theta, \phi) \]  

where \( V_i \) is the complex value of excitation, \( i \) is the port number, and \( g_i(\theta, \phi) \) is the complex active element gain pattern of the \( i \)th element. The beam can be steered by controlling the phase of \( V_i \).

Fig. 10. Simulated and measured array gain of the proposed 4×4 finite array antenna with scanning the beam up to 30° on the E-plane (ϕ = 0°), D-plane (ϕ = 45°), and H-plane (ϕ = 90°). The aperture limit is calculated by \( 4\pi NA/\lambda^2 \) where \( N \) is a number of the elements: 16 and \( A \) is physical aperture size of unit element: 120 × 120 mm².

Until 500 MHz, the cross-polarization gain is considerably less than copolarization gain. However, from 600 MHz onward, the gain of cross-polarization is comparable with copolarization while the gain of copolarization is decreased because of the polarization conversion. In addition, \( G_{array}(\theta, \phi) \) increases progressively with frequency and the maximum gain is 15.9 dBi within the operating band when scanning the broadside direction. When scanning to 30°, maximum gain is 15.1 dBi on the E-plane, D-plane, and H-plane. Owing to its size, the anechoic chamber cannot reach the far-field distance at low frequency bands; therefore, the gain was measured from 400 MHz. In fact, the measured results of cross-polarization at 400 MHz are considerably higher than simulated results. We presume
that the reason for that is from the down-shift of operating band of the PC. In addition, the cross-polarization level is lower than the expected value when the array gains are compared in Fig. 2(b). The PEC side walls for the proposed 4 × 4 finite array decrease the cross-polarization level since the rotated y-polarization is weakened at the side elements due to the boundary condition. Thus, it is expected that increasing the number of elements in the finite array will increase the cross-polarization level.

Fig. 11 shows the radiation efficiency and VSWR of the proposed 4 × 4 finite array antenna designed with FR-4 and RF-43 substrates. Notice that the radiation efficiency is significantly different, particularly at high frequency bands since the loss tangent of FR-4 is approximately eight times larger than that of RF-43. The minimum radiation efficiency is higher than 92% at 1901 MHz when using the RF-43 board.

The proposed array antenna is compared with the ultrawideband array antennas in Table I, in terms of their IBW, height, maximum scan angle $\theta_{\text{max}}$, and figure of merit $P_A$. The figure of merit is calculated as follows [22]:

$$P_A = \frac{B \log(1 - \eta_{\text{min}})}{2 \cos \theta_{\text{max}}}$$  (8)

where $B = (f_{\text{max}} - f_{\text{min}})/\sqrt{f_{\text{max}} f_{\text{min}}}$ is the maximum scan angle, and $\eta_{\text{min}}$ is the minimum total efficiency for the claimed IBW and scan range. The total efficiency includes impedance mismatch and ohmic losses. The proposed array antenna has lower ohmic loss without high $\varepsilon_r$ superstrate compared to [12]. In contrast, the antennas in [7] and [23] show higher height and considerably narrower bandwidth.

IV. CONCLUSION

In this study, we proposed a TCDA with PC to overcome the bandwidth limitation at $h = 0.5\lambda$ and $1\lambda$ of a conventional TCDA. The IBW of 91–1901 MHz (20.9:1) with frequency-dependent polarization was obtained. The height corresponds to 0.067 $\lambda_{\text{low}}$ of the array antenna at the lowest operating frequency. Without superstrate, it can be used to scan the beam avoiding surface wave generation and it can be low-cost and low-weight. The measured maximum gain, $G_{\text{array}}(\theta, \phi)$, is 17.4 dBi within the operating band at broadside direction. When scanning to 30$^\circ$, it is 17 dBi on the E-plane, D-plane, and H-plane ($\phi = 90^\circ$). The gain is normalized to $G_{\text{array}}(\theta, \phi)$.

Fig. 12 shows the simulated and measured gain pattern for each types of polarization at 400 and 1400 MHz, respectively. The simulated results show that there is no polarization conversion at 400 MHz. Thus, $G_{\text{array}}^{\text{co}}(\theta, \phi)$ is almost the same with $G_{\text{array}}(\theta, \phi)$ to the main beam direction. Whereas, $G_{\text{array}}^{\text{cr}}(\theta, \phi)$ is comparable with $G_{\text{array}}^{\text{co}}(\theta, \phi)$ since the copolarization is converted to the cross-polarization at 1400 MHz. In fact, the back lobe level at 400 MHz is inevitably high because the electrical size of the GP (0.8 $\lambda$ × 0.64 $\lambda$ at 400 MHz) is small at low-frequency band.

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