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Wideband Antennas of Passive Seekers for Anti-Radiation Missiles

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ABSTRACT

Suppression of Enemy Air Defence (SEAD) is a fundamental element of Air Power application by means of in protecting friendly air attackers and destroying the enemy's ability to defend against air attack. Most of the SEAD operation even today relies on Anti-radiation missile (ARM) which is an air-to-surface tactical missile designed to detect, seek, attack and destroy opponent's radar. Passive seeker of ARM is a miniaturized ESM receiver which is capable of extracting the necessary angular data from the enemy radar emissions. Single head passive seeker covering wide frequency range from L to Ku band is the preferred choice. Wideband antennas have been designed and utilized for Direction Finding applications of ESM/ELINT receivers for ground, air and ship borne platforms. Unlike these platforms, there are several restrictions for passive seeker based compact ESM receiver for missile borne platform specially air to surface missile where lesser diameter is one of the preferred design parameter. This review paper mainly discusses the existing wideband antennas such as spiral, log-periodic, printed circuit vivaldi and all-metal vivaldi antennas and the comparison of their various parameters for passive seeker. The paper also suggests their suitability with respect to their placement on the missile for three configurations: concealed inside the radome, flush-mounted and conformal antenna based. The paper also brought about the specific test facility required for testing and evaluation of passive seeker to characterize it with missile radome which is the most challenging and time consuming task. Among the three passive seeker configuration discussed, conformal antenna based passive seeker using all-metal Vivaldi is the best option avoiding radome aberration correction which is being utilized in the present third generations of ARM. The second commonly and established passive seeker configuration is concealed inside the radome using spiral antennas where handling radome aberration correction is a limitation.

Keywords: Anti-Radiation Missile; Passive seeker; Spiral antenna; Log-periodic antenna; Printed circuit vivaldi antenna; All-metal vivaldi

1. INTRODUCTION

Suppression of Enemy Air Defence (SEAD) is a fundamental element of Air Power application by means of protecting friendly air attackers and destroying the enemy's ability to defend against air attack. The purpose of SEAD is to ensure a favourable air situation for the air campaign and is defined[1] as "any activity that neutralises, destroys, or temporarily degrades enemy surface-based air defences by destructive and/or disruptive means". SEAD was developed in response to the increasing sophistication and efficacy of ground-based anti-aircraft systems, and it has effectively evolved with advances in air defence. The first SEAD mission was carried out by the US against North Vietnam's air defence under wild weasel operations[1]. Most of the SEAD operation even today relies on the anti-radiation missile (ARM), which is an air-to-surface tactical missile designed to detect, seek, attack, and destroy an opponent's radar. ARM is one kind of "hard kill[2]" electronic attacking weapon that detects, identifies, locates, and attacks the enemy's radar by homing in on the received radar signals. The development of ARM has gone through three generations.

The first generation of ARM is the typical representative of the US AGM-45 "Shrike" missile used against Vietnam. The first generation ARM has several limitations due to the narrow frequency band of the passive seeker, which makes it susceptible to interference, has low receiver sensitivity, and has a low hit rate[2]. The second generation of ARM has improved performance through the extension of radar frequency bands, increased seeker bandwidth, high receiver sensitivity, and guidance even from radar sidelobe beams[2]. US AGM-78 "Starm" (Standard ARM) falls under this category. This generation of ARM has a simple memory circuit that allows the missile to attack a target once it locks on, even if the radar is shut down. The third generation of ARM is based on the actual combat scenario[2], with improved performance in all aspects. This third generation of ARM covers all radar frequency bands from L to Ku in a single head with strong anti-electromagnetic interference capability, high speed, and multi-mode guidance. The US AGM-88E and its variants are the third generation of ARM, having a conformal antenna-based passive seeker for initial and mid-course guidance and an active seeker at millimetre wave for terminal guidance.

The passive seeker of ARM is a miniaturised ESM receiver that is capable of extracting the necessary angular data from

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enemy radar emissions. A single-head Passive seeker covering a wide frequency range from the L to Ku bands is the preferred choice. Antennas in passive seeker play a prominent role with respect to their design parameters, placement within the missile to cover the desired field of view, the direction finding technique for guidance, and more specifically, the missile radome. These seeker antennas can be implemented in a body-fixed configuration. For most missile guidance applications, mounting the antenna on a mechanical gimbal plays a crucial role.

The aim of this review paper is study of various wideband antennas used in passive seekers for ARM applications. Four types of wideband antennas considered for passive seekers are spiral antennas, log periodic, printed circuit vivaldi antennas, and all-metal vivaldi antennas. These antennas have been chosen due to their wideband capability, wide beamwidth, size, and shape, which make them suitable for mounting in passive seekers.

A spiral antenna[3] is a low-gain antenna that is extensively used in direction-finding receivers for Electronic Support Measure (ESM) and ELINT applications. This antenna is a frequency-independent antenna with broad bandwidth and circular polarisation. These antennas are mainly used in receiver wideband applications. In ARM application, the spiralantennas are used inside the radome either in body-strapped or mounted on a gimbal using phase comparison interferometry or monopulse amplitude comparison techniques. Comparing with other antennas like printed circuit Vivaldi, all-metal Vivaldi and log-periodic dipole arrays, these antennas exhibit excellent bandwidth. The sizes of spirals are restricted because the outer diameter depends upon lower operating frequency. A spiral antenna of 50 mm diameter typically covers 2-18 GHz and provides gain of 0 dB with a 3 dB beamwidth of 100 degree. The spiral antennas havebeen used in Russian Kh31P and Brazilian MAR-1 ARM.

A log-periodic dipole antenna (LPDA) is a wide-bandwidth and narrow-beam antenna that can be easily fabricated using microstrip printed technology. The antenna has multiple dipoles which are fed (in an alternate way) with two microstrip lines printed on the opposite sides of a dielectric slab. The electrical parameters of LPDA recur periodically with the logarithm of the frequency. The log-periodic dipole antennas[4]have been used for Direction-Of-Arrival (DOA) estimation of the target in radar and communication systems.

In 1979, Gibson[5] introduced the Vivaldi antenna, which is an exponentially tapered slot-line broadband end-fire travelling wave type. Sometime vivaldi is referred as a Tapered Slot Antenna (TSA), flared or notch antenna, end-fire slot Antenna, etc. Printed CircuitVivaldi antennas are mostly designed in arrays because of their wide bandwidth applications, including Active Electronically Scanned Arrays (AESAs).

Other high-gain antenna compared to printed circuit vivaldi antenna are all-metal Vivaldi antennas, which are made of conducting material and have several advantages, including high structural strength and the capability to withstand harsh environmental conditions of high temperature and vibrations.

The remaining sections of this paper are arranged as follows: Section-2 reveals the existing wideband antennas and their performance. Section 3 discloses various wideband antennas for passive seekers. Section-4 talks about the challenges in passive seeker development. Section-5 consists of perspective analysis of overall wideband antennas. Section-6mentioned about the future scope. At last, in Section-7, the overall conclusions are provided.

2. CONFIGURATIONS OF WIDEBAND ANTENNAS IN PASSIVE SEEKERS

For passive seekers, antennas are used for reception purpose only. Generally, three types of antenna placement configuration exist for passive seeker application: concealed inside the radome (with or without Gimbal), flushmounted (inside the radome but close to the radome skin; fixed without gimbal), and conformal to the missile body or radome skin.

A monopulse phase interferometer based passive seeker using spiral antennas concealed inside the radome has been realized. One such multi-channel passive seeker configuration has been described by Adam Rukkowski[6]with monopulse direction finding based on the phase method i.e .baseline interferometry technique using microwave phase discriminators. A similar type of configuration with seven spiral antennas based on phase interferometry technique has been used in RussianKh31P[7] ARM as shown in Fig.1 concealed inside the radome (with gimbal).

The second configuration of passive seeker is to have flush-mounted antennas inside the radome just touching the inner surface of the radome skin. US Patent[8] US2018/0013203 describes one such antenna array in a circumferential

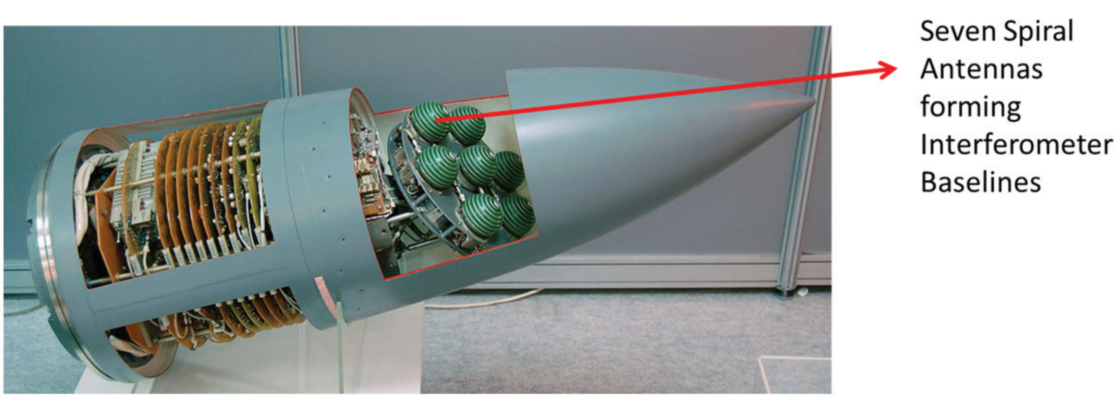
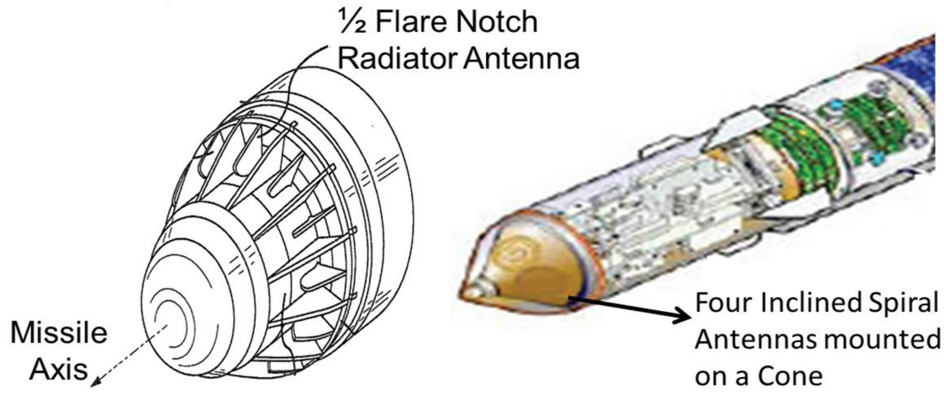
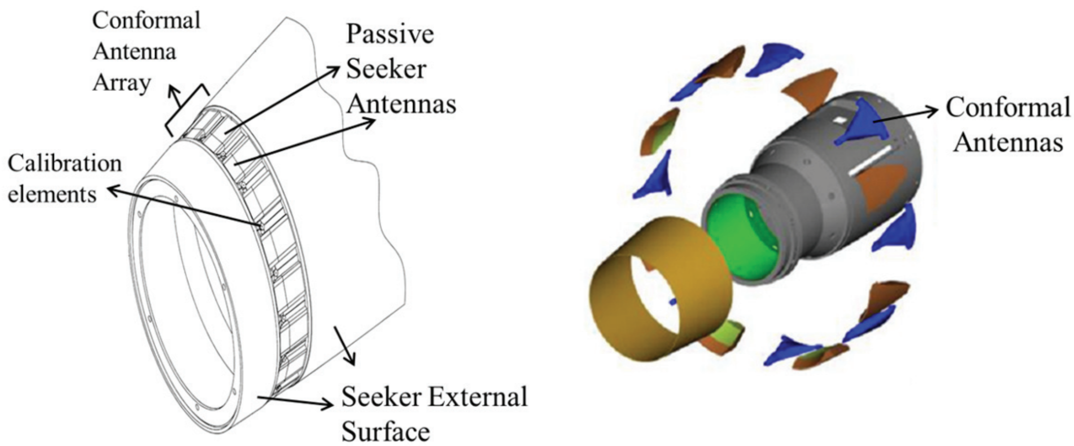


Figure 1. ARM Kh-31P[7] with spiral antennas concealed inside the radome.



(a) (b)

Figure 2. (a) Flush mounted notch radiator antenna[8]; (b) MAR-1[9]ARM with four flush mounted spiral antennas.



(a) (b)

Figure 3. (a) Conformal antenna array on missile surface[10]; (b) Passive seeker of US AGM-88E ARM[11]with conformal antenna array.

arrangement consisting of plurality of half-flared notch recessed within the nose cone as shown in Fig. 2(a) (without radome). The payload metal skin provides an image plane for each half-flared notch radiator to launch RF energy with a radial polarization normal to the image plane forward through the annular RF radome. Figure 2(b) depicts another such configuration of Brazilian ARM MAR-1[9] where four 0.5-18 GHz spiral antennas flush-mounted inside the conical radome.

The third configuration of the passive seekerhas conformal antennas mounted either on missile's conducting surface or on the radome itself. The advantage of this configuration is that it saves the installation space without affecting the aerodynamic performances. The other advantage is that the radome can be specifically designed for the other mode of guidance i.e. active seeker. US patent[10] US2002/6407711describes one such passive seekerhaving an antenna array that conforms to the external contours of the missile. The cylindrical antenna array consists of a plurality of individual receiving antennas (connected to a switching network and multichannel receiver) and calibration units mounted symmetrically on either side of the receiving antenna as shown in Fig 3.

A similar configuration has been utilized in US AGM-88E[11]ARM, where conformal antennas are mounted on a rigid conductive support whose upper surface faces approximately radially outward the missile surface.

3. DESIGN AND STUDY OF WIDEBAND ANTENNAS FOR PASSIVE SEEKER APPLICATION

There is a vast future of research for wideband antennas such as spiral antennas, log-periodic antenna, printed circuit vivaldi antenna and all-metal Vivaldi antennas suitable for passive seeker of Anti-radiation missiles. The following section briefly describes these antennas and the comparative study with respect to various design parameters like frequency of operation, gain, axial ratio, VSWR, dimension, their application and design software.

3.1 Spiral Antenna

A spiral antenna belongs to the class of frequency-independent antennas based on the angle concept, which states that if a structure can be defined entirely in terms of angles without defining it in terms of physical dimensions, then it exhibits frequency-independent performance. Theoretically, this type of antenna will have an infinite frequency bandwidth of operation. However, as the antenna dimension is finite, the highest frequency of operation is limited by the precision fabrication of the feed, while the lowest frequency is limited by the acceptable size of the antenna. Spiral antennas operate in the multi-octave band, have lesser gain with circular polarization and are being used in receiving applications. These elements have been widely used in radar warning receivers and ESM/

ELINT receivers since the mid -1960s. The radiation principle of spiral antenna is based on current band theory (ring theory)[12]. The antenna radiates from an active region where the circumference of the spiral equals the wavelength.

Spiral antennas are classified into different types: archimedean spiral, logarithmic spiral, square spiral, star spiral, etc. The archimedean[13] spiral is the most popular configuration. Usually the spiral is cavity-backed; there is a cavity of air or non-conductive material or vacuum, surrounded by conductive walls behind the spiral. Lossy cavities are usually placed at the back for reducing the back lobes. Sometimes, a metal cavity is used to get unidirectional pattern by reflecting backlobe power.

The archimedean spiral is a planar structure that is fabricated by photolithography techniques on a copper-clad substrate. To obtain unidirectional beam for direction finding applications, the spiral is mounted at the open end of a closed-back metallic cavity which, when in the region of $\lambda/4$ deep[13], redirects its half of the energy constructively to form a single beam. However, the energy within the cavity is absorbed to achieve broadband performance of the antenna. The spiral radiator, being a balanced device, needs to be fed from a balanced transmission line. This necessitates the incorporation of a balun transformer. This balun transforms the unbalanced RF signal launched through a standard connector into a balanced out-of-phase signal through Tchebychev tapered impedance transformer from a 50 Ω coaxial input to a 110 Ω of spiral antenna on a printed line.

Archimedean Spiral arms are constructed using the archimedean equation, $r = a*\varphi + r_1$ where ‘r’ is radius, ‘a’ is growth rate, ‘r_1’ is initial radius and φ is angular position. The smallest and largest diameters of the spiral arms are determined by the highest and lowest frequencies[14]. To avoid end-effects (reflections from the spiral outer terminals), the sides are taken 10 per cent more than that of theoretical calculation. A two-arm archimedean spiral is shown in Fig. 4.

Spiral antennas offer a very broad 3-dB beamwidth (50° to 110°) and smooth radiation patterns over the entire band of operation, which are prerequisites for any direction finding system. Hence, these antennas are attractive candidates for

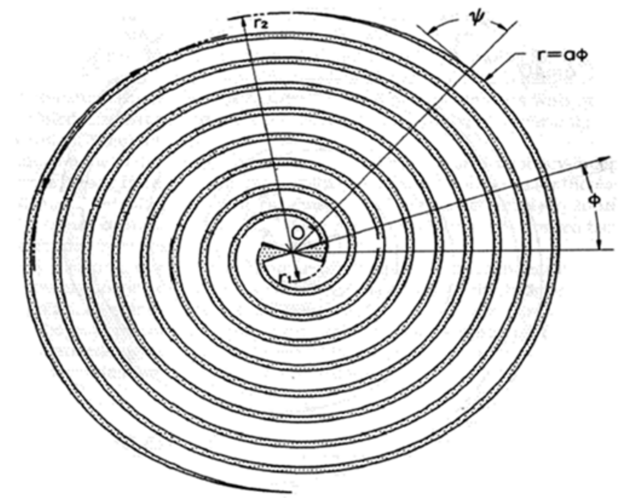


Figure 4. Two arm archimedean spiral.

baseline interferometer (BLI) arrays because of their inherited frequency-independent and circular polarization characteristics. Spiral antennas have been used earlier for passive seeker application using interferometric techniques. These are mounted on a gimbal and placed inside the radome, forming multiple baselines for phase comparison based direction-of-arrival estimation.

The comparison of various spiral antennas is tabulated in Table 1.

In Table 1, it is found that ultra-wideband spiral antenna scan be designed for2-18 GHz[17]& 1-18 GHz[15,20] with 50 mm and 80 mm diameter respectively. The above study shows that though a spiral antenna is not high gain, it provides a wide 3 dB

Table 1. Comparison of circular polarised spiral antennas

Year & Ref	Freq (GHz)	Gain	VSWR	Axial ratio	Beam width 3 dB (deg)	Dimensions (mm)	Applications	Software’s
2018 [15]	1-18	Not mentioned No plots	1.9:1	< 3 dB	90 as depicted from figure	ϕ 80 mm x 74.95 mm (without connector)	UWB applications	ANSYS HFSS
2017 [16]	2-6	-10- 6 dBi	2.5:1	< 3 dB	60-30	ϕ 36 x20	Wireless communications	CST
2017 [17]	2-18	0- 2.5 dBi	1.9:1	<2.6 dB	Not mentioned, No radiation plots	ϕ 50 x 22	Wideband sensing, Spectrum monitoring, Radar systems and broadband communication	ANSYS HFSS
2014 [18]	0.5-6	-5 -7.5 dBi	1.9:1	< 2 dB	50-70	ϕ184 x 50	Satellite and Radar Applications	CST
2011 [19]	0.4-4	3.4-6.1 dB	2:1	< 3 dB	90-120	188x270.8	Commercial and military applications	ANSYS HFSS
2011 [20]	1-18	-11 to +2 dBli	1.5:1	<4 dB	80 as depicted from figure	ϕ 84.8 x 50	Wideband direction finding application	Not mentioned
2011 [21]	2-18	2.33 to 6.30 dB	2.5:1	<4 dB	100 - 64	Not mentioned	wideband application	FEKO

beam width of 60°-100° over the 2-18 GHz band and is one of the best choices for concealed antenna and interferometer based passive seeker configurations. However, for a lower frequency of operation i.e. 0.4 GHz, the size of the spiral antenna is of the order of 188 mm[19] and is not suitable for concealed inside the radome configuration requiring larger missile diameter to place multiple antennas to form baselines. Helix spiral antennas is the optimum choice for low frequency of operation.

The performance of spiral antenna depends upon balun design[15] and can be improved using hecken and exponential microstrip balun[15] for amplitude-based direction finding systems.

For a given dimension, the reflection coefficient of a Ultra Wideband (UWB) spiral antenna suffers at low frequencies as compared to higher frequency. Zhong[16] has proposed the use of four lumped resistors in a two-arm planar archimedean spiral with tapered balun for improving the reflection coefficient & reducing the size.

The absorbing material, or resistive termination[19] in the cavity is generally placed for a unidirectional radiation pattern. Feed network[18] having 90° and 180° hybrids can be use in place of absorbers or resistive termination. Optimization[21] using multilayer dielectric absorbers may further enhance the unidirectional radiation pattern.

No reference paper has been found for a spiral antenna being used in conformal configuration for passive seeker applications.

3.2 Log-Periodic Dipole Antenna (LPDA)

Frequency-independent antennas have some kind of basic geometric pattern of repetitiveness in their physical structure, which results in a repetitive behaviour of the electrical characteristics. The physical structure either grows or shrinks by a constant scale factor and is repeated with a changing size of the pattern.

A log-periodic antenna is a wideband frequency independent antenna with impedance and radiation characteristics that are repetitive as a logarithmic function. There are several types of log-periodic antennas such as planar, trapezoidal, zig-zag, V-type, slot and dipole. The mostly used one is the log-periodic dipole array, in short, LPDA developed by Isbell in1960. It consists of a number of dipoles, as shown in Fig. 5, of different length and spacing, fed by a two-wire line that is transposed between each adjacent pair of dipoles. The longest dipole works as a reflector, and other dipoles act as directors. The array is fed at the small end of the structure, and the maximum radiation is toward this end. The lengths of the dipoles and their spacing are designed in such a way that certain dimensions of adjacent elements (designated as R and l) bear a constant design ratio 'τ' (a number less than one) to each other, as given below:

$$\frac{R_2}{R_1}=\frac{R_3}{R_2}=\frac{R_4}{R_3}=\frac{1}{\tau}=\frac{l_2}{l_1}=\frac{l_3}{l_2}=\frac{l_4}{l_3}$$

The bandwidth of the LPDA antenna is improved by increasing the number of dipoles. All dipoles in LPDA are active elements resonating at their particular center frequency with the longest dipole resonating at the lowest frequency and the shortest dipole resonating at the highest frequency. LPDAs have excellent characteristics like very large bandwidth and reasonable gain, making them suitable for UWB transmitting and receiving systems[22].

LPDA has been used earlier in passive seeker applications. One such configuration using LPDA for passive seeker in mid-course guidance for dual mode guidance system of ARM, where conformal LPDAs[23] were etched on the missile radome skin as shown in Fig. 6(a). Figure 6(b) shows the inside view of the radome where secondary sensor i.e. active seeker, is mounted on a stabilised gimbal platform for terminal guidance.

The comparison of various log-periodic dipole antenna arrays is tabulated in Table 2. It is found that LPDA with 30:1 bandwidth in 0.5 - 15 GHz has been realized in 392mm x 250 mm by Zhang[25] by adding a parasitic dipole and tuning short dipoles. This however may not be a practical solution for passive seeker application where a minimum 4 LDPA are required to estimate azimuth and elevation direction-of-arrival and handling both polarizations and difficult to accommodate inside the missile due to its large size.

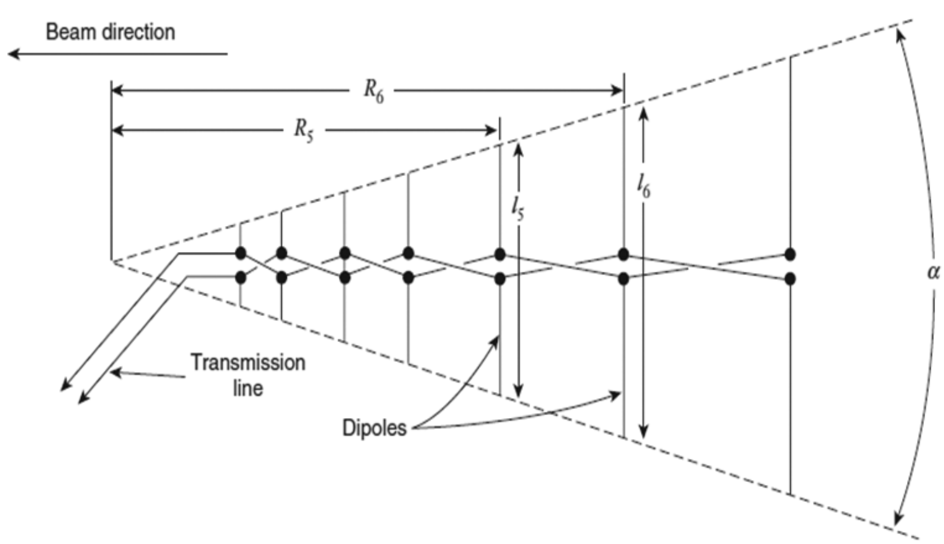
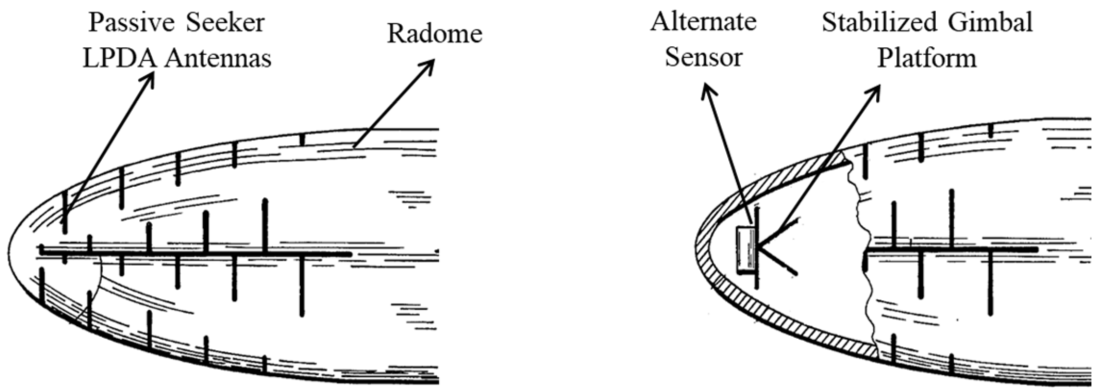


Figure 5. Log periodic dipole array.



(a) Side view **(b) Inside random view**

Figure 6. (a) Conformal LPDA23 for passive seeker application; and (b) Location of active/secondary terminal guidance sensor.

Table 2. Comparison of LPDA antennas

Year & Ref	Freq (GHz)	Gain	VSWR	Beam width 3 dB (deg)	Dimension (mm)	Applications	Software's
2020 [24]	3.57-12.95	5.7-7.6 dB	2:1	25-60 as depicted from fig for one of the lobe.	65x40x1.54	Communication, reconnaissance and electronic countermeasures	Not mentioned
2019 [25]	0.5-15	4-8.91 dBi	2:1	80-100	392x250x1.5	Broadband and portable devices	Not mentioned
2018 [26]	2-18	7.2-9 dBi	2:1	70-100	289.5x100.5x7.9	Missiles or unmanned aerial vehicles and airborne applications	ANSYS HFSS
2017 [27]	2.5-6	5-6.5 dB	2:1	100-110	60x80x0.5	Communication system such as WiMAX,WLAN, C-band satellite	CST
2017 [28]	0.2-0.803	3.2-5.5 dBi	2:1	150	420x576.6x29.6	High-power radiation applications in air-borne platforms	ANSYS HFSS
2015 [29]	2-8	-	3:1	40-50 as depicted from fig	67x52	Radar systems	Not mentioned
2015 [30]	1-8	7.5-10 dB	3:1	100-80	190x480	Missile applications	Full wave electromagnetic simulation software
2015 [31]	3-10	7 dB	2:1	70-90	56x40x1	Wireless communication	CST
2014 [32]	8-18	6.2-6.8 dB	2:1	80-100	33x9x0.5	Wireless communication, Radar systems	CST
2013 [33]	0.8-7.2	5-10 dB	2:1	Not mentioned	150x1.6	Engineering applications	FEKO
2013 [34]	4-18	6.5-8 dB	2:1	80-90	56.92x30x0.51	Ultra-wideband applications	CST
2010 [35]	4.25-13.25	9 dB	2:1	60 typical	29.34x0.51	Ultra-wideband applications	CST

Wang[24] has proposed miniaturizing UWB conformal LPDA array on a cylinder using the fractal Koch technique without compromising gain and radiation pattern along the longitudinal spacing with 9.38 GHz bandwidth. Many papers have been published for low-profile log-periodic arrays mounted on missile cylindrical surface. Chen[26]has proposed one such LPDA in 2-18 GHz using monopoles of different heights for higher frequency, top-hat monopoles with different hat sizes for medium frequency and folded top-hat monopoles for the lower frequency. LPDA in 1-8 GHz for passive seeker application with monopoles configuration is presented by Linhong[30]with the sum and difference radiation pattern. This is one of the best configurations for a conformal antenna based passive seeker.

The above study shows that LPDA has been used for conformal passive seeker applications. However, no literature from open source has been found which confirms its usage in the ARM deployed in the past or presently being used. LPDA can be utilized for other configuration of concealed inside the radome or flush-mounted, by keeping sufficient numbers to handle the dual polarisation.

3.3 Printed Circuit Vivaldi Antenna

Vivaldi antennas (also called tapered slot antenna)which were invented by Gibson in 1979, are co-planarextremely broadband slot antenna wherein the slot is widened conically. Vivaldi antennas has three main categories[36] namely coplanar vivaldi antenna, conventional antipodal vivaldi antenna (CAVA) and balanced antipodal vivaldi antenna (BAVA). The coplanar vivaldi antenna is made of thin copper sheets or simple double-laminated printed circuit board material and the feeding of the antenna is on the narrow side slot as shown in Fig. 7(a)[36]. Its properties, such as the thickness of the carrier material and its dielectric constant have an influence on the properties of the antenna. The opposite side to the beam direction is short-circuited by a $\lambda/4$-stub. The polarisation of a single radiator is linear, and the electric field lines are parallel to the printed circuit board material. It has excellent directional radiation characteristics such as wide bandwidth, low side lobes, high gain, broadband performance and constant beam-width. The coplanar vivaldi antenna have several advantages[36] such aslight weight, easy fabrication, easy integration, and low cost.However, there are some challenges concerning coplanar vivaldi antennas, including complexity of feeding structure, large size, limitation on low end of frequency band, low gain at low and/or high frequencies, and instability of directivity in radiation patterns, i.e., E-plane tilt of beam, especially at high frequencies.

The conventional antipodal vivaldi antenna (CAVA)[37]was proposed by Gazit in 1988 to solve the feeding in coplanar vivaldi. In CAVA, one of the layers is printed on top, and the other, which is tapered in the opposite direction, is printed on the bottom of the dielectric substrate material, as shown in Fig. 7(b). The CAVA[36] can be fed easily by soldering the connector to the two sides of the PCB material. The gain of the CAVA is low, and impedance bandwidth of the CAVA is limited at the low end of the frequency band.

The balanced antipodal vivaldi antenna (BAVA) consists of three copper layers as shown in Fig. 7(c)[36]. A dielectric layer has been added on top of the antipodal structure, and an additional metal plate just like the one at the bottom of the antenna has been printed on top of the newly added layer.

A broadband conformal inclined vivaldi antenna array[38] has been used for missile applications, as shown in Fig. 8. Figure 8(a) shows a linearly polarised inclined vivaldielement with symmetrical and asymmetrical E-plane elements by making the flaring of the vivaldi symmetric and asymmetric. Fig. 8(b) shows dual-polarized configuration with an inclined H-plane array flanked on both sides by an inclined E-plane

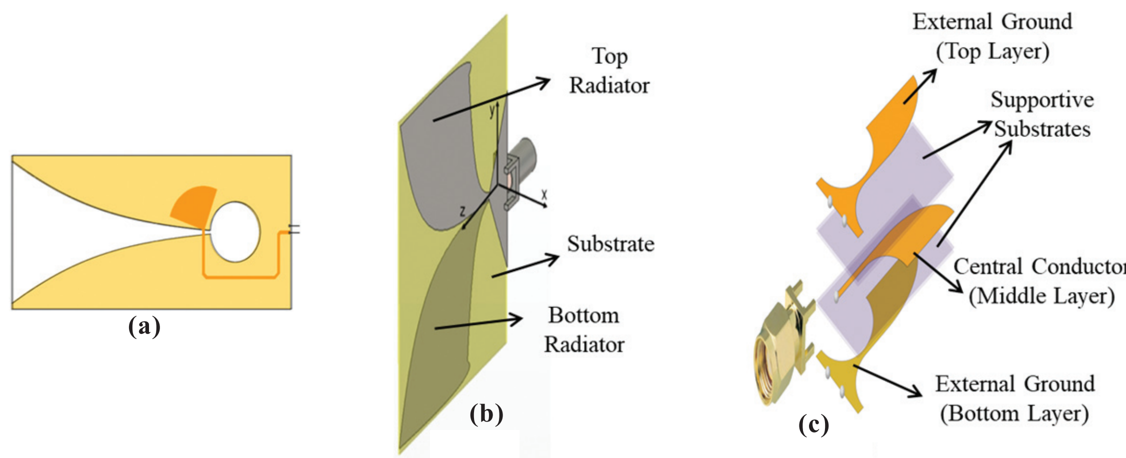


Figure 7. (a) Conventional coplanar vivaldi antenna; (b) CAVA; and (c) BAVA.

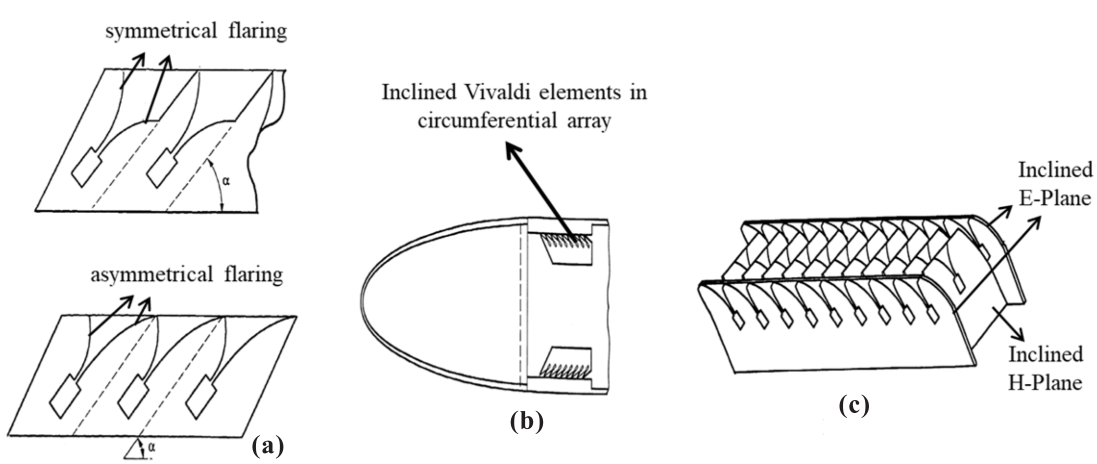


Figure 8. (a) Symmetrical flaring & asymmetrical flaring[38] of Vivaldi antenna; (b) Inclined vivaldi elements in circumferential array; and (c) Inclined E &H –Plane vivaldi.

array. The inclined angle 'α' varies from 30° to 90°. Figure 8(c) shows conformal configuration of passive seeker with inclined vivaldi in a circumferential array using the above-mentioned two arrays mounted on the metallic missile surface. Tilting the antenna elements helps adapt them for conformal applications. The concept is utilised for dual polarisation by employing an inclined H-plane array flanked on both sides by an inclined E-plane array as shown in Fig. 8(c).

The comparison of various printed circuit vivaldi antennas and their arrays in terms of frequency, gain, VSWR, beam width, dimensions and its applications is tabulated in Table 3.

Table 3 shows that an UWB printed circuit 3-18 GHz[42] vivaldi antenna has been designed and realized in 40 mm x 9.7 mmusing RT-duroid 5880 of 31mil thickness.

L-Band (1.01-2.37 GHz) vivaldi antenna for L-Band passive seeker applications has been realized by Li[40] in 154 x 230 mm size with a 3 dB beamwidth greater than 90° by slotting and rounding the radiation patch.

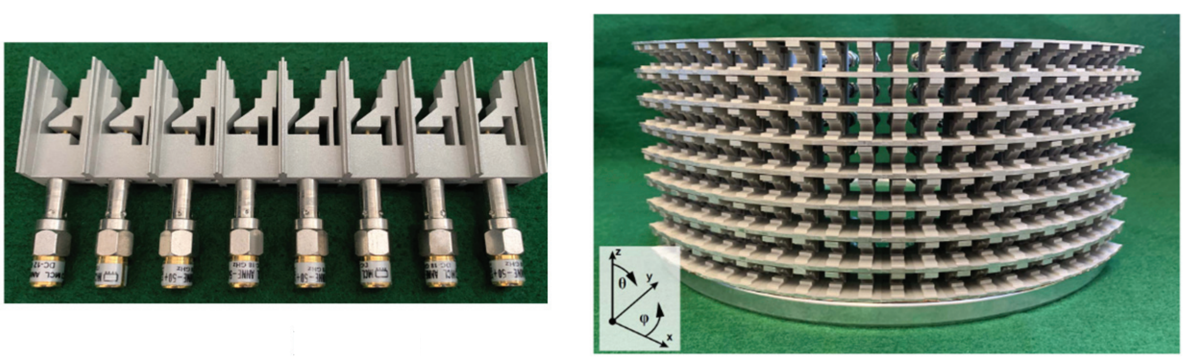
The orthogonally placed vivaldi antenna in 2-8 GHz has been realized for circular polarization by Ren[43] with good 3dB axial ratio. This antenna is designed for the concealed inside the radome configuration only. Zengrui Li[45] has realizeda conformal UWB anti-podal vivaldi antenna in 2.2-12 GHz with an end-fire radiation pattern. This is one of the best conformal configuration for passive seeker application. Similarly, Li-Ming Si[47] has realized a 6-18 GHz anti-podal vivaldi antenna array for conformal application suitable for passive seeker applications.

3.4 All-Metal Vivaldi Antennas

The design of all-metal antennas is gaining popularity for 5G and satellite applications. Most all-metal antennas are designed with vivaldi antennas. The conventional vivaldi antenna is made of printed circuit technology and has several advantages including light weight, low cost and faster production. However, the major disadvantage of printed circuit

Table 3. Comparison of printed Circuit Vivaldi antennas

Year & Ref	Freq (GHz)	Gain	VSWR	Beam width 3 dB (deg)	Dimensions (mm)	Applications	Software's
2020 [39]	7.5-12.5	10 dBi	2:1	40-50	110x16x0.7	Remote sensing and phased array applications	CST
2020 [40]	1.01-2.37	5-7 dB	2:1	90-120	154 x230 x1.6	Missile borne and mobile communications	ANSYS HFSS
2020 [41]	2-16	7-10 dBi	2:1	60	175x50x10	Circularly Arranged for MTI Radar	ANSYS HFSS
2018 [42]	3-18	5.8-16 dB	2:1	10-60	90x110x1.5 [for 8 x 1]	Direction Finding and Electronic Warfare Jamming Applications	CST
2018 [43]	2-8	1-7 dBic	2.5:1	50-90	60 x 60 x 51	Wideband Applications	ANSYS HFSS
2017 [44]	3.1-10.7	4.8-8 dBi	2:1	100-160	50x40	Ultra-wideband Radar Applications	CST
2016 [45]	2.2-12	3.5-9 dBi	2:1	60-120	116x124x0.5	Missiles, Radars and Aircrafts	ANSYS HFSS
2016 [46]	1-4	Not mentioned	2.25:1	30-40	260.8x88.2x1	UWB phased arrays	CST
2013 [47]	6-18	5-10 dB	2:1	40-60	80 x 40 x 1	Conformal on cylindrical surface	Electromagnetic field full wave analysis software
2012 [48]	3-11	3-8 dBi	2:1	Not mentioned	62 x 62	Imaging, radar, localization systems	Not mentioned



(a) (b)

Figure 9. (a) Eight-element all-metal Vivaldi Antenna linear Array[49]; (b) 120◦ circular array consisting of 21 elements in a row.

vivaldi is its large micro-strip loss, complex installation and integration, and low structure strength especially for airborne and missile applications.

An UW Ball-metal vivaldi antenna array with small aperture operating in 5.6-20 GHz[49] and VSWR less than 2.5 is shown in Fig. 9.

The comparison of varioussall-metal vivaldi antenna arrays in terms of frequency, gain, VSWR, beam width, dimensions and its applications are tabulated in Table 4.

It is found from the study of above table that an all-metal vivaldi antenna in ultra-wideband is possible and suitable for conformal configuration like a printed circuit vivaldi antenna. There are various advantages of using an all-metal vivaldi antenna array in a conformal based passive seeker application over printed circuit vivaldi array, like handling of extreme temperatures on the missile body, and high structural strength.

4. CHALLENGES IN PASSIVE SEEKER DEVELOPMENT

The passive seeker of ARM is a very complex subsystem with respect to its design, configuration, size, weight and power. Moreover, the performance of passive seekers depends on the type of radome being used. Missile radomes are designed to meet the stresses of high-speed flight maneuvers and aerodynamic heating. Missiles radomes are designed for broadband electrical characteristics. However, the electrical characteristics generally become a secondary priority in the design. The missileradome cause the incoming electromagnetic (EM) waves to scatter in various undesired directions and affects the radiation pattern of the antenna.

A radome acts as a protective shield between the missile antenna and outer atmosphere, and also it must not, interfere with its performance. The nose of a radome can be blunt, but for missile-specific applications, a radome with pointed nose preferably Ogive-shaped, is preferred to reduce aerodynamic drag. Aerodynamic heating and stress occurring due to high missile speed are some factors that a missile radome should be able to withstand, and this restricts the materials for radome fabrication. The wall of the radome is one of the most important design variables. The walls of the radome are made of one or more homogeneous layer of dielectric constant of varying thickness, depending on specific needs. Small local variation in thickness, gradual tapers, materials with configurationally isotropy, and metallic layers improve the radome performance.

Several events, such as reflection, refraction, attenuation, guided-wave excitation, and scattering take place by the radome tip[57], when an electromagnetic wave illuminates a radome, as shown in Fig. 10(a). Radome analysis is challenging for a wide frequency band since the mechanisms are varied and occur simultaneously. As seen in Fig. 10 (b), radome reflections can cause wave front distortion which can lead to increase in sidelobe levels of an enclosed aperture antenna. The wave front deformations that are asymmetric are a cause of boresight error.

Specialised measurement systems are required to characterize the combined performance of the passive seeker antennas and missile radome. There are several approaches typically employed to measure radome performance. While the details of the mechanical positioning system can be very different for each approach, a basic test system[58] includes a control computer, transmit RF signal source, source positioned, radome positioned, position control equipment, test passive seeker antenna, RF signal multiplexer, and receiver. Measurements typically[59] made on radomes include boresight shift, transmission loss and the effects of the radome on the pattern and polarisation of the passive antenna mounted beneath it. Efficient implementation of radome aberration correction is carried out by calibration at fine steps in anyone of the three radome testing facility, namely, the far-field test facility, Compact Antenna Test Range (CATR) and near field test facility.

4.1 Far Field Test Facility[58]

Traditional radome testing has often employed an outdoor Open Air Test Site (OATS) under far field condition. While OATS has its own inherent disadvantages, the relatively long range allows for slightly less precision in the mechanical

Table 4. Comparison of all metal vivaldi antennas

Year & Ref	Freq (GHz)	Gain	VSWR	Beam width 3 dB (deg)	Dimension (mm)	Applications	Software
2022 [50]	2-50	4.5-12 dBi	2:1	40-80	80 x 90 x 2.5	Communication, radar, biomedical, plasma microwave diagnostics	ANSYS HFSS
2021 [51]	2-6	-1-6.5 dBi	1.6:1	Not mentioned	254.8x29.7x4.6	Radars	Not mentioned
2020 [52]	2-6	-3.5- 6 dBi	3:1	100-60	60x30.5x3	UWB applications	ANSYS HFSS
2019 [53]	3-18	3-9.4 dB	2.5:1	80-40	140x24	ESM-DF applications	ANSYS HFSS
2018 [54]	6-12	Not mentioned	2.5:1	120	150x35x6	Phased arrays	ANSYS HFSS
2018 [55]	1.5-7.5	2.5-17 dBi	2:1	30-120	112x18x1.72	UWB applications	ANSYS HFSS
2017 [56]	2-7	20 dB	2:1	60-120	44.8x44.8x33.7	Conformal applications, wireless communications	ANSYS HFSS

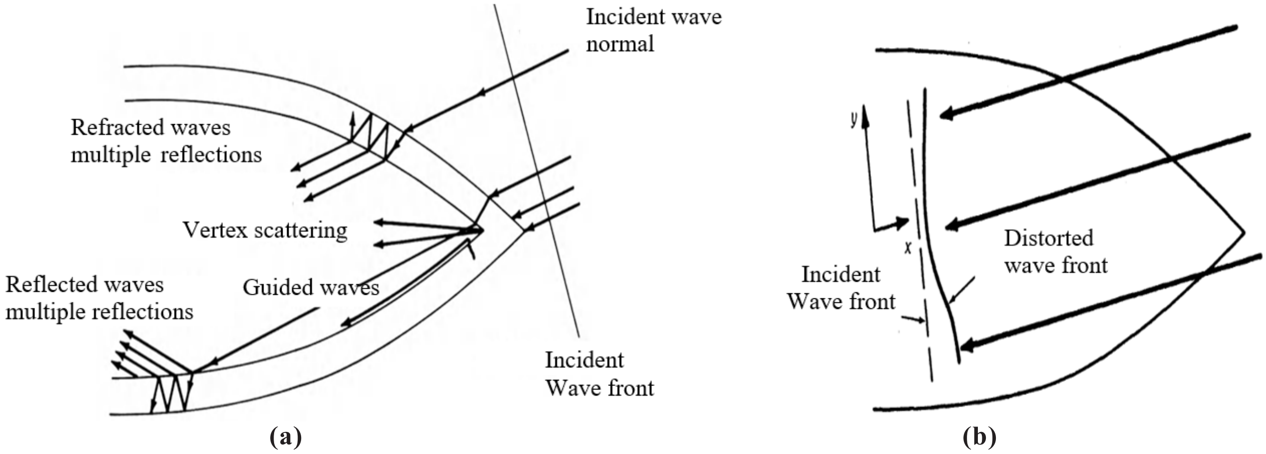


Figure 10. (a) Effect of missile radome[57] on incident wave; and (b) Distortion of EM wavefront by missile radome.

positioning systems as compared to CATR. OATS require a significant amount of real estate, due to the separation distance between the transmit and receive antennas.

4.2 Compact Antenna Test Range

Compact Antenna Test Range (CATR)[58] is an indoor facility for producing a localized plane wave (defined by Quiet zone) within a confined space. It operates by collimating a RF point source with a paraboloidal reflector. CATR avoids the problems associated with weather and other outdoor anomalies. CATR allows electrically large antennas to be measured at a significantly shorter distance than would be necessary in a traditional far-field test facility. Compact ranges use a source antenna (feed) to radiate a spherical wave in the direction of a parabolic reflector, collimating it into a planar wave for aperture illumination of a Device under Test (DUT). It's lowest operational frequency is determined by the size of the reflector, its edge treatment and the absorbers.

The CATR system includes a tracking pedestal controlled by an auto track controller, a measurement receiver, a multiple feed arrangement and a laser autocollimator for coordinate system referencing. The auto-track controller detects the boresight shift induced by the missile radomeas well as the radiation patters of passive seekerantenna, polarization and transmission loss. These subsystems are integrated with specialized hardware and software to perform high-accuracy automated radome measurements. A tracking system continuously steers the antenna mounted under the radome to the direction-of-arrival of the primary plane wave generated by the CATR.

4.3 Near Field Test Facility[58]

Now-a-days the antenna and radome characterisation have been migrated to near-field scanning techniques[59]. This has become possible with the increased speed of high-performance computing workstations with large data storage capacities for data acquisition and processing associated with near-field antenna measurements and the reduced size of the near-field range. Near-field testing is being recognised for its excellent radiation pattern accuracy. Near-field testing is being used for various types of antenna and radome measurement using planar, cylindrical and spherical scanners.

The first and second configurations, i.e., concealed inside the radome and flush-mounted based passive seeker, are very prone to radome aberration effects. The removal of radome aberration requires radome and passive seeker antenna characterization, which is a complex task involving large amounts of time for data acquisition and analysis.

The third configuratione conformal antenna based passive seeker offers, the advantage over radome aberration correction and avoids the design of common radome in microwave frequency for passive seeker and millimeter frequency for active seeker.

5. PERSPECTIVE ANALYSIS OF WIDEBAND ANTENNAS FOR PASSIVE SEEKER

In section 3, the comparison of wideband antennas was mentioned. The detailed perspective analysis of four types of wideband antennas parameters for the antenna covering the maximum frequency coverage is shown in Table 5. From the study the following points have emerged.

5.1 Spiral Antenna

It is a well-established antenna for amplitude and phase comparison based direction finding application of electronic warfare and ELINT receivers. It is a frequency-independent antenna and can be designed in ultra-wideband from 1-18 GHz, covering all radar bands with a diameter less than 100 mm. It provides a minimum 3 dB beam width of ± 40 degrees, which is sufficient for the field-of-view of the body-fixed type passive seeker, thereby avoiding the gimbal and its associated complex mechanical structure. Size reduction is possible in spiral diameter by means of inductive and dielectric loading by sacrificing the gain at lower frequencies. The other advantage of spiral antenna is that it is circularly polarised and can handle both horizontal and vertical polarised radar. As the radiation pattern of a spiral antenna is broadside, it is not a suitable solution for conformal passive seeker. It has been used in the passive seeker of the Russian Kh31P and Brazilian MAR-1 ARM missiles for the concealed inside the radome and flush-mounted configuration respectively. Radome aberration

Table 5. Comparison of wideband antennas

Parameter for comparison	Spiral antenna [19]	Log-periodic dipole array [34]	Printed circuit vivaldi antenna [40]	All Metal vivaldi antenna [51]
Maximum frequency band coverage	1-18 GHz	4-18 GHz	3-18 GHz	2-50 GHz
3 dB Beam width (deg)	80° as depicted from figure	90° minimum	160-45	40-80
Minimum dimension for maximum frequency coverage	ϕ 84.8 x 50	56.92x30x0.51	90x110x1.5 mm	80x90
Gain	-11 to +2 dBli	6.5-8 dB	5.8-16 dB	4.5-12dBi
VSWR	1.5:1	2:1	2:1	2:1
Polarization	Circular	Linear	Linear	Linear

correction is one of the complex task for the passive seeker based on spiral antennas.

5.2 Log-Periodic Dipole Array

Log-Periodic Dipole Array **(**LPDA) also falls under the frequency independent class and can be designed for wideband frequency from 4-18 GHz with a size less than 60mm x 30mm, providing a 3dB beamwidth of ± 45 degrees and a gain of 5-10 dBi. In order to cover lower frequencies in the L and S frequency bands, i.e., 1-4 GHz, the size of the LPDA becomes greater than 200mm x 200mm and is difficult to accommodate in all three configurations of passive seeker. Another issue with LPDA is that it is linear polarized, and more LPDA are required to sense the type of polarization. The radiation pattern of LPDA is end-fire, and this offers an advantage in its utilization for conformal passive seeker by placing it such that the beam direction lies on the missile axis. Hence, LPDA is suited in C-Ku frequency band for flush mounted and conformal based passive seeker applications.

5.3 Printed Circuit Vivaldi Antenna

A vivaldi or tapered slot antenna is a miniaturized and light weight coplanar antenna constructed on a substrate using the microwave photolithographic thin film technique. It can be designed for 3-18 GHz with a size less than 100mm x 100 mm and gain of 5-15 dBi. The beamwidth of vivaldi is not as high as that provided by Spiral and LPDA for higher frequencies. Vivaldi is a linear polarized antenna and can be made dual polarized by crossing two planar structures. The radiation pattern of planar vivaldi is end-fire, and as the size of vivaldi is smaller as compared to LPDA, this makes it one of the potential candidates for conformal-based passive seeker. The sense of polarisation is possible by keeping six or more numbers of vivaldi mounting them on a regular polygon in a circumferential arrangement.

5.4 All-Metal Vivaldi Antenna

The design of the all-metal Vivaldi antenna is same as that of printed circuit vivaldi antenna. Unlike printed circuit vivaldi, all-metal vivaldi is structurally strong and can withstand harsh environment of temperature and vibration. As the skin temperature of high-speed ARM at the nose cone and seeker section is very high, thus making them preferred option for conformal passive seekerover conventional vivaldi antenna. It can be machined on curved surface using selective Laser melting method of metal 3D printing technique or wire electrical discharge machine cutting technology. Recent literature shows the design of a 2-50 GHz all-metal vivaldi in 80 mm x 60 mm with a gain of 4.5-12 dBi.

6. FUTURE SCOPE

The study shows that the diameter of anti-radiation missiles ranges between 200mm to 350mm, and it is possible to accommodate nearly six to eight wideband antennas. Miniaturisation of passive seeker antennas is one of the design parameters while configuring ARM to have low RCS. Proper cares needs to be taken in passive seeker design when using conventional linear polarized antennas to handle both vertical and horizontal radar emitters. The latest trend in performance enhancement and miniaturisation of wideband antennas is possible using metamaterial and metasurface based antennas.

Metamaterials are man-made composite materials that are designed and manufactured artificially. Unlike natural materials, which have unique properties derived from their chemical composition, synthetic materials have distinctive properties that are derived from their internal microstructures. By modifying the arrangement of atoms into specific geometries, metamaterials can be engineered to have properties and capabilities that can bend electromagnetic waves in ways that are impossible for materials found in nature.The refractive index of the metamaterial can be changed to positive, close to zero, or even negative values by arranging the nanoscale unit cells in the required configuration. Metamaterials are typically built of multiple identical elements fashioned from conventional materials, such as metals or nonconductive materials. Smaller antenna elements with a larger frequency range are made possible by metamaterials, allowing circumstances where space is limited to be better utilized.

Metasurfaces are the two-dimensional analogue of metamaterials, consisting of single- or multi-layer stacks of planar structures. They are thin artificial layers consisting of periodic arrangements of small inclusions in a dielectric host medium. Meta surfaces overcome the meta material obstacles of extensive losses and challenges associated with nanofabrication and assembly issues. Its operating theory is based on the diffraction phenomena, which splits the incident light into a few rays. The number and direction of the rays depends on geometrical parameters such as the angle of incidence, wavelength, and period of the lattice. The majority of currently produced metasurfaces are passive, which means that they cannot be tuned post-production. Active metasurfaces, in contrast, enable dynamic adjustment of their optical properties in response to external stimuli.

Significant progress has been made on the miniaturisation of antennas using metamaterials and metasurfaces. He-Xiu Xu[60] has demonstrated polarisation-insensitive metalens that are capable of collimating the quasi-spherical wave emitted from different feeding sources of different polarisations at the focal point into highly directed radiation patterns of identical polarisation sense. He has demonstrated that for an incoming wave of any polarisation (example: horizontal, vertical, LHCP and RHCP), polarisation -insensitive metalens are able to focus into a fixed focal spot with preserved polarisation sense.

7. CONCLUSION

Passive Seeker is the most vital and mandatory subsystem of ARM.A comprehensive review of four types of wideband antennas for three configurations of passive seeker applications has been discussed in this paper. The study shows that for the first configuration, i.e., concealed inside the radome, spiral antennas covering 1-18 GHz band are the best using monopulse amplitude and phase comparison based direction finding techniques. This configuration is well established and has limitation of radome aberration correction. For the second configuration, i.e., flush mounted Passive seeker, spiral and LPDA are the suitable option for frequency in C-Band and higher. This configuration also has limitation of radome aberration correction. For the third configuration, i.e., conformal antenna based passive seeker, all-metal vivadi antenna is the best choice due to its end-fire radiation beam pattern and withstanding harsh environmental conditions. The third configuration has an advantage over the other two configurations with respect to radome aberration correction. However, special care in design needs to be taken to handle dual polarisations. The paper also brought about the specific test facility required for testing and evaluation of passive seeker to characterize it with missile radome. A brief on the future area of research with metamaterials and metasurface based wideband antennas has been covered.

REFERENCES

1. Haugen, N.K. A simulation analysis of a Suppression of Enemy Air Defense (SEAD) operation. Naval Postgraduate School, Monterey, California, 1998. Master's Thesis.
2. Tang, J.; Cao, F. & Li, S. Analysis of anti-radiation missile antagonizing active decoy technology. *In* International Conference on Automation, Mechanical Control and Computational Engineering (AMCCE), 2017. doi: 10.2991/amcce-17.2017.158.
3. Werntz, P.C. & Stutzman, W.L. Design, analysis and construction of an Archimedean spiral antenna and feed structure,Proceedings. Proc. *IEEE* Energy. Inf. Tech. in the Southeast, 1989, **1**, 308-313. doi:10.1109/secon.1989.132385.
4. Zhou, H.; Sutton, N.A. & Filipovic, D.S. Surface micromachined millimeter-wave log-periodic dipole array antennas. *IEEE Trans. Antennas Propag.*, 2012, **60**(10), 4573–4581. doi:10.1109/TAP.2012.2207335.
5. Gibson, P. J. The vivaldi aerial. *In* 9th European Microwave Conference, 1979, 101-105. doi:10.1109/euma.1979.332681.
6. Rutkowski, A. & Kawaleca, A. A concept of a microwave seeker designed for an anti-radiation missile. *In* 12th Conference on Reconnaissance and Electronic Warfare Systems, SPIE, 2019, 210-215. doi: 10.1117/12.2524749.
7. https://en.wikipedia.org/wiki/Kh-31 (Accessed on 21 June 2023).
8. Wangsvick, C. Conformal broadband directional 1/2 flared notch radiator antenna array. U.S. Patent 10103444, 2018.
9. https://www.brasilemdefesa.com/2013/07/misseis-anti-radiacao-mar-1-mectron.html. (Accessed on 21 June 2023)
10. Mark, B.; McNaul, B.; Tony, R.; Jon, D. W.; Sinclair, R.; Wittmond, J. & Zimmer, W. Antenna array apparatus with conformal mounting structure. U.S. Patent 6407711, 2002.
11. Larratt, D.R. Advanced Anti-Radiation Guided Missile (AARGM). https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2009/gunmissile/AARGM.pdf. April 08, 2009. (Accessed on 21 June 2023).
12. Guinvarc'h, R.; Serhir, M. & Fabrice, B. A compact dual-polarized 3: 1 bandwidth omnidirectional array of spiral antennas. *IEEE Antennas Wirel. Propag. Lett.*, 2016, **15**, 1909–1912. doi: 10.1109/LAWP.2016.2542982.
13. Lam, T.; Bidwell, R. & Blee, S. Spiral antenna design considerations. *Microwave J.*, 2013, **56**(1), 84-94.
14. Lee, M.; Kramer, B.A.; Chen, C.C. & Volakis, J.L. Distributed lumped loads and lossy transmission line model for wideband spiral antenna miniaturisation and characterization. *IEEE Trans. Antennas Propag.*, 2007, **55**(10), 2671–2678. doi:10.1109/TAP.2007.905823.
15. Sakomura, E.S.; Ferreira, D.B.; Bianchi, I. & Nascimento, D.C. Analysis of Archimedean spiral antenna fed by Hecken and exponential microstrip baluns. *IEEE* International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2018,851–852. doi:10.1109/APUSNCURSINRSM.2018.8608479.
16. Zhong, Y.W.; Yang, G.M.; Mo, J.M. & Zheng, L.R. Compact circularly polarized archimedean spiral antenna for ultrawideband communication applications. *IEEE Antennas Wirel. Propag. Lett.*, 2017, **16**,129–132. doi:10.1109/LAWP.2016.2560258.
17. Ali, A.; Hamza, M. & Khan, W. Smallest form factor, high performance 2-18 GHz cavity-backed archimedean spiral antenna. International Symposium on Antennas and Propagation (ISAP), 2017, 1–2. doi: 10.1109/ISANP.2017.8228902.

18. Fang, H.R.; Serhir, M.; Balakrishnan, R.; Guinvarc'h, R. & Mouthaan, K. Low profile cavity-backed four-arm Archimedean spiral antenna with 8:1 bandwidth. The 8th European Conference on Antennas and Propagation (EuCAP), 2014, 2528–2531. doi: 10.1109/EuCAP.2014.6902333.
19. Ding, F.; Zhang, F. & Zhang, Y. The broadband composite structure spiral antenna with a ladder-shaped backed-cavity. 4th IEEE Int. Sym. on Microwave, Antenna Propag. & EMC Technologies for Wireless Communications, 2011, 120–123. doi: 10.1109/MAPE.2011.6156249.
20. Baker, D.E. & Toit, J.B. A Compact 1 to 18 GHz planar spiral antenna for interferometer and other direction finding applications. IEEE-APS Topical Conference on Antennas Propag. in Wireless Comm. (APWC), 2012, 1016-1019. doi: 10.1109/APWC.2012.6324984.
21. Rahman, N.; Sharma, A.; Afsar, M.; Sandeep, P. & Cheung, R. Dielectric characterisation and optimisation of wide-band, cavity-backed spiral antennas. *The Appl. Compt. Electromagn. Soc. J. (ACES)*, 2011, **26**(2), 123-130.
22. Yu, C.; Hong, W.; Yu, C.; Kuai, Z.Q. & Qin, W. Band-notched UWB printed log-periodic dipole antenna fed by half mode substrate integrated waveguide. Proc. Int. Symp. Antennas and Propagation (ISAP), 2009, 496–499. doi: 10.34385/proc.51.2C4-5.
23. Groutage, F.D.; Borunda, G.S. Dual mode guidance system. U.S. Patent 4108400, 1978.
24. Wang, Z.; Zhao, X.; Ji, F.; Huang, S. & Jiang, Z. Ultra-wideband cylindrical conformal array antenna based on LPKDA. *IEEE* MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO), 2020, 1–4. doi: 10.1109/NEMO49486.2020.9343641.
25. Zhang, M.; Zhu, L.; Wang, Y. & Cui, J. A printed log periodic dipole antenna with broadband application from 0.5 to 15 GHz. Photonics & Electromagnetics Research Symposium-Fall (PIERS-Fall), 2019, **36**, 3027–3031. doi: 10.1109/PIERS-Fall48861.2019.9021514.
26. Qiaoyu, C.; Hu, Z.; Shen, Z. & Wu, W. 2-18 GHz Conformal Low-Profile Log-Periodic Array on a Cylindrical Conductor. *IEEE Trans. on Antennas Propag.*, 2018, **66(**2), 729–736. doi: 10.1109/TAP.2017.2782259.
27. Yang, Z.; Jingjian, H.; Weiwei, W. & Naichang, Y. A printed LPDA antenna fed by a microstrip line to double sided parallel strip line from backside. *Int. J. Antennas Propag.*, 2017. doi: 10.1155/2017/6259682.
28. Chang, L.; He, S.; Zhang, J.Q. & Li, D. A compact dielectric-loaded log-periodic dipole array (LPDA) antenna. *IEEE Antennas Wirel. Propaga. Lett.*, 2017, **16**, 2759–2762.
29. Song, L.; Nie, Y. & Wang, J. A novel meander line microstrip log-periodic dipole antenna for dual-polarized radar systems. *Prog. Electromagn. Res. Lett.*, 2015, **56,** 123–128. doi: 10.2528/PIERL15081403.
30. Song, L. Design and experiment of a conformal monopulse antenna for passive radar applications. *Int. J. Future Gener. Commun. Netw.,* 2015, **8**(3),147–160. doi: 10.14257/ijfgcn.2015.8.3.14.
31. Kang, C.Y.; Lin, S.; Zhao, Z.H. & Jing, L.W. The simulation and experiment of a non-cross-feeding printed log-periodic antenna. *Int. J. Antennas Propag.*, 2015. doi: 10.1155/2015/783405.
32. Sun, Q.; Wang, J.; Cui, J.; Fu, J.; Zhou, C. & Wang, E. A compact printed log-periodic antenna with loaded stub. Proceeding of 2014 3rd Asia-Pacific Conference on Antennas and Prop,2014, **3**, 593–595. doi: 10.1109/APCAP.2014.6992564.
33. Liu, Y.; Shui, X.; Lu, H.; Si, L.; Ge,Y. & Lv, X. Design of ultra-wideband printed log-periodic dipole antenna. *IEEE* International Conference on Microwave Tech. & Comp. Electromag. (ICMTCE), 2013, 176–178. doi: 10.1109/ICMTCE.2013.6812415.
34. Casula, G.A.; Maxia, P.; Mazzarella, G. & Montisci, G. Design of a printed log-periodic dipole array for ultra-wideband applications. *Prog. Electromag. Res.*, 2013, **38**, 15–26. doi: 10.2528/PIERC13012704.
35. Casula, G.A; Maxia, P. & Mazzarella, G. A printed LPDA with UWB capability. International Workshop on Antenna Technology (iWAT), 2010, 1–4. doi: 10.1109/IWAT.2010.5464929.
36. https://www.radartutorial.eu/06.antennas/Tapered%20Slot%20Antenna.en.html. (Accessed on 22 June 2023)
37. Moosazadeh, M. Antipodal vivaldi antennas for microwave imaging of construction materials and structures. Springer Nature, Switzerland AG, 2019. pp 11-12. doi: 10.1007/978-3-030-05566-0.
38. Salvail, G. & Steven, W.B. Broadband conformal inclined slotline antenna array. U.S. Patent US5220330A, 1993.
39. Farooq, M.; Fatima, S. & Cheema, H.M. A wideband miniaturised tapered slot Vivaldi antenna. IEEE International Symposium on Antennas & Propagation, 2020, 597–598. doi:10.1109/IEEECONF35879.2020.9330006.
40. Li, K.; Liu, M. & Zhang, H. An L-Band ultra wide-band vivaldi antenna with wide beam angle. 13th UK-Europe-China Workshop on Millimetre-Waves and Terahertz Technologies (UCMMT), 2020, 1-3. doi:10.1109/UCMMT49983.2020.9296122.
41. Mohapatra, S. Array of vivaldi antenna arranged in circular fashion for MTI Radar. *J. Xidian University*, 2020, **14**(8) 685–693. doi: 10.37896/jxu14.8/074.
42. Shukla, S.; Koul, S.K. & Abegaonkar, M.P. 6:1 bandwidth linearly polarised compact Vivaldi antenna array. Asia-Pacific Microwave Conference (APMC), 2018, 1540–1542. doi: 10.23919/APMC.2018.8617261.
43. Ren, X.; Liao, S. & Xue, Q. Design of wideband circularly polarised Vivaldi antenna with stable radiation pattern.

IEEE Access, 2017, **6**, 637–644.
doi: 10.1109/ACCESS.2017.2773566.

44. Perdana, M.Y.; Hariyadi, T. & Wahyu, Y. Design of vivaldi microstrip antenna for ultra-wideband radar applications. IOP Conference Series: Materials Science and Engineering, 2017, **180**(1), 012058.
doi: 10.1088/1757-899X/180/1/012058.
45. Li, Z.; Kang, X.; Su, J.; Guo, Q.; Yang, Y.L. & Wang, J. A wideband end-fire conformal Vivaldi antenna array mounted on a dielectric cone. *Int. J. Antennas Propag.,* 2016.
doi: 10.1155/2016/9812642
46. Yue, Y; Dong, Y & Zhou, J. An ultra-wideband vivaldi antenna array in L and S bands. *In* IEEE 5th Asia-Pacific Conference on Antennas & Propagation (APCAP), 2016, 301–302.
doi: 10.1109/APCAP.2016.7843213.
47. Si, L.; Tang, H.; Shui, X.; Lu, H.; Liu, Y.; Ge, Y & Lv, X. Design of a 6-18 GHz UWB conformal antipodal Vivaldi antenna array. *In* IEEE International Conference on Microwave Tech. & Comp. Electromag. *(ICMTCE)*, 2013, 153–156.
doi: 10.1109/ICMTCE.2013.6812409.
48. Adamiuk, G.; Zwick, T. & Wiesbeck, W. Dual-orthogonal polarized vivaldi antenna for ultra wideband applications. *In* 17th International Conerence on Microwaves, Radar and Wireless Communications (MIKON), 2008, 1-4.
49. Logan, L.T.; Dorsey, W.M. & Valenzi, J.A. Modular All-metal ultrawideband cylindrical array for multifunction operation. *IEEE Trans. on Antennas Propog.*, 2022, **70**(10), 9175-9183.
doi: 10.1109/TAP.2022.3177504.
50. Zhao, C.; Bai, Y. & Wei, Q.A. 2 to 50 GHz all-metal Vivaldi antenna for ultra-wideband (UWB) application. *AEU-Int. J. Electron. Commun.,* 2022, **148**.
doi: 10.1016/j.aeue.2022.154162.
51. Lim, T.H.; Park, S.; Lee, C.S. ; Park, J.R. & Choo, H. A broadband dual-slant polarized metal vivaldi antenna for a high-power jammer. International Symposium on Antennas and Propagation (ISAP), 2021, **1**, 485–486.
doi: 10.23919/ISAP47053.2021.9391471.
52. Li, X.; Wu, H. & Tao, J. Design of an Ultrawideband All-metal vivaldi array with offset feed structure. *In* Cross Strait Radio Science & Wireless Technology Conference (CSRSWTC), 2020, 40–42.
doi:10.1109/CSRSWTC50769.2020.9372709.
53. Prasanna, C.L.; Lakshmi, M.B. & Sastry, N.N. A parametric analysis & design of all metal vivaldi antenna covering 3.0-18 Ghz for DF and phased array applications. *Prog. Electromagn. Res. C.*, 2019, **92**, 57–69.
doi: 10.2528/pierc19020601.
54. Ma, X.; Chai, S.; Xiao, K. & Ding, L. Design of all-metal vivaldi phased array antenna. *In* IEEE 3rd International Conference on Signal and Image Processing (ICSIP), 2018, 547–551.
doi: 10.1109/SIPROCESS.2018.8600487.
55. Tianang, E.G.; Mohamed, A.; Elmansouri & Filipovic, D.S. Ultra-wideband lossless cavity-backed Vivaldi antenna. *IEEE Trans. Antennas Propag.*, 2017, **66**(1), 115-124.
doi: 10.1109/TAP.2017.2775286.
56. Gulati, G.; Liang, M. & Xin, H. A conformal dual-polarised all-metal vivaldi array for feeding broadband luneburg lens. IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2017, 2243-2244.
doi:10.1109/APUSNCURSINRSM.2017.8073164.
57. Tricoles, G.P. Radome Electromagnetic Design. Tn:Lo, Y.T., Lee, S.W.(eds). Antenna Handbook, 2081.
doi: 10.1007/978--4615-6459-1_31.
58. Darling, T.B. Military radome performance and verification testing. https://www.nsi-mi.com/images/Technical_Papers/Articles/NSI-MI%20-%20Military%20Radome%20Performance%20and%20Verification%20Testing.pdf
(Accessed on 2023-06-23)
59. Hess; D.W.; Luna, R. & McKenna, J. Electromagnetic radome measurements: A review of automated systems. Proceedings of the Loughborough Antennas Prop. Conf., Loughborough, 2005, England.
60. Xu, H.X.; Wang, S.; Wang, C.; Wang, M.; Wang, Y. & Peng, Q. Polarization-insensitive metalens and its applications to reflectarrays with polarization diversity. *IEEE Trans. Antennas Propag.*, 2022, **70**(3), 1895-1905.
doi: 10.1109/TAP.2021.3112553.

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