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Review on Ultra-Wideband Phased Array Antennas

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ABSTRACT Ultra-wideband (UWB) phased array antennas are essential for radar, communication, and Electronic Warfare (EW) applications. Systems can operate over wide-band coverage. The high gain systems require wide-band, wide-angle scanning, good radiation pattern, and return loss over a multi-octave bandwidth. This review discusses the problems present in the UWB phased array system, which include mutual coupling, grating lobe rejection, active return loss, gain fluctuation with scanning, and multiple beam generation. In this, the aperture size of the array is limited by the overall gain requirement of the system. On the other hand, low gain systems require a wide-band with a good radiation pattern and axial ratio. Here the matching over wide-band is simpler as it depends on broadband balun configuration. This system has limited bandwidth over scan angles. These antennas are more preferred as wearable antennas in communication applications. This paper mainly discusses the existing UWB phased array antennas such as Vivaldi Arrays, All-metal Arrays, Spiral Arrays, Sinuous Arrays, and Coupled Arrays. This review paper presents a correct direction for selecting the type of antenna in terms of impedance bandwidth, gain, and materials influencing antenna performance, suited for different applications.

INDEX TERMS All-metal array, coupled arrays, high gain, low gain, phased array, spiral arrays, sinuous arrays, UWB, Vivaldi arrays, wide-angle scan.

I. INTRODUCTION

Rather than using a single large antenna, several isolated elements can be used in an array to achieve a similar kind of performance. The antenna arrays are more popular due to their high directivity and high gain, which is essential for the majority of applications such as communications, radars, satellites, electronic warfare, and radio astronomy. The antenna array can be formed by arranging identical elements in various geometrical configurations such as linear, rectangular, circular, triangular and spherical, etc. Phased array antenna provides a unique feature of electronic scanning of the radiation pattern. Shape and electronic steering of the array radiation pattern can be controlled by changing the excitation of all radiating elements in terms of amplitude and phase. The vector sum of the electric fields of individual radiating elements yields the array's resultant electric field.

To produce a good directional pattern, the fields of the antenna arrays must interfere constructively in the desired direction and destructively in other unwanted directions. The phased arrays were confined electrically and mechanically by limited impedance bandwidth, scan volume, size, and weight.

Recently, UWB phased array antennas have gained prominence in radars [1], [2], communications [3], satellites [4], next-generation systems (5G) [5], electronic warfare (EW) [6]–[8], and radio astronomy [9]–[13] applications. The demand for higher bandwidth is abrupt increases in commercial applications, as well. Hence, there is an interest in developing UWB antennas that can offer greater performance, such as high gain, conformal, low weight, wide bandwidth, simultaneous multiple-beams, and wide scan capability for phased array applications. They become more attractive and useful in a wide variety of applications if they provide dual or circular polarization. Especially in radio astronomy applications, these UWB array antennas are used as reflector antenna feeds [14], which exhibit wide instantaneous bandwidth and low noise behavior. Numerous antenna technologies for UWB phased arrays used in various applications have been developed over several decades, including tapered slot antenna arrays like Vivaldi arrays, all-metal arrays, coupled

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dipole arrays, and spiral arrays, and sinuous arrays. The above arrays can be classified as high gain and low gain antennas. The high gain UWB system exhibits octave bandwidth, wide scan, and good radiation properties. But, in the case of a low gain system, scan performance is limited. The above mentioned existing UWB arrays are elaborated here.

Out of all, one of the most existing popular UWB antennas is the tapered slot antenna, often known as the Vivaldi antenna, initially proposed by Gibson [15]. These arrays are popular owing to their high gain, wide-band, and wide scan (W-W) capability [16]. The parameters to design the Vivaldi array antenna and its optimization towards bandwidth, scanning, and cross-polarization are described in [17]–[20]. Initially, a dual-polarized ''bunny-ear'' Vivaldi antenna was proposed with limited bandwidth of 5:1 [21]. Later, a low profile version of Vivaldi called BAVAs (Balanced Antipodal Vivaldi Arrays) was developed to achieve 10:1 impedance bandwidth over 1.8 to 18GHz [22]. Even though these array antennas provide wide impedance bandwidth, they undergo unwanted radiation and loss of polarization purity during scanning. However, the performance of BAVA arrays is compromised while scanning, VSWR > 4.5 at a scan angle of 45°. Vivaldi arrays [23] with a crossed-notch configuration provide better scanning performance with low cross-polarization over a band of 7–21 GHz. The new array element [24] has been introduced to overcome the problems associated with Vivaldi arrays, like manufacturing and maintenance drawbacks. In [24], the author offers additive manufacturing as an alternative to conventional subtractive (CNC milling) processes in order to gain production flexibility, batch processing capabilities, and precision. In conclusion, from the above, the Vivaldi arrays are suitable for high gain systems, but it has a serious drawback of maintenance issues when used for dual-polarization.

Another high gain antenna that allows UWB is the all-metal Vivaldi/Body Of Revolution (BOR) antenna. This antenna is made up completely of conducting material. As compared to the Vivaldi antenna, it has higher gain, UWB, wide scan, and mechanical stability, which are more popular in a wide sense.

The planar UWB antenna provides high gain is the coupled dipole antenna. Initially, H. Wheeler acknowledged in 1965 that wide bandwidth could be achieved by the current sheet array [25]. The coupled dipole arrays are initially current sheet arrays with an extension of scanning range and bandwidth capability, which was proposed in [26].

The currents with a wavelength significantly longer than the element size can be supported by coupled arrays. Thus the array allows extension of lower frequency of operation. In constituent, to attain wide scan performance, different dielectric layers [27] are stacked to the array. The detailed topologies are presented in [28], [29]. These arrays are predominately suitable for conformal platforms.

The UWB antenna provides low gain is the spiral antenna. The bandwidth is decided based on return loss of balun characteristics. It is one of the frequency-independent antennas [30]. Out of all frequency-independent antennas, the spiral antenna [31], [32] is the best choice for wide-band applications due to its excellent features, such as broad bandwidth, circular polarization, and compactness. Spiral antennas are further improved by different techniques [33]–[35]. As it has a low gain, mainly these are used in receive applications in military communication. But in radio astronomy applications, the radiating elements are projected on a pyramid or cone shape to get higher sensitivity, low noise, and broadband operation with frequency-independent characteristics. Primarily spiral antennas exhibit excellent bandwidth. However, because of their size requirement and low gain, they are not suitable as phased arrays. But later, the spiral arrays are used in UWB phased array applications [36]–[39]. The spiral antennas bandwidth is restricted by size, where size or outer diameter grows in proportion to the lower working frequency. The spiral antennas bandwidth is increased as a result of this.

Unfortunately, increasing the bandwidth forces the wider element spacing pushes the lowest operating frequency to be lower. This, in turn, gets grating lobes at smaller scan angles. In [40], the author shows two interleaved sub-arrays in a linear array that can eliminate grating lobes as one sub-array for each polarization. The same principle was elongated to concentric ring arrays [41]. An interwoven planar spiral array was projected to improve the coupling of spirals [42]. An interwoven array demonstrates adequate performance at lower frequencies [43], [44]. In comparison to array designs, interwoven arrays will connect every element in the array to mitigate the inductance effect presented by using a ground plane, which will improve the coupling at lower frequencies. Adjacent spirals of paired polarizations with connecting arms will develop dual-polarization [45] capabilities of spiral arrays. These types of low-profile planar array elements [46], [47] suffer from impairment in bandwidth when elements are placed close to the ground structure. Electronic Band Gap (EBG) structures [48] are introduced to reduce the ground plane effects in antennas. But EBG structures operate in a limited bandwidth. In spiral antennas, for wide scan performance, the impedance bandwidth is limited (VSWR-1.5:1).

Apart from the spiral antenna, the element that produces low gain, UWB, and poses frequency-independent nature is the sinuous antenna. A traditional UWB log periodic antenna was modified to a sinuous antenna by DuHamel's [49]. The operating principle of a sinuous antenna is the same as the spiral antenna. But it demonstrates dual circular / dual linear polarization characteristics along with a self-complementary, frequency-independent nature. The features of sinuous make a great option for UWB applications such as radars, electronic warfare, and high sensitivity requirement at square kilometer array radio telescopes [50]–[53]. But in the case of radio astronomy applications, instead of cavity backing structure, sinuous array antennas are arranged on the surface of the cone at 45°. It provides a uniform phase center over broadband and low back lobes. In the next sections, the arrays stated above are explained in detail, along with practical concerns.

Reaming sections of this paper are arranged as follows: Section 2 discusses the issues of UWB array elements. Section 3 demonstrated the existing UWB phased arrays and described their performance. Finally, in section 4, overall conclusions are furnished.

II. ISSUES OF UWB PHASED ARRAY ELEMENTS

The design of array antennas is more sophisticated and challenging than an isolated antenna. According to pattern multiplication theory, the total pattern is the product of the array factor and the element radiation pattern. In general, array antennas start with element design for desired impedance bandwidth and radiation properties, along with optimization of the element in an array environment. The main disputes confronted by UWB phased array antennas are grating lobes rejection in the operating band, mutual coupling/maintaining better active return loss overall scan angles, gain variations and, multiple beams generation are discussed in this section.

A. GRATING LOBE REJECTION

Grating lobes are the lobes the same as the main lobe, which causes interference resulting in a decrease in the gain of the array. Generally, to avoid the grating lobes in phased array antennas, the inter-element spacing [54] of elements will be bounded by wavelength (λ_{high}) at the highest frequency of operation and scan angle.

$$d < \frac{\lambda_{high}}{1 + |\sin(\theta_{0\,\max})|}, \tag{1}$$

where d is the element spacing, λ_{high} is the free space wavelength at the highest operating frequency, and $\theta_{0\,\max}$ is the maximum scan angle, respectively. To eliminate the grating lobes throughout the entire operational band, the antenna elements must be comparable in size at low frequencies. This will lead to strong mutual coupling.

B. MUTUAL COUPLING

In practice, all the array elements are excited simultaneously. To evaluate the impedance matching of the array, mutual coupling between array elements is adopted. This is known as the active reflection coefficient or Active Return Loss (RL).

$$ActiveRL\ S_n = \sum_{m=1}^{N} \frac{b_m}{b_n} S_{nm}, n = 1, 2, \ldots, N, \tag{2}$$

where N is the number of ports, b_m and b_n are the complex excitations of the mth and nth element, S_{nm} is the transmission coefficient between mth and nth element. During scanning, the impedance mismatch problem arises between the ports, which leads to higher active reflection. Also, earlier investigations mainly concentrated on lowering the active return loss, which worsens during scan angle and limits the operating bandwidth of the array.

In addition, antenna inter-element mutual coupling may cause scan blindness. With this, the input power gets reflected; hence, efficiency degrades. The mutual coupling also relies on element type, the orientation of antenna elements, and the components feed network. The antenna array parameters affecting mutual coupling [55], [56] are impedance bandwidth, gain, and wide scanning ability. Therefore, wide-band and better active RL over scan angles is requisite.

C. GAIN FLUCTUATIONS

The gain fluctuations over wide scan angles are also an issue in phased array antennas. The reduction due to gain fluctuations must be less than 3 dB while the antenna is scanning. As per the projection method [57], the array factor directivity will decay by cos (θ_0), where θ_0 is the scan angle. Apart from the directivity, the element beamwidth is also a critical parameter in scanned arrays. In a wide-band antenna, the aperture size is decided by the highest frequency of operation. During wide-angle scanning, the beamwidth at a higher frequency should be narrower to support low gain variations. One method is to enhance the wide-angle scanning in arrays is choosing a wide beamwidth element [58], [59]. Increasing the inter-element spacing can reduce the mutual coupling, improving active return loss, but a grating lobe may appear. Contrary to the above statement, decreasing the inter-element spacing can provide wide beamwidth with lower gain variations over scan angles. It can lead to strong mutual coupling, hence worsening the active return loss. Hence, the design of phased arrays is obstructed by issues like size, bandwidth, and scan angle. These issues are interlinked to each other.

D. BEAMFORMER NETWORK

Another aspect of phased arrays is the multiple beams generation [60]. In advanced phased array antennas, to acquire far-field directional radiation patterns or shaped beam patterns, the beamforming networks [61] provides excitation vectors in terms of amplitude and phase. There are different beamforming networks that exist to generate multiple beams [62] to scan over a broad area or to increase the field of view. To get the desired beamforming in the RF chain without any active component, a passive multi-beam phased array antenna plays an active role. It consists of reflectors, lenses, and various beamforming circuits such as blass matrix [63], butler matrix [64], etc., where it provides a fixed number of beams, each pointing at a predefined direction. As compared to passive, active multi-beam antennas exhibit multiple independently digitally controlled beams [65], [66]. Care must be taken while selecting a beamforming network. In this review, different techniques to generate multiple beams are outlined but not focused in detail.

It can be concluded from the above discussion that designing a phased array antenna with low gain variations, maintaining narrow beamwidth at a higher frequency, avoiding grating lobe, decaying directivity in wide scan angle, and avoiding scan blindness is a challenging task. Therefore, these challenges constrain each other.

TABLE 1. Comparison of ultra-wideband array antennas.

S.No	Antenna Array	Advantages	Disadvantages	Applications
1	Tapered Slot Antenna Array/Vivaldi Array	❖ Low Profile; ❖ wide bandwidth; ❖ Mechanically and electrically flexible; ❖ Maintain low cross polarization over scan angles.	❖ Integration in vertical is complicated; ❖ Requires external wide-band hybrid/balun; ❖ Phase center changes with frequency; ❖ Bandwidth limited at higher scan angles.	❖ Wireless communications; ❖ Radars; ❖ Remote Sensing; ❖ Defence applications.
2	Spiral Array	❖ Multi octave bandwidths; ❖ Circular polarization; ❖ Easy to fabricated.	❖ Not exhibits Linear Polarization; ❖ Limited bandwidth over scanning.	❖ Wideband Communication ❖ Radio Astronomy ❖ Microwave Direction Finding ❖ Navigation ❖ Monitoring of the frequency spectrum
3	Sinuous Array	❖ Multi octave bandwidths; ❖ Dual Circular (RHCP/ LHCP) polarization; ❖ Easy to fabricated.	❖ Not exhibits Linear Polarization; ❖ Limited bandwidth over scanning.	❖ Sensing applications ❖ Defence Industry
4	Coupled Array	❖ Low Profile; ❖ Mechanically and electrically flexible; ❖ Maintain low cross-polarization over scan angles. ❖ Higher scanning rates are possible with wide bandwidth.	❖ Vertical integration is complicated; ❖ Requires external wide-band hybrid/balun; ❖ Phase center changes with frequency;	❖ Mobile communications; ❖ Commercial applications; ❖ Defence Industry.

III. RECENT PROGRESS IN WIDE-BAND ARRAY ANTENNAS

There is a vast future for UWB array antennas. Researchers have proposed UWB array antennas such as Vivaldi arrays, all-metal/body of revolution array, spiral antenna arrays, sinuous antenna arrays, and coupled arrays. The comparison of UWB array antennas is mentioned in Table 1. These array antennas are discussed in detail.

A. VIVALDI ARRAYS

The commonly used UWB array antenna is the Vivaldi array, where it has high impedance bandwidth, high gain, wide scan coverage, dual-polarization, and mechanical stability. As it has predominant features, also, these are more popular in receive-only applications in radio astronomy. In [67], the author presented a focal plane array, cryogenically cooled, and low noise and its realization for radio astronomy applications.

It was developed as part of a European technology demonstrator project called PHAROS, (Phased Arrays for Reflector Observing Systems).

This array mounted at the focus of a large parabolic reflector operates over a 4–8 GHz frequency band. The antenna array with radome is shown in Fig. 1. The author explains the front-end design implementation with low noise amplifiers and beamformer networks [68]. The low noise amplifier provides low loss with low thermal conduction RF connections

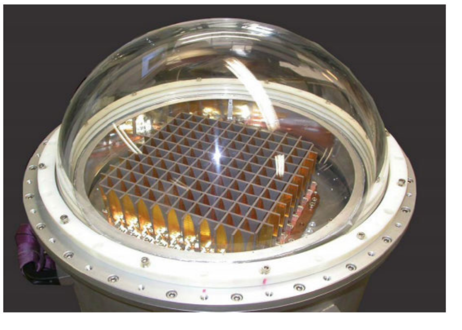


FIGURE 1. [67] Vivaldi antenna with Radome.

to the beamforming system. This system consists of four beamformer modules; each beamformer has 13 RF inputs. The formation of the number of beams over the array field of view decides the imaging and surveying speed of the radio telescope in astronomy. The beamformer systems play an important role in this type of array.

In [69], a dual-polarized 8×9 elements Vivaldi antenna array has been used for the focal plane array demonstration of the PHAROS project. This array operates over 4–8 GHz band. The antenna should design carefully as the antennas are placed into the cryostat to get a low system temperature. Fig. 2(a) and (b) shows the front and back view of the array. It consists of a beamformer network, where the beams are synthesized using an analog beamformer network [68]. Fig. 2(c) shows the radiation pattern of the antenna array. As it

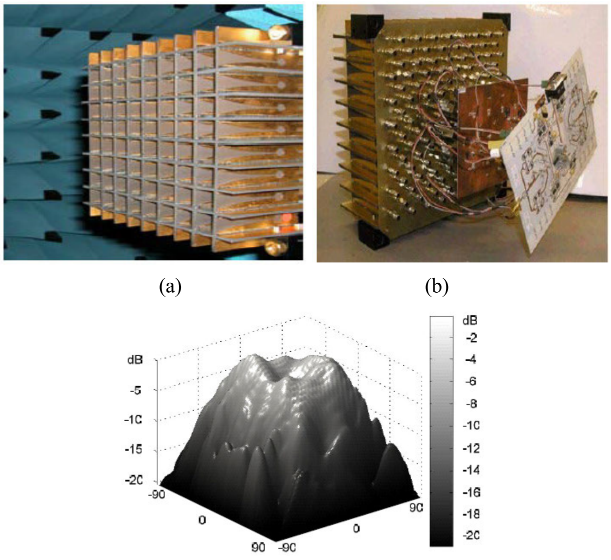


FIGURE 2. [69] Vivaldi antenna array (a) front view (b) back view with beam former unit (c) radiation pattern.

provides significant improvements in illumination performances and single beam capability, these focal plane arrays are of great importance for radio astronomy applications.

B. ALL-METAL / BODY OF REVOLUTION (BOR) ARRAY

Out of all advantages, the Vivaldi antenna can be built entirely of metal, making it structurally robust, stable, and simple to construct. To achieve ultra-wide bandwidth, researchers first developed Body-of-Revolution antennas based on microstrip patch antennas [70], [71]. In [72], a tapered slot dual-polarized broadband phased array antenna made of full metal is presented. These array antennas have prominent applications in electronic warfare and communications. This antenna is mechanically stable. This paper presented BOR elements with dual-polarization and it is easy to plug and unplug with the active modules. A 17×10 dual-polarized all-metal phased array with a 6–18 GHz bandwidth and a 45° conical scan volume were realized in [72] and is shown in Fig. 3. There are $18 \times 10 = 180$ bullet-like protuberances in a circularly symmetric pattern in this array. For x and y polarized elements, feeds are given in the spacing across each protrusion in each x and y-direction. There are a number of feed points of 17×10 for horizontal polarization and 18×9 for vertical polarization. Fig. 3(c) and (d) show the active reflection coefficients of the center elements measured in the E and H plane, respectively. In these contour plots, the active reflection coefficient magnitude is displayed in linear scale in the context of frequency (4–18 GHz) on the y-axis, while scan angle (−70° to +70°) is on the x-axis. Contour lines are given for the values of 0.3, 0.5, and 0.7 (to make these plots as easily understood as feasible). A VSWR of around 1.9 corresponds to the value 0.3; it comes close to meeting the criteria of a VSWR < 2. This VSWR is necessary for scan angles up to 45° in all planes in the

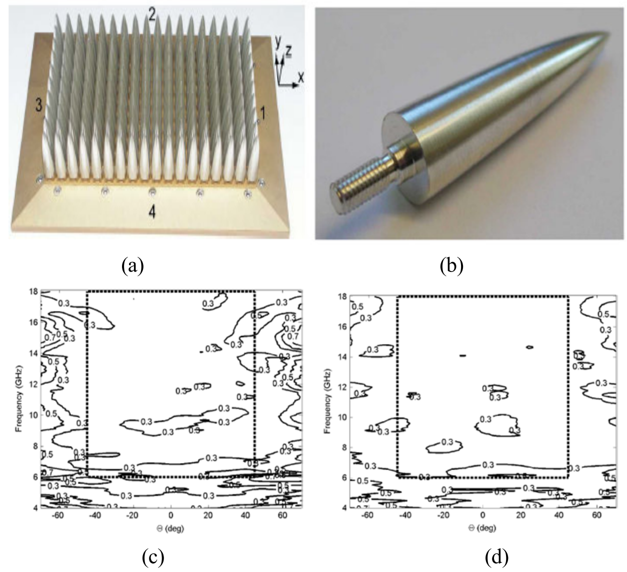


FIGURE 3. [72] Dual polarised phased array made entirely of metal (a) manufactured element (b) manufactured all-metal bullet-like array, the overall size is about 16 cm × 9 cm (c) E-plane scan active reflection of the central element (d) H-plane scan active reflection of the central element.

operating frequency range. The advantage [73] of the BOR array over the tapered slot array is maintenance simplicity due to the fact that its neighboring elements are not related to one another. These antennas are a better choice as there is no dielectric loss.

C. SPIRAL ANTENNA ARRAYS

It is one of the ultra-wideband radiating elements widely used in electronic warfare and radio astronomy applications. In general, spiral antennas have lesser gain. Hence these are more suitable for receive applications. Especially, this antenna has a low profile, used as a wearable antenna in defense applications. Despite the lower gain, this antenna provides circular polarization over a multi-octave bandwidth. A spiral antenna's radiation principle is explained based on the current band theory [74]–[76]. Instead of getting 2:1 bandwidth with dual-polarized cavity-backed spiral antenna, connected spiral array antennas [77] can achieve more bandwidth. With the same size of spiral, using concentric ring configuration, with connected spirals bandwidth is expanded three times more than the original 0.35–2.1 GHz (6:1). The connected spiral array consists of eight spirals arranged in ring fashion is shown in Fig. 4(a), and its side view is shown in Fig. 4(b). This array achieves a low sidelobe level and scan performance up to $\theta = 30°$. As shown in Fig. 4(c), the sidelobe level relative to the main beam is < -10 dB from 0.35–1.1 GHz (RSLL < -10 dB). The array radiation pattern as simulated and measured presented for two cuts $\varphi = 0°$ and $\varphi = 45°$ at 500 MHz is shown in Fig. 4(d) and (e). Due to the sequential rotation technique implemented in a circular array, good circular polarizations of LHCP and RHCP are achieved with cross-polarization levels of greater than 15 dB. Because the elements are separated

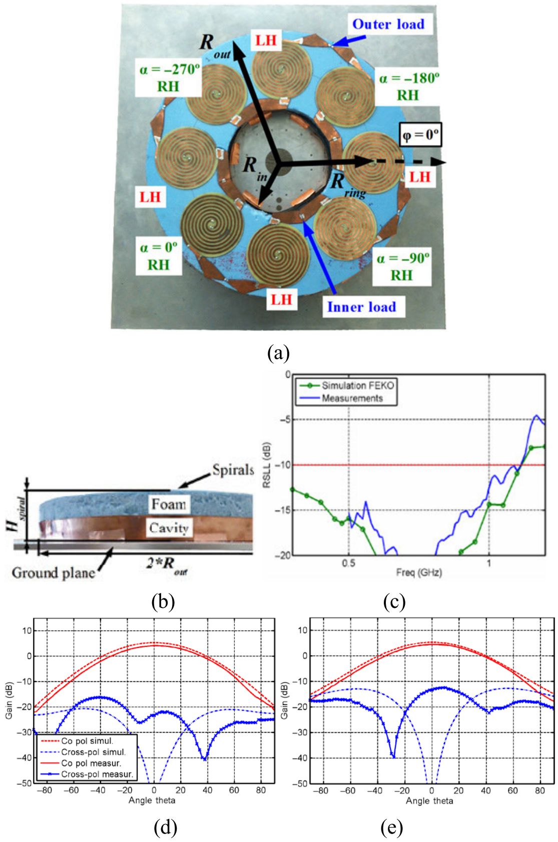


FIGURE 4. **[77] Manufactured array (a) view from the top (b) view from the side (c) relative Side lobe level of antenna (d) radiation pattern at $\varphi = 0°$ at 500 MHz (e) radiation pattern at $\varphi = 45°$ at 500 MHz.**

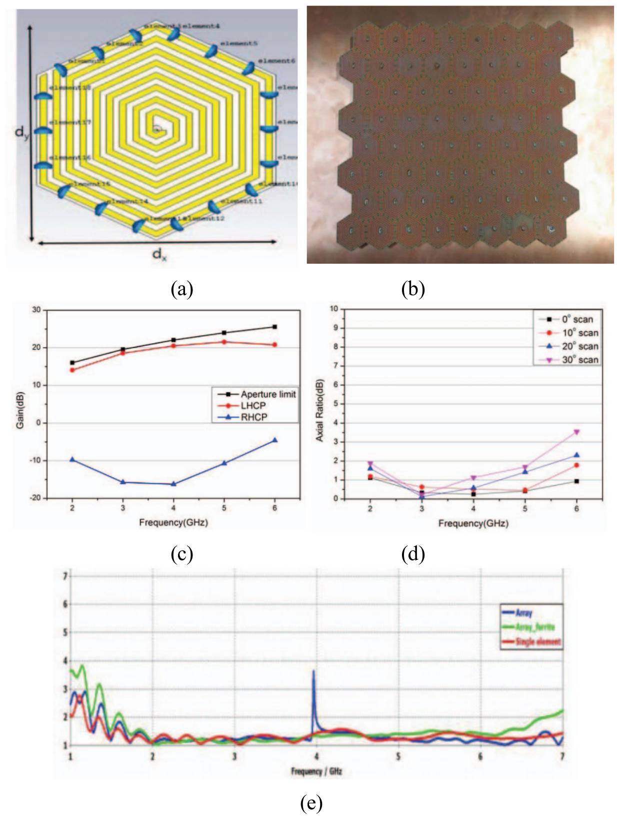


FIGURE 5. **[78] Hexagonal spiral array (a) simulated spiral element (b) manufactured array (c) gain (d) axial ratio (e) VSWR of a single element and array.**

by 21.92 cm, no scanning and alternative four elements used for one polarization, there is a chance of appearance of grating lobes at below 1.37 GHz providing grating zone free area of lower than 1.1 GHz. This drawback can be eliminated by increasing the number of concentric rings and fine-tuning their radii [77]. With this, the grating lobes can be controlled independently.

In [78], a balun less hexagonal spiral array antenna is presented in Fig. 5. The array is constituted with hexagonal spirals fed by a 50-ohm coaxial cable. This circularly polarized array operating over 2–6 GHz without a grating lobe and achieved scan performance up to 30° within 3:1 bandwidth. As the array is a periodic structure, the author introduces ferrites to suppress the resonances appearing at the feeding structure. In [78], the author presented a fabricated and measured prototype 8×8 array, and its results are shown in Fig. 5. The gain plot in Fig. 5(c) shows the higher gain of 21 dB achieved at LHCP polarization.

As the antenna operating in LHCP polarization, see Fig. 5(d), the array shows less than 3.5 dB of axial ratio at a 30° scan angle. In this array, a triangular lattice of spiral elements is used to prevent the occurrence of grating lobes. As a result, a VSWR of less than two is shown in Fig. 5(e). Still, the axial ratio improvement is needed at higher scan angles to get a better circular polarized antenna.

In [79], a 2–14 GHz dual-polarized ultra wide-band conical quad spiral antenna as a reflector feed for radio astronomy receiving applications is presented. In this, dual-polarization (either RHCP or LHCP) is achieved with combinations of excitation of opposite spirals. Fig. 6(a) shows the axes symmetry of four spirals is at an angle of 16° with a Z-axis. As the array is meant for receiver applications, LNA is connected through the unbalanced port of the wide-band balun. The configuration of four baluns is shown in Fig. 6(b), and its s-parameters are presented in Fig. 6(c) and (d). Which shows the common-mode rejections are better than -10dB. The co and cross polarizations of the manufactured antenna are presented in Fig. 6(e). This antenna is an option wherein radio astronomy, receiving applications.

D. SINUOUS ANTENNA ARRAY

This is also one of the widely used ultra-wideband antennas. The predominant feature of this antenna is dual-polarization. Due to lower gain, these antennas are used in receive applications. Fisher & Bradley [80], [81], selected a sinuous antenna as a full sampling array receiver for parabolic dish antenna, with the inter-element spacing of 0.7λ at an operating frequency of 1.4 GHz. Fig. 7 shows the array of nineteen-element dual-polarized sinuous antennas placed in a hexagonal pack. The aperture arrays at low frequencies are cost-effective as its size is bigger and it needs wide bandwidth, dual-polarization, and highly directional

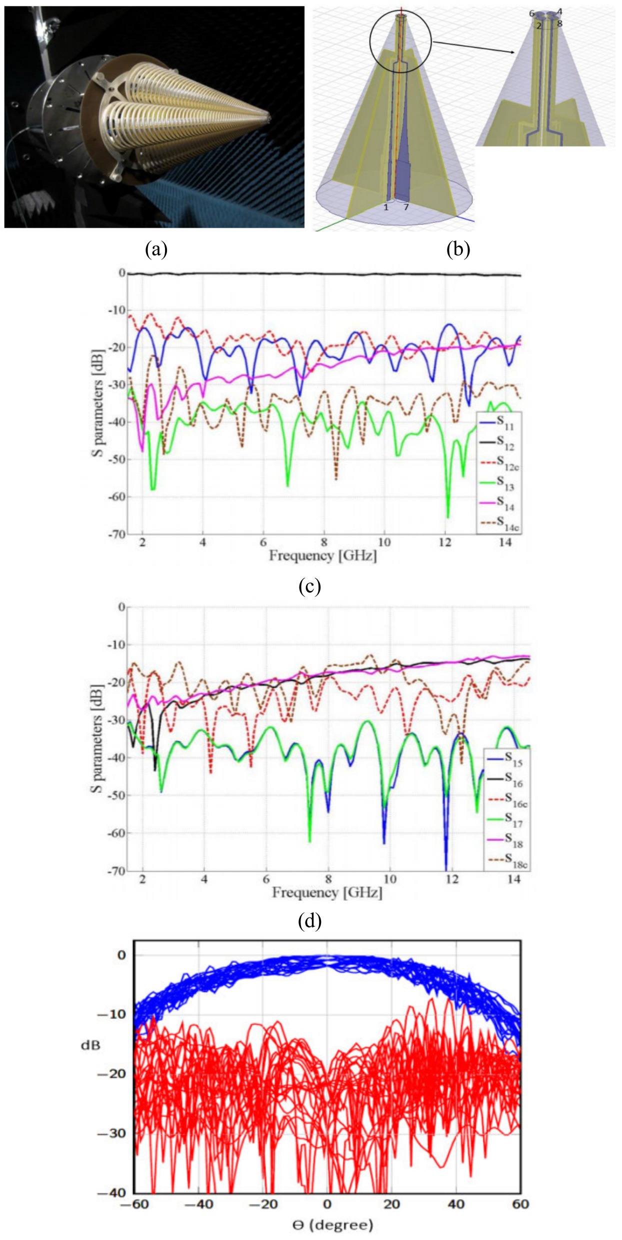


FIGURE 6. [79] Conical quad-spiral Array (a) fabricated antenna (b) four balun configuration (c) S-parameters between port1 and port with same polarization (d) S-parameters between port1 and port with other polarization (e) radiation pattern.

radiation pattern. Hence, the chosen sinuous array is an aperture array. This is suitable for low noise application.

In [82], the author presented a triangular lattice sinuous antenna array over 4–18 GHz bandwidth. Its dual-polarization characteristic is an attractive feature for Electronic Warfare (EW) applications. In this paper, the return loss optimization has been done with different growth rates with fixed outer diameters. The dense arm achieves better return loss. The simulated model is shown in Fig. 8(a).

The active return loss of unit cell approximation of sinuous antenna to an extent to infinite array is

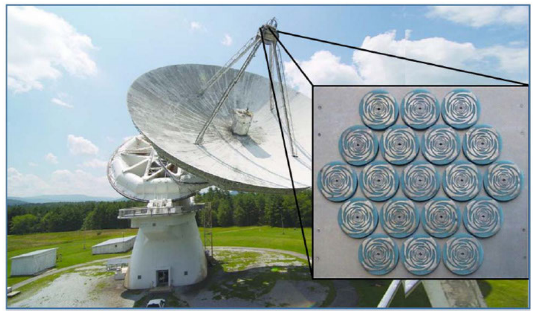


FIGURE 7. Hexagonal 19 element sinuous array.

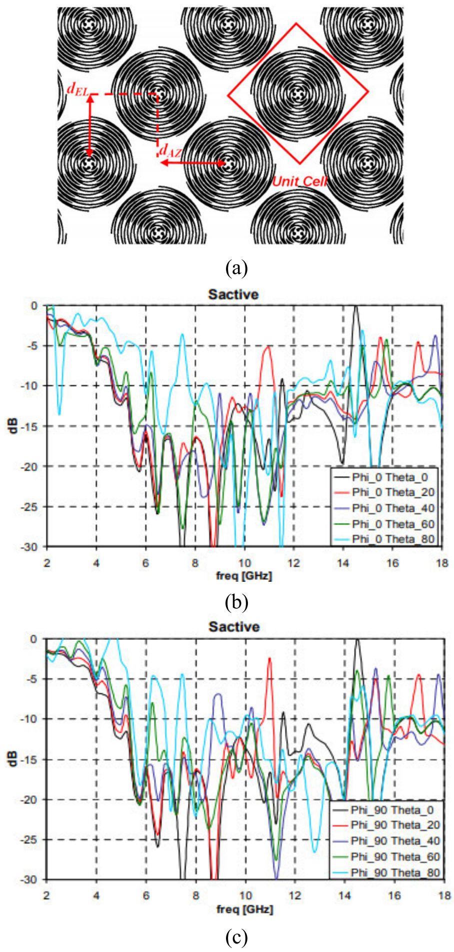
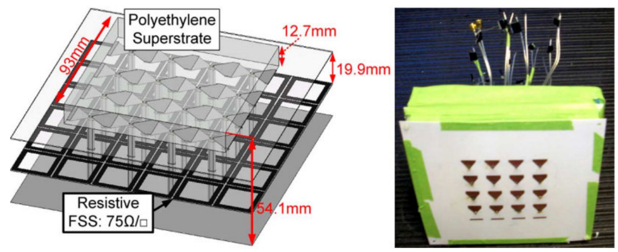


FIGURE 8. [82] Sinuous antenna array (a) simulated model (b) active return loss of unit cell model at different scan angles phi =0° (c) phi =90°.

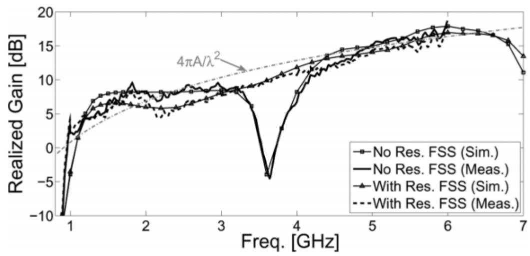
shown in Fig. 8(b) and (c). This shows peak resonances at 15 GHz. Due to the infinite array approximation, these resonances have occurred. But, these antenna arrays are best suited as low-profile structures with broadside radiation characteristics.

E. COUPLED ARRAYS (CA)

Coupled Array antennas have become more popular in recent investigations owing to their low profile with ultra-wideband, wide scan performance, and better polarization purity



(a)



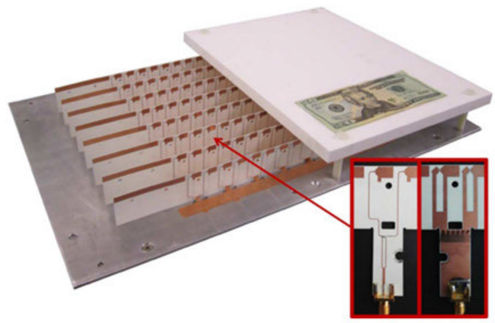
(b)

FIGURE 9. **[83] (a) Fabricated 4 × 4 coupled bowtie array prototype (b) broadside gain of array prototype.**

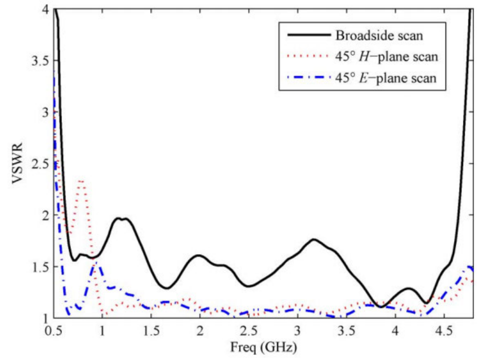
characteristics. These array antennas are more popular in EW and communication applications.

In 2012, [83] Coupled bowtie array proposed with resistive FSS structure and superstrate loading shown in Fig. 9(a). Fig. 9(b) depicts the gain, without FSS deteriorates at ∼3.6 GHz, and with the resistive FSS, the upper frequency of operation increases to 5.91 GHz, attaining a VSWR ≤ 3 over 21:1 bandwidth. In this article, the twin 50 Ω coaxial lines are soldered to the elements. These lines are fed by two 16-way power splitters with a 180° hybrid coupler. As mentioned, the feed network has 2-7 dB loss, and it must be deducted from the measured gain shown in Fig. 9(b). With a complementary superstrate structure across the band, this array obtains a radiation efficiency of more than 73%.

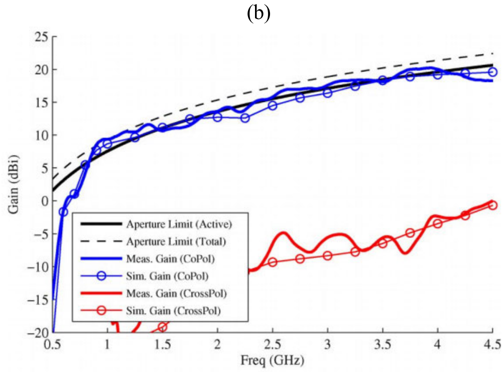
Fig. 10 shows a tightly coupled dipole array (TCDA) with an integrated balun (IB) [84]. Initially, the concept of TCDA-IB was reported in [85], [86]. In this configuration, dipole elements and balun are printed together on three layer board. The major problem in connected arrays is common-mode [87], [88] currents. When the length of the vertical balun feed reaches λ/2, the common-mode resonances present. Hence to avoid this, the author chooses the length of the balun to be 93% of λ/2. Another possible source of resonances is the surface waves [89], which are present in scanned arrays. This occurs when the array supports traveling waves at a particular scan angle. But in TCDA's surfacewaves can be avoided using a low dielectric superstrate. On the single substrate, the array and the balun both are printed; hence their cost and weight are minimal. Fig. 10 shows that, due to the removal of an external balun, bandwidth is amended by 30%, E and H plane scanning range of ±45° and 6.6:1 bandwidth with an active VSWR < 2.65 is achieved. This array with dual-polarization configuration achieves low cross-polarization of < −20 dB in the entire band of operation. The measured VSWR in Fig. 10(b) showing less than 2:1 at broadside and under 2.5:1 at a ±45° scan in both E and H planes. The measured co and cross-polarized gain at 45° scan angle are shown in Fig. 10(c) and 10(d).



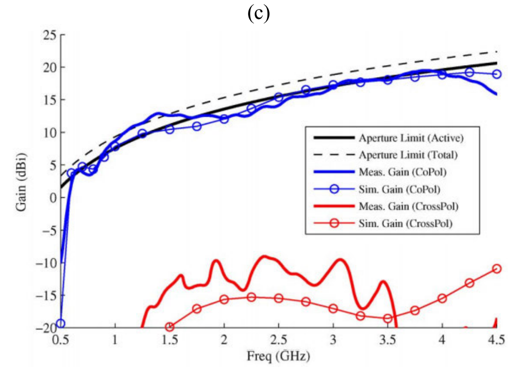
(a)



(b)



(c)



(d)

FIGURE 10. **[84] TCDA-IB 8 × 8 prototype a) prototype b) measured VSWR c) measured H-plane gain at scanning of 45° d) measured E-plane gain at scanning of 45°.**

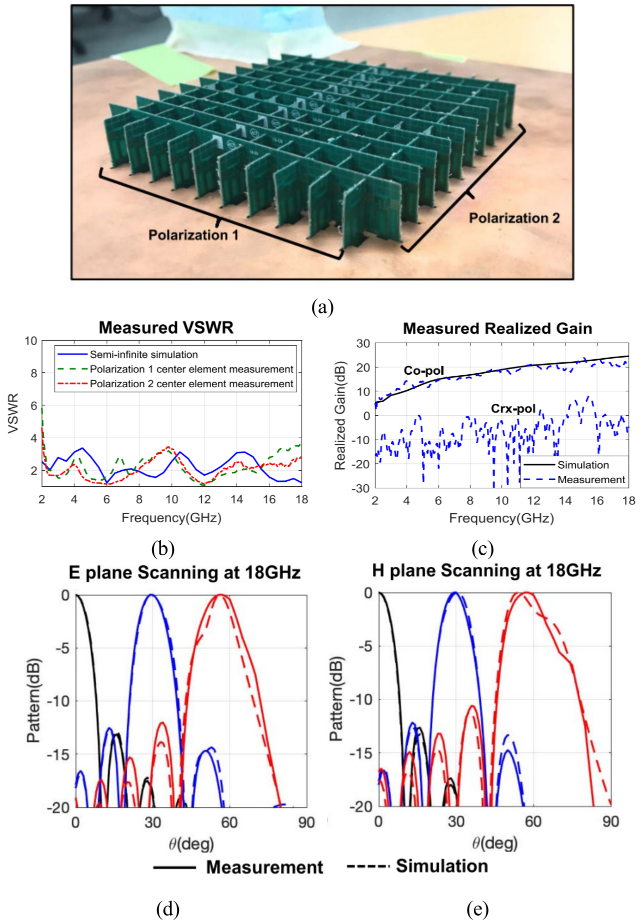


FIGURE 11. [90] UWB TCDA with dual linear polarized (a) manufactured prototype (b) center element return loss (c) simulated and measured realized gain (d) E-plane scanning @18 GHz and (e) H-plane scanning @18 GHz.

In [90], a feed integrated 11 × 11 coupled dipole array was confronted, as shown in Fig. 11. This is an extension to work presented in [84], where the scanning range is limited to 45°. The dual linear polarized array operates over 2–18 GHz and achieves scanning performance up to 60° within 9:1 bandwidth. The prototype array's measured center element VSWR is displayed in Fig. 11(b). This shows VSWR < 3 over 2.1–18 GHz. Measurements of realized gain and radiation patterns were carried out using the unit element active excitation method [91] proposed by D. M. Pozar. The pattern and gain of each radiating element are measured while everything else is terminated by a 50 Ω load. The previous works [92], [93] exhibits larger bandwidth. The double-layer FSS superstrate was implemented [94] to improve the wide-band scan performance.

In [95], the author presented the enhancement of scanning performance using the FSS superstrate. Fig. 11(c) shows the realized gains at the broadside of the antenna. Fig. 11(d) and (e) illustrate the normalized radiation patterns in the E-plane and H-plane, simulated and measured, respectively. Since the only radiating aperture is planar, these arrays are difficult to scale to lower wavelengths.

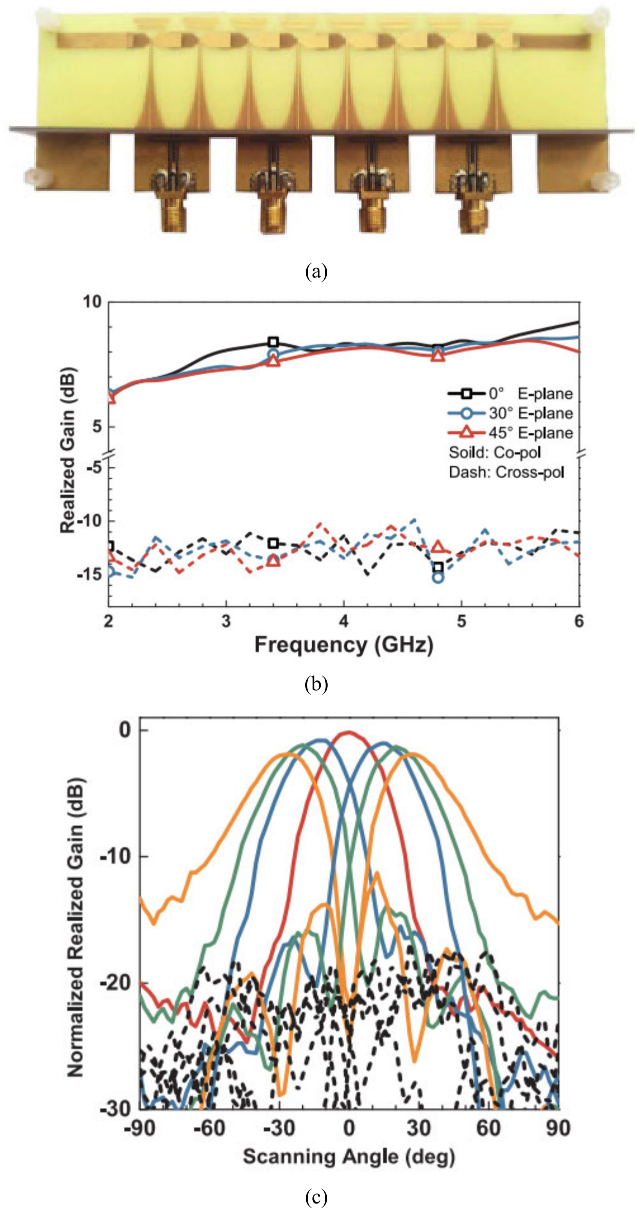
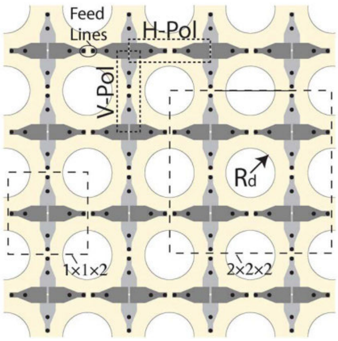


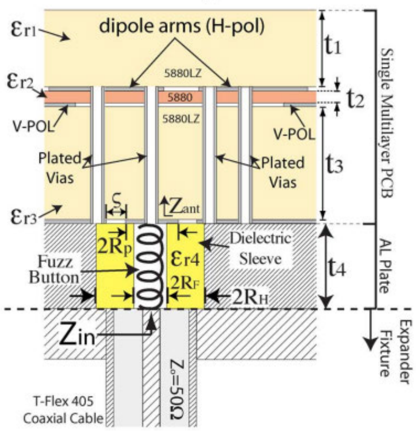
FIGURE 12. [96] (a) TCDA prototype (b) measured gain (c) normalized E-plane pattern at 5.5 GHz.

In [96], the author presented a wide-band coupled dipole array thickness of 0.176 λ_{low} operating from 2 to 6.0 GHz with a high gain of 6.9 dBi and scan coverage of ±45° from the broadside. The prototype of the 1-D 8 element TCDA array is shown in Fig. 12(a). In this paper, the author provides expanded dipole arms with parasitic strips to the TCDA. When parasitic strips [97], [98] are added to the TCDA, the bandwidth enhances. The insertion of parasitic strips balances the TCDA's capacitance. The dipole arms are extended to diminish the effect of surface wave propagation.

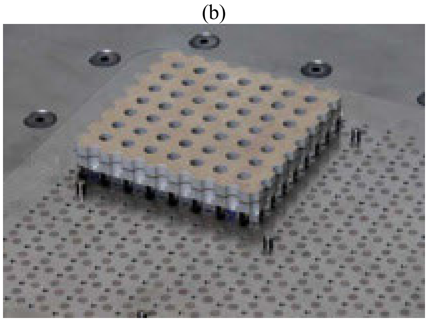
The measured realized gain and E-plane radiation pattern at 5.5 GHz are shown in Fig. 12(b) and (c). Over the operational band of 2.2–6 GHz, impedance bandwidth is enhanced by 92.7 % using tight coupling dipole components, parasitic strips, and a feed network.



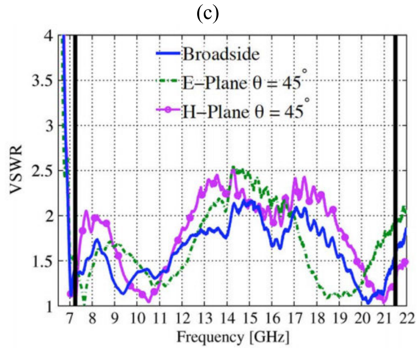
(a)



(b)



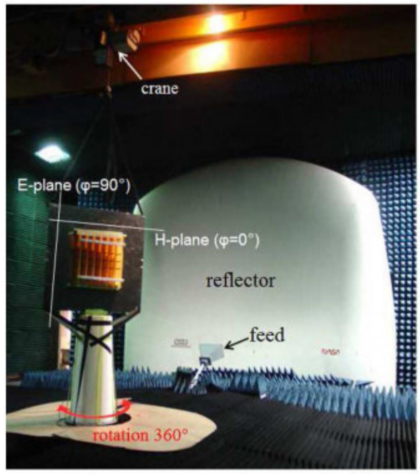
(c)



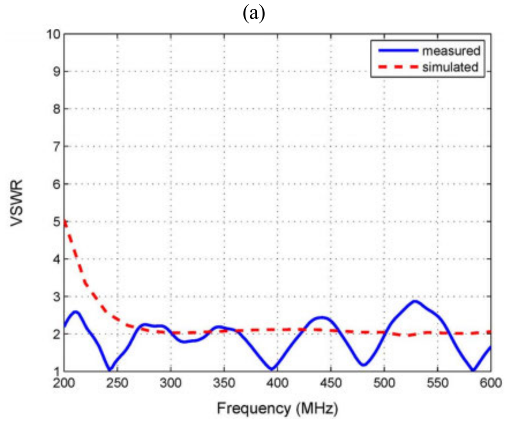
(d)

FIGURE 13. [99] 7–21 GHz dual-polarized array (a) CAD model of dipole layers (b) single element cross-section view (c) mounting of array module (d) 16 × 16 array center element active VSWR.

In [99] author presented the design of a low-cost 16 × 16 dual-polarized PUMA (planar ultra-wideband modular antenna) array working in 3:1 bandwidth from 7–21 GHz is shown in Fig. 13.



(a)



(b)

FIGURE 14. [102] (a) Measurement setup of dipole array (b) measured and simulated VSWR.

This array comprises coupled dipole elements printed on a grounded substrate material. In this, the feeding technique to excite the dipoles is implemented using unbalanced 50-ohm ports, which decimates the use of outer wide-band balun and hybrids shown in Fig. 13(b). In Fig. 13(b), through a short solderless impedance transformer, the right side feed line is connected to the ground directly, whereas the left side through is connected to the inner conductor of a 50 Ω coaxial line. As shown in Fig. 13(b), the dipole arms are connected to the ground via an additional pair of plated vias, as it eliminates the common-mode resonances [87]. The PUMA [100] array assembly can be done modularly using multilayer PCB emulation, which provides robust, low cost, and fully planar fabrication as in Fig. 13(c). The PUMA array achieves center element VSWR < 2.1 over the complete operating frequency band and VSWR < 2.8 over the scan coverage of ±45° from the broadside, as shown in Fig. 13(d). This array obtained cross-polarization values of below 15 dB over the frequency band and the scan coverage of ±45° in all the planes. The PUMA array allows full planar array fabrication.

Generally, finite coupled dipole arrays suffer from less mutual coupling at edge elements, which changes the edge elements from wide-band to narrowband [101]. In this

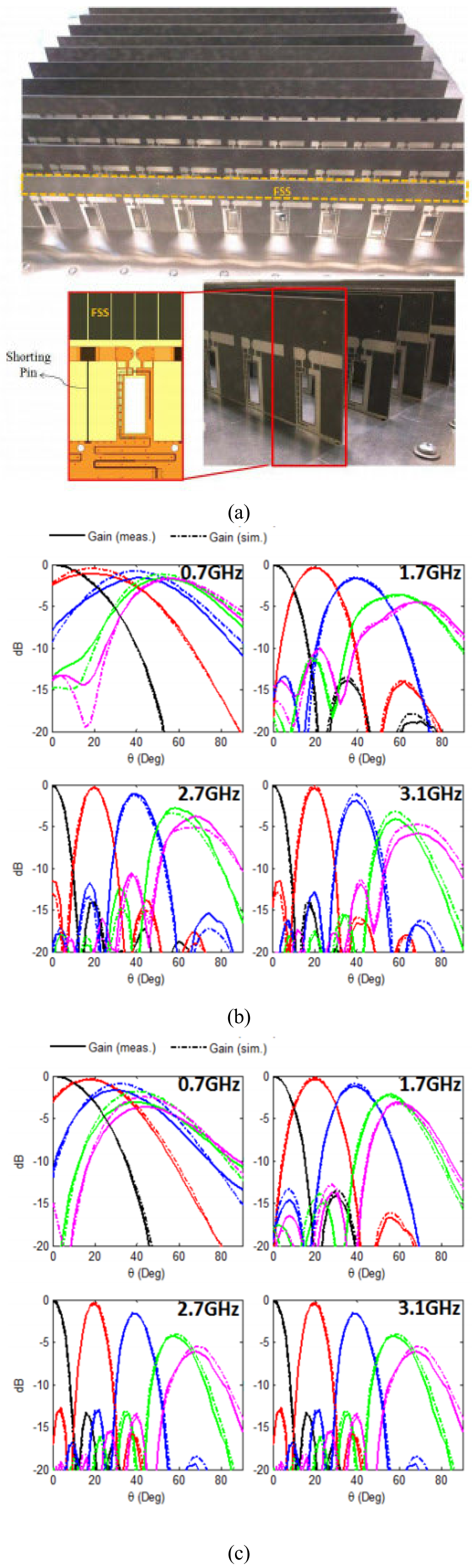


FIGURE 15. **[103] Coupled dipole array using FSS superstrate (a) 12 × 12 fabricated prototype array (b) E-plane scanning (c) H-plane scanning for scan angles of 0°, 20°, 40°, 60°, and 70°.**

article [102], the author uses commercially available coil-based ultra wide-band balun. In this balun, 50Ω coplanar waveguide (CPW) interconnects with coplanar strips. In [102], the author presented the coupled phased array with uniform excitation of all center elements and bypassed edge elements with matched load or resistors. With this, the array achieves 3 dB more gain and increased 50% efficiency. The demonstrated 7×7 dipole array operating from 200–600 MHz is shown in Fig. 14(a). The measured and simulated VSWR are shown in Fig. 14(b).

Earlier literature coupled dipole arrays use dielectric superstrates to enhance the scan performance up to ±60°. In [103], the author presented coupled array with FSS layer printed on the same layer instead of using bulky dielectric layer separately is shown in Fig. 15, achieves 0.5–3.1 GHz impedance bandwidth with VSWR < 3.2 over the scan angles of ±75° in E plane and ±60° in H plane.

IV. CONCLUSION

A comprehensive review concerning UWB phased array antennas for various applications has been carried out in this paper. Issues of ultra-wideband phased arrays such as grating lobes rejection, low profile, wide-angle scanning, ease to manufacture, low gain variations, better active VSWR, and multiple beam generation are still need to be amended to encounter the challenging demands of radars, communications, satellites, and 5G applications. Some beamforming techniques for producing multiple beams are mentioned. However, it is not detail-oriented. Most of the existed UWB array antennas, such as Vivaldi arrays, all-metal Arrays, spiral arrays, sinuous arrays, coupled arrays, etc., are discussed. From this review, it is clear that Vivaldi arrays, all-metal arrays, and coupled arrays are classified as high gain arrays. As seen in the literature, these systems exhibit UWB, wide scan, and good radiation properties. The spiral and sinuous arrays are defined as low gain arrays. These exhibit UWB, circular polarization, and good radiation properties, but scan performance is limited. The selection of the antenna arrays for high and low gain systems relevant to different applications is explained.

Although a lot of research has been proposed for realizing the ultra-wideband wide scan phased array antennas, demands are increasing day by day.

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